PRELIMINARY DESIGN OF A PRESSURIZATION SYSTEM FOR SMALL BIPROPELLANT ROCKET ENGINES

by

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For my Father who inspired me to become an engineer.

Jack Stanley (1945-2007)

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ABSTRACT

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A study was conducted on the feasibility of developing a device or system that would improve the performance of small, bipropellant rockets through pressurization of the propellants. Due to the limitations in the space industry, namely high development costs and resistance to change, the new approach needed to be as simple and robust as possible. After reviewing several different potential methodologies, a concept was developed from first principles based on small gas turbine engine fuel injection approaches. The concept is simple and has heritage in the field of gas turbine engines, but it is new for the field of rocket propulsion.

Using the basic physics of the proposed baseline concept, a simulation was developed to optimize the design parameters and to explore the trade space. Exercising the resulting simulation led to the identification of the critical design parameters and

key performance metrics. During the iteration process, the design was updated and finalized. The resulting configuration appears to be feasible and has the potential of providing a new capability for small bipropellant rockets. Based upon the results of the study, recommendations were developed and a plan was created to further the development of the pump.

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NOMENCLATURE

A	flow area
CdP	combustor pressure drop
CDR	critical design review
CEA	Chemical Equilibrium and Application Program
Ceff	combustor efficiency
CFD	computational fluid dynamics
CoDR	concept design review
CRo	ratio of combustor outer radius to combustor inner radius
Cv	loss factor in fluid systems
d	ball bearing diameter
delta V	change in velocity associated with orbital manuevers
dN^2	bearing speed parameter
DP	design point
dP	pressure differential
duty cycle	pulse mode operation ratio of on time to total cycle time
Eff	efficiency
Eff_Pump	pump efficiency
Eff_turb	turbine efficiency
F	thrust

FORP	fuel and oxidizer reaction products
FuelSplit	fraction of total fuel flow split off for the rocket
GHe	gaseous helium used as a pressurant
HAN	hydroxyl ammonium nitrate
H_{in}	inlet enthalpy
H_{out}	outlet enthalpy
HPturb	turbine power output
HydMargin	hydraulic dam inner margin
InjdeltaR	injector height
Isp	specific impulse
K	loss factor in fluid systems
L	pump length, scroll recovery loading parameter
L1-L3	miscellaneous length dimensions
Mdot	mass flow rate
MMH	monomethylhydrazine
MON-3	dinitrogren tetroxide with 3% nitrogen dioxide
MRR	manufacturing readiness review
N	shaft speed
NC	normally closed pyro valve
NEO	near Earth objects
NPSS™	Numerical Propulsion System Simulation
O/F	oxidizer to fuel ratio

OD	off design
OxSplit	fraction of total oxidizer flow split off for the rocket
P	pressure
Pc	chamber pressure
PDR	preliminary design review
P_{in}	inlet pressure
P_{out}	outlet pressure
Poturb	turbine outlet pressure
PRturb	turbine pressure ratio
r	radius
R1-R5	miscellaneous radial dimensions
Rfl_in	fuel inner shaft inner radius
R_i	inner radius of hydraulic dam fluid level
Ri_brn	combustor inner radius
Ri_fuel	fuel hydraulic dam inner radius
Ri_ox	oxidizer hydraulic dam inner radius
R_o	outer radius of hydraulic dam fluid level
Ro_brn	combustor outer radius
Ro_fuel	fuel hydraulic dam outer radius
Ro_ox	oxidizer hydraulic dam outer radius
Rox_in	oxidizer inner shaft inner radius
R_{rim}	outer radius of shaft

Rrim_fuel	fuel inner shaft outer radius
Rrim_ox	oxidizer inner shaft outer radius
SSME	Space Shuttle Main Engine
ShaftDuct	flow passage on the inside of a rotating cylinder
ShaftDuctDelta	hydraulic dam outer margin
T	temperature
t	film thickness
TET	turbine exit temperature
TRIT	turbine rotor inlet temperature
TRR	test readiness review
V	velocity
V_e	rotary injector exit velocity
Vrim_fuel	fuel inner shaft rim speed
Vrim_ox	oxidizer inner shaft rim speed
W	system weight
Wcomb	combustor mass flow rate
Wfuel	fuel mass flow rate
Wox	oxidizer flow rate
ΔH	change in enthalpy
$\Delta Hideal$	ideal change in enthalpy
ΔP	pressure differential

ΔR	change in radius or difference in to radii
ΔT	change in temperature
ΔT_{ideal}	ideal change in temperature
ρ	density
ω	rotational speed

CHAPTER 1

INTRODUCTION

1.1 Purpose

The purpose of the study described herein is to explore the potential implementation and characteristics of a novel pump concept called a Combustion Driven Drag Pump intended to improve the performance of small bipropellant rocket engines. The rockets of interest are larger than thruster class rockets and produce more than 400 N (100 lbf) of thrust, yet smaller than upper stage rockets requiring 8,000 N (2,000 lbf) of thrust. Additionally, the propellants addressed in the study are monomethylhydrazine (MMH) and dinitrogren tetroxide with 3% nitrogen dioxide (MON-3), which are common propellants for rockets in this thrust class. For brevity, monomethylhydrazine will be referred to as MMH, and dinitrogren tetroxide with 3% nitrogen dioxide will be referred to as MON-3. It should be noted, and will be addressed further, that the choice of propellants is somewhat arbitrary, and with minor modifications, the pump could be designed to work with other combinations of propellants.

The study covers the genesis of the pump concept, as well as how the pump was investigated. Unfortunately, fully developing a pump for use with small bipropellant rockets is prohibitively expensive for a single individual to pursue and is beyond the scope of the investigation described herein. Thus, the boundaries of the study are set to allow for a preliminary design and evaluation, but stops short of the development of any hardware, detailed design, or specific detailed analyses. Exploration of the concept is intended to help define the performance characteristics and aid in the optimization of a design consistent with the efforts prior to a Preliminary Design Review (PDR).

Like with most preliminary designs, the basic concept was selected and optimized to arrive at a conceptual design that could be refined. Consistent with an initial design effort, the design will likely need adjustments, but not extensive modifications, going into the next phases of a development program. Therefore, the study is intended to provide the foundation for future design and development efforts relating to the Combustion Driven Drag Pump. In keeping with the preliminary nature of the study, the basic physics of the concept are modeled to aid in the design maturation process. The selection of the baseline, the development of the performance model and the optimization of the design features are explored in detail. As with any study of this nature, conclusions and recommendations provide a plan regarding future efforts in the development of the Combustion Driven Drag Pump.

1.2 Industry Background

A basic understanding of the rocket industry is helpful in order to understand some of the concepts and rationale relating to the development of the Combustion Driven Drag Pump. The discussion will take the form of observations and commentary on different aspects of the industry. Much of the information is common knowledge to the industry, but requires some clarification on how the peculiarities of the space propulsion industry affected the development of the study.

1.2.1 Classes of Rockets

Modern liquid propellant rocket engines come in a variety of forms and thrust levels, depending on their intended usage [1]. Large engines, such as the F-1, J-2, RL-10 and Space Shuttle Main Engine (SSME), provide high levels of thrust for launch or stage thrust applications [2]. These engines are characterized by the use of high performance propellants, large expansion ratio nozzles and produce a considerable amount of thrust, usually in excess of 65 kN (14.6 klbf) [2].

For the large rocket engine category, performance is most important, which explains a great deal about the design approach used for large rockets. Among the performance enhancing attributes, one will usually find a means to provide pressurized propellant to the rocket in order to improve overall performance [2]. Any general rocket textbook, such as those written by Sutton [2] or Huzel [1], describes and evaluates the benefits of high pressure propellants used in large thrust applications.

All of the engines mentioned previously have devices called turbopumps, as do most other engines in the large or lift engine category. A typical turbopump is a miniature gas turbine style engine where fuel and oxidizer react in a combustion chamber and then the combustion products pass through a power turbine [3]. The power turbine provides the shaft power to rotate the pumping elements. Fuel is pumped by one impeller or a set of impellers in series, and the oxidizer is pressurized by a different impeller or set of impellers. The high pressure propellants are then injected into the rocket chamber to produce thrust.

The specifics of turbopumps can vary from engine to engine depending on the design philosophy and intended usage of the engine. It is common to see propellants pressurized before being combusted and to find engines where the pump is split into two separate pumps, one for each propellant, as in a J-2 rocket [2]. There are even cases where the turbine is driven solely by gas that is generated by using fuel or oxidizer to cool the main chamber of the rocket engine instead of combusting the propellants [2]. The last, called an expander cycle rocket, can be represented by an RL-10 [4]. In all cases, the pump is composed of some form of turbomachinery where aerodynamic forces in the impeller and turbine are used to improve the performance and/or the size of the overall system. Figure 1.1 is an illustration of different rocket pump systems for modern engines in the large or lift category.

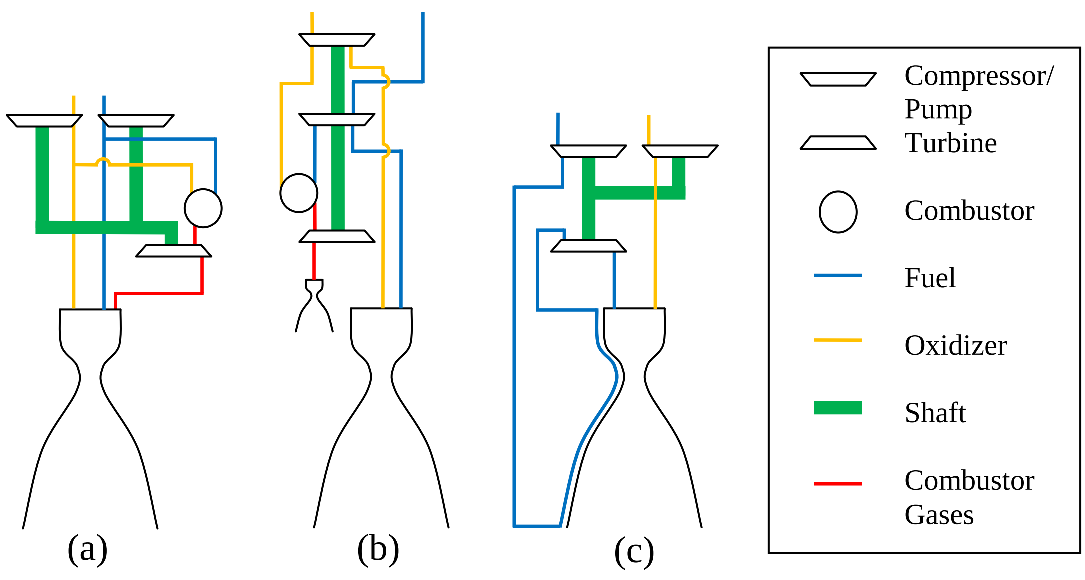


Figure 1.1 Examples of Different Rocket Pump Propulsion Systems (a) Staged Combustor, (b) Gas Generator and (c) Expander

The first basic style is a staged combustor cycle where a small amount of the propellants are burned. The hot gases provide the impulse for a turbine, which is used to drive the two pumps. The exhaust of the turbine feeds directly into the engine. Sometimes staged combustor engines put all the fuel through the pump to eliminate one injector stream and increase the turbine exit pressure. A gas generator cycle is similar except that only small portions of the propellants drive the turbine resulting in lower turbine exhaust pressure. The lower turbine exhaust pressure drives the need for a separate exhaust nozzle or injection of the turbine exhaust into a low-pressure region of the nozzle. Finally, an expander cycle uses heated fuel or oxidizer to drive the power turbine. In an expander cycle, the heated propellant is initially pressurized by the turbopump. It then goes to the nozzle where the propellant picks up heat by cooling the nozzle and chamber. The heated propellant drives the power turbine before entering the thrust chamber. The other propellant stream runs through its side of the pump on its way to the chamber.

By contrast, rockets used to provide very small thrust levels emphasize reliable operation and consistent performance [1]. Interestingly, the small rocket class of engines does not require very high performance. Typical use of these engines is almost exclusively for orbital manuevers and spacecraft control. Often they provide six (6) degrees of freedom control on satellites and space vehicles or for launch vehicle stability during accent and high altitude staging manuevers. Currently, the largest of these engines is the Space Shuttle Orbital Maneuvering System Engine (OMS-E), which generates a total thrust of 22.2 kN (5 klbf) [2]. The engine is used at the end of the shuttle mission to help slow down the shuttle for reentry or to help with orbital transfers [2]. On the smaller side, thrusters help manage angular momentum in satellites. These thrusters produce low thrust levels, measured as low as 1 N or 2 N (0.225 lbf or 0.45 lbf).

An interesting contrast to the larger class of engines is that performance of these smaller engines does not play a significant role. Instead, the performance drivers are on precise thrust levels, repeatability and reliability over long durations, sometimes decades. Many of the Voyager 1 and Voyager 2 thrusters are still firing over thirty years later [5]. For the most part, the smaller engines have to be able to produce a very small predictable amount of thrust every time they run.

Within the small rocket class, there are two primary sub-classes of rockets. The classes are broken up along the type of propellant that is used [2]. The more common sub-class uses monopropellant thrusters where only a single propellant provides thrust, usually by way of catalytic reaction [6]. The other sub-class uses two propellants and is called bipropellant rockets. Due to the higher performance of the bipropellant rockets, they are typically used for larger delta V maneuvers, while the monopropellant thrusters with their greater simplicity are used for attitude control systems [7]. The actual usage and architecture of the system is highly dependent upon the mission and other factors associated with the spacecraft. As a result, bipropellant rockets tend to be larger and need to provide higher performance than monopropellant rockets. Therefore, bipropellant rockets are similar to the larger class of rockets in that respect.

Unfortunately, their overall performance is sacrificed for simplicity and reliability dictated by the propulsion system architecture.

1.2.2 Small Rocket Propulsion System Architecture

Due to the difference in emphasis between the larger rockets and the smaller rockets, an entirely different architecture for small rocket propulsion systems developed [1]. The architecture for small rockets and thrusters consists of propulsion systems with highly pressurized propellant tanks that provide pressurized propellants to the rockets. The systems, called blow down systems, decrease in feed pressure as the rocket consumes propellant. A basic schematic of a blow down system is shown in Figure 1.2.

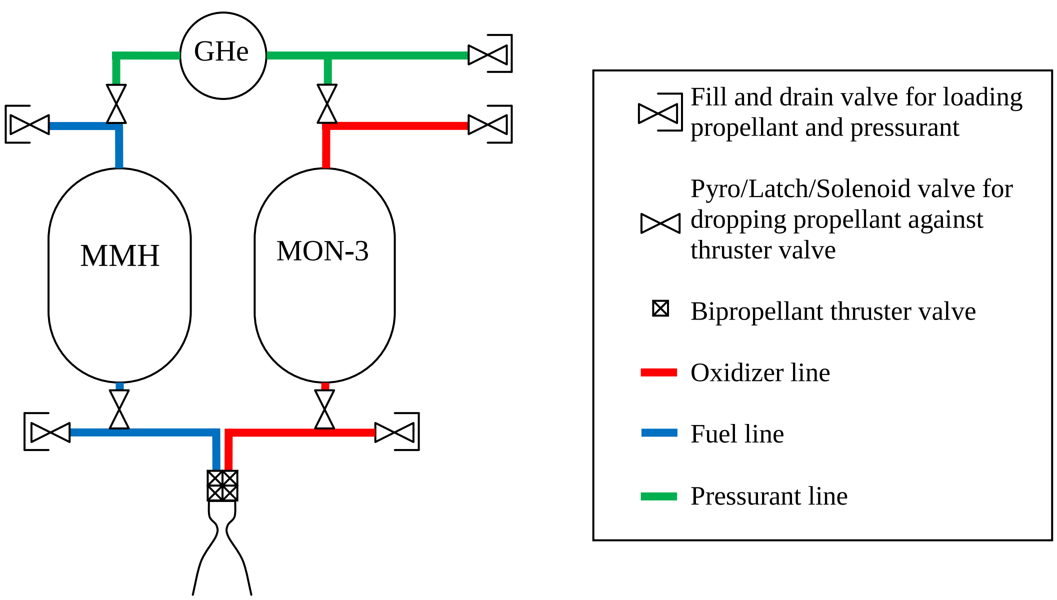


Figure 1.2 Schematic of a Simple Blow Down System

As Figure 1.2 shows, the system is quite simple and provides very reliable operation. Occasionally, higher performance is needed or desired, so the system is modified to provide a high pressure recharge of the propellant tanks to increase the overall system performance [8]. The process refers to a repress or repressurization operation. Figure 1.3 shows the slight modifications characterized by two or more high pressure, pressurant tanks that are needed for the repressurization system variant. The system behaves like the more traditional blow down system, except that when the pressurant in the first tank drops low enough in pressure, the normally closed pyro valves are opened to recharge the system.

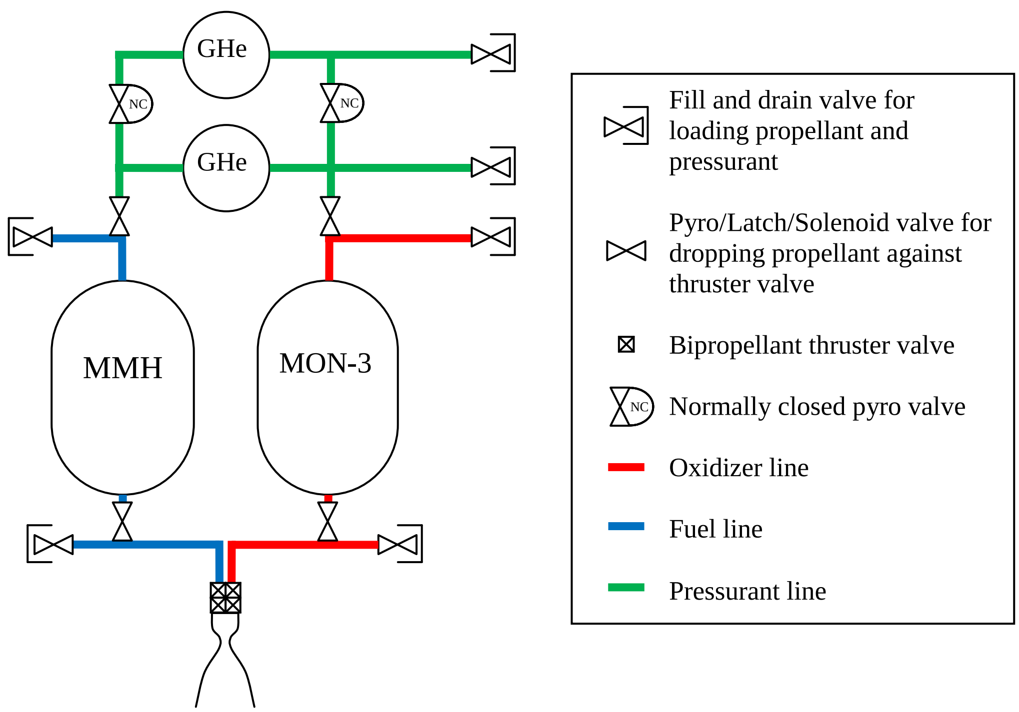


Figure 1.3 Schematic of a Repressurization System

The third common propulsion system that is used is a regulated blow down system shown in Figure 1.4. In a regulated blow down system, the propellant feed pressure remains constant in order to preserve performance [1]. Regulating the supply pressure maintains the feed pressure at a particular value by resupplying the pressurant tank as the system blows down. The resupply uses a regulator to meter flow from a very high pressure source. Regulated systems are more complicated and require more hardware to accomplish the task, principally a high pressure tank and a regulator. Both elements add to the cost and complexity of the system.

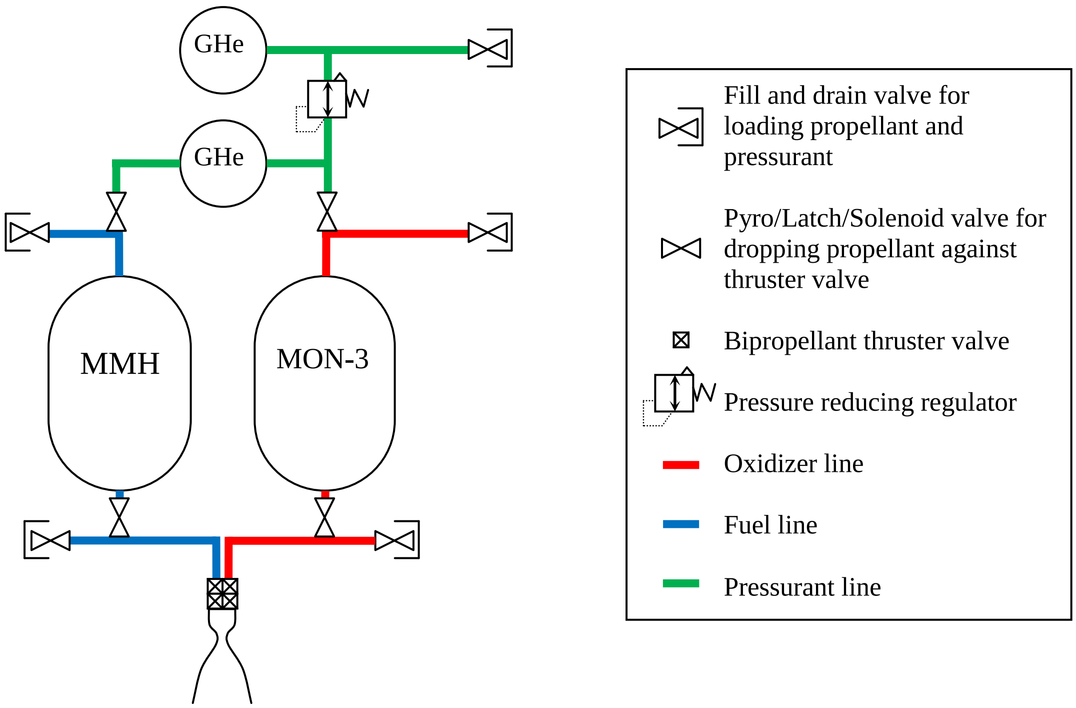


Figure 1.4 Schematic of a Regulated Blow Down System

A fourth class of blow down system, shown in Figure 1.4, called a dual mode system, is sometimes used when a wide variety of thrust levels is needed. A typical application needing different thrust levels is interplanetary exploration missions, where a large thrust level provides for orbital manuevers, but small thrusters are needed for precision pointing [9]. The large thrust level is often provided by small bipropellant rocket engines, and monopropellant thrusters provide the small thrust levels for attitude control. The interesting element of this system is the fact that the fuel is common for both the bipropellant engine and the monopropellant engines. Using a common fuel makes it a challenge to maintain the mixture ratio on the bipropellant engine within the qualified heritage since the pressures of the oxidizer and fuel may not be the same at all times. Figure 1.5 provides an example of a dual mode system where the fuel tank is shared between the bipropellant rocket and the monopropellant rockets.

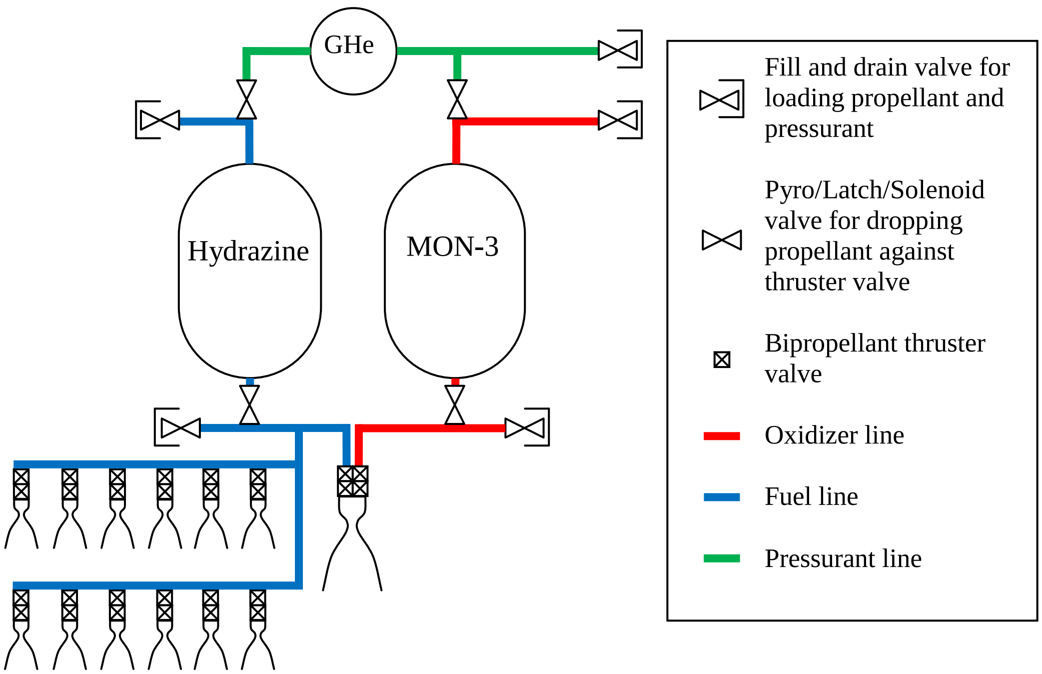


Figure 1.5 Schematic of a Dual Mode System

1.2.3 Small Rocket Operation

The operation of small rockets is also different from larger engines. Larger engines are normally throttleable in a continuous and smooth manner by adjusting the propellant flow rates. Smaller rockets are throttleable only through using discrete pulses. A discrete pulse occurs when the propellant valve(s) are opened for a short period of time and then closed for a short period of time [6]. Operating a rocket in this manner is inefficient in that every time the rocket starts and every time the rocket stops the transient portion of the thrust reduces the overall rocket performance [7]. The primary reason for this difference in operation is the fact that for small rockets the overall performance is not as important as for large engines. In fact, the ideal performance of a small rocket is characterized by being able to produce very small incremental bursts of thrust, not sustained high efficiency thrust.

Several interrelated issues drive the pulses that characterize small rocket performance. The first is the ability of the valves to open and close quickly. The valve response time determines the minimum pulse width that the rocket may be capable of attaining. Coupled to that is the size of the dribble volume, which is the volume between the valves and the thrust chamber. The reason the dribble volume is important is that after the valves close, the dribble volume contains a small amount of propellant that has to evaporate and vacate the chamber before the next pulse. The larger the volume the longer it takes to evacuate the chamber. Evacuation of the volume is critical because any leftover propellant may form an explosive mixture, referred to as Fuel and Oxidizer Reaction Products (FORP) [10]. FORP can be explosive, such that in the presence of FORP, any additional fuel and oxidizer will overpressure the thrust chamber and cause significant damage. Thus, if the dribble volume is large, then the valve may not be the driving factor in the minimum pulse width.

A pulse itself consists of a surge flow period right after the valves open when there is no pressure in the rocket chamber [6]. Then the oxidizer and fuel react in the thrust chamber and create a high temperature gas. As the gas builds up, the nozzle throat chokes and the pressure builds in the chamber, this slows the propellant flows. Following the surge flow is a pseudo steady flow period where the rocket approaches both fluid dynamic and thermodynamic equilibrium. The pulse terminates with the valves closing, decreasing the pressure within the thrust chamber. Finally, the fuel and oxidizer slowly evaporate in the low pressure and leave the chamber. Figure 1.6 shows a generic illustration of how the pressure in the chamber and thrust might appear during pulse operations.

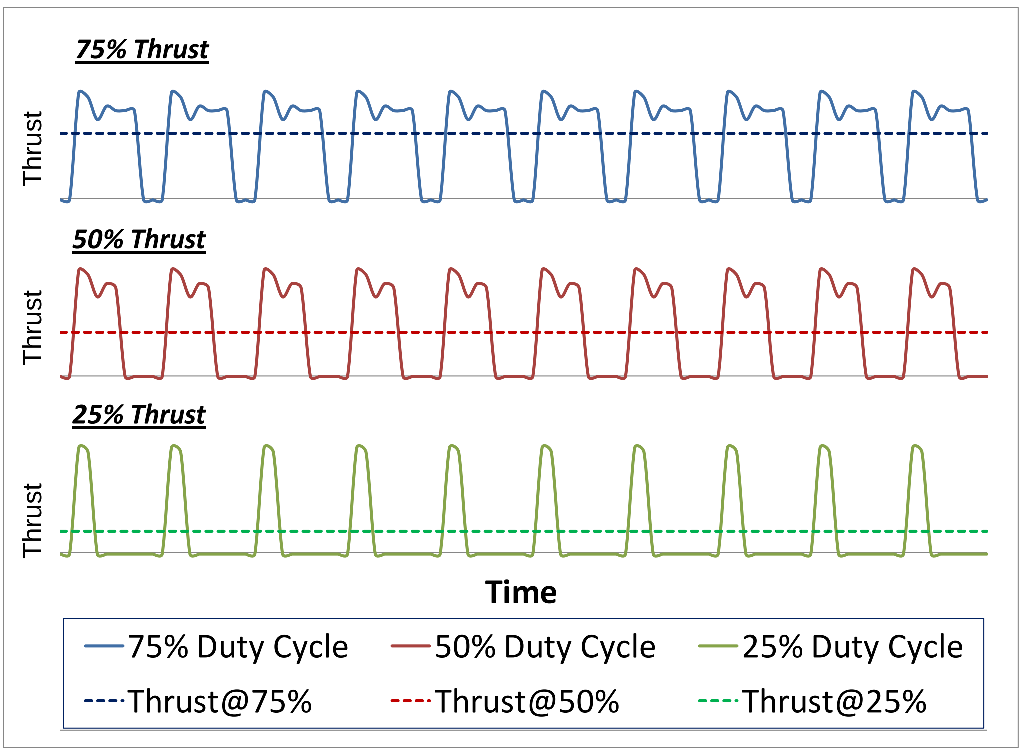


Figure 1.6 Example Pulse Trains to Produce Different Levels of Thrust

The initial time period of the pulse contains inefficiencies in both the thermal transients and in the work required to pressurize the chamber. The thermal loss is only significant for the first few pulses [6]. Once the system has heated up, the thermal loss decreases. However, the overall performance is decremented each time by the need to pressurize the chamber and the fact that some of the thrust occurs at lower pressure and lower temperature conditions. Similarly, during shutdown some of the thermal energy stored in the rocket structure is lost. The most notable loss is due to the propellants that vaporize after shut down and exit the chamber without producing significant thrust [6]. Once the pulses achieve a steady state of operation where each pulse is more or less in thermal equilibrium, one pulse looks like the next; the only losses are due to the transient pressure and temperature in the pulses. Regardless, using a pulsing operation to throttle a rocket is less efficient than a steady state rocket operating at part power [7].

1.3 Description of Problem

Up to this point, general observations about the rocket propulsion industry and characteristics of small propulsion systems have been addressed. In this section is a more detailed discussion of the limitations of the current architectures and how the Combustion Driven Drag Pump can improve overall performance.

As a blow down system consumes propellant, rockets lose performance as the feed pressure decreases [11]. For the control thrusters, the loss in thrust is not that important. The system simply has to turn the thrusters on for slightly longer times or increase the number of pulses in a pulse train in order to cancel out the effect. However, for the larger engines used for delta V manuevers in the small rocket engine class, performance is a more important parameter. The thrust loss and efficiency loss have to be carefully understood and planned for in order to successfully execute the mission [12].

1.3.1 Current Limitations

Numerous approaches have been investigated for improving bipropellant rocket performance, but all of them require more complicated architectures or different propellants than the current blow down propulsion system for space vehicles [11]. The different architectures include highly pressurized systems, regulated systems, repressurized systems or pump systems.

The highly pressurized system requires high pressure tanks, components, lines and rockets. A highly pressurized system provides the desired performance improvement but at the expense of risk and cost for the tanks and components [11]. Similarly, a regulated system provides the desired performance, but requires the addition of a high pressure gas source to maintain the pressure within the propellant tanks, which adds complexity and cost [11]. Next, a repressurization system provides some performance benefit, but also incurs the complexities and cost penalties of the highly pressurized system and the regulated system [11].

A pump system requires the addition of one component to the engine for maximum benefit. Additionally, the benefit of a pump system is that by using existing tank sizes and pressure capabilities, a rocket may be designed much smaller than those typically used today [2]. Rockets of this size scale inversely with feed pressure levels [1]. Thus, any increase in feed pressure will produce a smaller, lighter rocket.

The benefits of using a pump system have been known for quite some time as Robert Goddard spent a substantial amount of his time developing pumps for his rocket research in the 1920s and 1930s [13]. Unfortunately, making a pump for engines of this size is challenging [14]. There are different options available for developing a pump system, but they can be grouped into four categories. Based on how the power is provided for pressurizing the propellants determines which category the pump system goes into [3]. The first is an electric motor [11]. The second is through a power turbine, driven by a stored gas, such as helium or nitrogen [1]. Thirdly, the pump can be driven by heated propellant that is vaporized to keep the rocket combustion chamber cool [2]. Finally, combustion gases can drive a pump where a small amount of each propellant reacts in a combustion chamber independent of the rocket [1].

1.3.2 Technical Challenges

The successful development of a pump revolves around meeting and overcoming two primary challenges facing the pump. The first is how the power is developed and the second is how the pressure rise is achieved. The first challenge of how to drive the pump is difficult to address because the power needed for the pump is slightly more than is practical for an electric drive motor, yet too small for traditional power turbines when applied to small bipropellant rockets [15].

The second principle challenge of how to raise the pressure is difficult to meet at the sizes of interest for small bipropellant pumps because the volumetric flow rate is typically too low for highly efficient rotating impellers but too high for positive displacement pumps [16]. Since both of the primary challenges place the pump in a sort of no man's land, it is no wonder that pump development has yet to be successful for small bipropellant rocket engines.

1.3.2.1 Shaft Power Source

The option of using an electric motor to drive the pump appears to be a good fit for some space vehicles, especially ones with excess power generation capability. Unfortunately, using an electric motor has the disadvantage of requiring additional control electronics, higher power consumption and the presence of a motor, which has or generates a strong magnetic field. Strong magnetic fields have been shown to be detrimental to instrumentation and communications to or from spacecraft [9]. Never the less, using an electric motor to drive a pump, especially for very small rockets in the thruster sub-class, may be feasible. However, for the current study, the motor size required to drive a pump for a bipropellant rocket outweighs any realizable performance benefit.

Another option for developing the power necessary for driving the pump is to use pneumatic gases stored independently on the spacecraft to drive a small power turbine, similar to how high pressure air provides the power for a dentist's drill. Using pneumatic gases stored on the spacecraft requires additional tanks, feed lines and more complicated control systems. Furthermore, the amount of power that the turbine would produce is subject to the blow down rate of the system. A balance between the turbine power production and the propellant flow rates would need to be investigated and accounted for. Additionally, the amount of cold gas necessary to drive the turbine would quickly become a major factor in the overall system architecture. An example of the pneumatic gas style is the pump developed by John Whitehead of Lawrence Livermore Laboratory [17].

Conversely, using combustion gases from the propellants normally carries a penalty associated with overall performance. Any combustion process extracts energy from the rocket by siphoning off some of the propellant to drive the turbine. In contrast to the pneumatic gas driving system, the high temperature combustion products produce more power per pound of driving gas, which in itself is a net benefit to the system [18]. However, the exhaust of the turbine needs to be used in a beneficial manner to produce thrust in order to match or exceed the performance of the standard system. Two examples of the combustion gas driven pump system are Aerojet's design of a pump for the shuttle OMS engine called TRANSTAR [15] and the XLR-132 by Rocketdyne [19].

Finally, using preheated propellant to drive the pump offers the best overall performance option [2]. The heat rejected from the rocket provides the energy to drive the turbine. However, developing a small, liquid cooled bipropellant rocket is in itself a major development effort that is well outside the scope of this study.

Thus, the most appropriate option for generating power with the smallest impact to current systems and existing rockets is the use of a combustor and power turbine. The combustor approach has little impact on the system, as the propellants used to drive the turbine are extracted from part of the main flow to the rocket. Additionally, making maximum use of the turbine exhaust gases can be accomplished in a number of different ways. The combustion products can be injected into the rocket chamber to create a staged combustion system or they can be expanded in a separate thrust nozzle to create a gas generator system. Finally, the combustion products can be used as a coolant for the rocket or as a pressurant for one of the propellant tanks.

1.3.2.2 Pressure Rise Approach

The second major technical challenge is providing the pressure rise for the pump in an efficient manner. Two different styles of pumps provide the best options for the pumping element. The first is a centrifugal pump using rotating vaned elements for the pumping features. Interestingly, this class of pumping element requires very fast shaft speeds, especially as the volumetric flow rate decreases [14]. The fast shaft speeds typically require high performance bearings, precision machining, close tip clearances and high performance seals [3]. Herein, lies the most restrictive aspect facing the development of a pump in the size being discussed. Clearances for any moving parts have to be tightly maintained in order to attain a reasonable level of performance and creates a significant technical barrier.

Traditional turbopumps associated with larger rocket engines consist of impellers, rotors, seals, turbines, rotating shafts and in some cases gears [1]. In turbo machinery, the tip clearance between the rotating impellers and turbines and their static structures is important to the overall performance of the device [20]. Likewise, the seals must provide good isolation between high pressure and low pressure. When constructed for large rocket engines, the tip clearances and the seals do not have an overwhelmingly strong influence on the overall performance. However, when a turbopump scales down to the volumetric flow rate of a smaller engine, the tip clearances end up being almost as large as the blade spans themselves, which makes the tip clearance very important. Additionally, when the vanes become very small, the flow in the passages are completely engulfed in the boundary layer. Finally, because the shaft speed tends to go up as the size goes down, the seals end up being much more challenging to successfully implement.

The difficulties in using turbo machinery in small rocket engine sizes are a large part of the reason that the existing pressurization approaches are not traditional turbo machinery based pumps. Accordingly, the second method for providing pressure rise is a positive displacement pump, such as a gear pump or piston pump. However, for gear pumps, it is usually necessary to drive the pump with an electric motor, which requires batteries or a drain on the spacecraft power as discussed earlier. Additionally, the flow rate needed for a small bipropellant rocket drives the gear pump pressurizing elements to a rather large size.

For a piston pump, a driver gas, usually stored in a high pressure vessel, expands on one side of the pump to displace the propellant [14]. The driver gas can be from stored helium, nitrogen or combustion products. However, the need for sliding seals within the piston or gears and the fact that the driver gas exhausts at a lower pressure, results in an overall loss since the driver gas does not generate thrust. Thus, it seems as if there is not a practical solution for a pump in the size class of interest, since turbopumps cannot scale down to the correct size without major performance loss and positive displacement pumps have difficulty making use of the driver gas. Therefore, the industry would benefit from a new approach.

1.3.3 Cultural Challenges

Unfortunately, technical challenges are not the only challenges facing the development of a pump for small bipropellant rockets. A more pragmatic set of challenges impede the development of the pump of interest and drive many of the technical aspects of the studied pump.

One of the driving forces in the space industry is the cost of doing business. In an industry where years or sometimes decades of work can disappear in a heartbeat due to a catastrophic failure, it does not take much imagination to understand that caution and conservatism rule [21]. The approach to coping with the potential for disaster has created a methodology where every piece of hardware needs to be understood, modeled, tested and proven before it is used [22]. The need for a high degree of certainty and understanding manifests itself in every detail of the industry [22]. Ultimately, the environment results in a bias against new products or ways of doing business. As a result, incorporating a change, improvement or advancement has become difficult. It is common for customers to require the use of heritage systems only, or more exactly, systems that have already proven themselves in space.

Due to the conservative nature of the industry, the cost of developing new hardware, new approaches, or new technologies is very high. Essentially, any new device that is proposed must go through a full qualification program to convince people that the concept may work in space [22]. Following that, the new technology must demonstrate that it can operate in space, which requires it to fly on a space mission. The last requirement is somewhat circular in that by the very nature of being new, it cannot have heritage. It is interesting to observe that the cultural and the cost barriers have transformed a high tech industry, such as rocket propulsion, into an industry where innovation appears to be discouraged.

The discussion is not intended to support or refute the correctness of the bias against new ideas, but merely point out that the environment is a major driver behind the development of the Combustion Driven Drag Pump. Due to the non-technical barriers and the technological challenges, implementing a pump system has not been seriously addressed by the industry in spite of the fact that it is common knowledge that a pumped rocket provides better performance in a smaller package than current systems [23]. Therefore, the biggest driver in the development of the Combustion Driven Drag Pump is to develop a concept that would cope with the restrictions in the industry while demonstrating technical feasibility. In other words, keep the concept simple, easy to manufacture, risk tolerant and resistant to failure.

1.4 Performance Improvements

The question to ask becomes, “Is a performance improvement truly needed?” It is not entirely clear that the performance improvement from a high pressure rocket will provide a tremendous benefit to the industry or its customers. Never the less, there are clear advantages to the propulsion system for improving the overall rocket performance [24]. The benefit to the industry is outside the scope of this study. However, several benefits to the system can be qualified or at least described.

The first advantage is that a pump system provides high pressure local to the inlet of the rocket. With the inlet of the rocket being the only point where higher pressure occurs in the system, the tanks, lines and components upstream of the pump will not have to meet the high pressure requirements. For the tanks specifically, a tank is a single point of failure in the propulsion system in that if the tank fails, the system fails [25]. As a result, tanks designed with considerable structural margin undergo extensive testing to verify that they can withstand the worst possible combination of operating conditions. Normally, determining whether a tank is acceptable or not, requires building several additional tanks and testing them to failure in vibration, shock and burst [22]. Qualifying a tank can become very expensive, especially for high performance systems. To complicate the matter further, tanks are also the heaviest element in the system, so there is considerable pressure to reduce the tank margins in order to reduce its weight. Therefore, using a pump in a propulsion system can dramatically reduce the tank operating pressures and the associated risk of a single point failure. Unfortunately, the tanks would still be a single point of failure, but the probability of failure decreases with lower stresses.

The next benefit of a pump system is that the rockets in a pump system are smaller for the same thrust level [24]. If everything is to scale perfectly, a rocket operating at twice the feed pressure will be half the length, half the diameter and close to half the weight. In actuality, components of the rocket do not all scale: the propellant lines, propellant valves, flanges, bolts, etc. probably will not see an improvement [11]. However, a substantial weight savings is possible, especially in combination with the weight savings for a lower pressure tank.

The size savings also has secondary benefits. With a rocket that is half as long and half as big in diameter, the structural loads and the mass of the support structure both decrease [11]. Thus, the weight of the system may decrease even further. Just a decrease in size or mass of the propulsion system may be sufficient to improve overall performance in some applications. For example, if heat shields are needed to protect the spacecraft from the rocket heat, they would end up being smaller and so would the support brackets and shrouds.

From a pure performance standpoint, there is some benefit to increasing the pressure within the rocket chamber. This benefit comes from the fact that higher pressure tends to suppress dissociation of the combustion products [25]. Dissociation within a rocket exhaust decreases the overall temperature of the exhaust gas, which reduces the amount of thrust generated for the mass of the propellant [2]. Thus, operating at higher pressures will provide a small performance advantage.

However, this is not the only possible performance benefit. When high pressure fuel and oxidizer are generated, it is possible to use the fuel and/or oxidizer to improve the actual cycle of the rocket. One possibility is to use the highly pressurized fuel in an expander cycle to cool the rocket chamber and nozzle [1]. The preheated fuel is then injected into the rocket chamber and allowed to combust. Preventing the heat from leaving the rocket chamber generates more thrust per kilogram or pound of propellant, and cooling the chamber would allow higher temperature mixture ratios. Higher temperature mixture ratios normally provide an improvement in overall engine efficiency or specific impulse.

Another possibility is that high pressure pump combustion products or driver gas may be used for film cooling within the rocket chamber [1]. Again, the heat stays inside the rocket and is recovered in the exhaust stream. In both options, the rocket engines will have higher specific impulse or efficiency. The space shuttle OMS-E engine is an example of a fuel-cooled rocket, lending support to the concept [1].

By themselves, each of these improvements does not provide much of an advantage or enticement to develop a pumped system. In aggregate, they may justify the development of a pumped system. It is for the industry to determine the merit of using a pump. For this study, it was predetermined that the driver gas would provide film cooling within the rocket chamber as that would be the minimal impact on current system designs. In actual development, the integration of the propulsion system, the pump and the rocket is a system level trade, which is beyond the current scope.

1.5 Possible Uses

The uses of a pumped rocket propulsion system can be numerous. The most readily adaptable scenario is the use of a pumped system on a satellite that has to make multiple, large delta V maneuvers. Any geostationary satellite or polar orbit satellite will have significant delta V maneuver requirements [2]. Since both geostationary and polar satellites are typically costly and need to operate for many years, they represent likely candidates for performance enhancements. However, it should be noted that the performance provided by a solid booster could, in some cases, surpass the performance of a bipropellant rocket. The only advantage is that the pumped system can provide throttling, as well as, on/off functionality.

Another use is interplanetary probes, probes to the Moon, or Near Earth Objects (NEOs) typically require the use of several, large delta V manuevers [2]. These missions have very tight mass budgets and can benefit from any weight savings options available, providing performance remains high. Finally, missions to or from the surface of other planets, moons, or objects will likewise benefit from performance improvements [11].

1.6 Scope

It is clear that there is a potential performance benefit in developing a pumped bipropellant rocket propulsion system for satellites and spacecraft. However, it is not clear that the benefit is necessary or desired. The question about the usefulness is beyond the scope of the current study as it has been addressed in numerous other studies [7], [11], [23], [24], [26], [27]. However, the usefulness was considered. Private companies are taking a larger interest in space at the encouragement of President Obama [30] and this may affect a change in the current culture, enabling the development of a practical, pumped propulsion system [30]. However, the development of a pumped system must be consistent with a low cost approach. Therefore, the study emphasizes performance, low cost design, reliability and overall practicality of a pump for small bipropellant rockets. The scope of this study is limited to the initial evaluation of a low cost, reliable pump, the Combustion Driven Drag Pump, for use with small bipropellant rockets.

CHAPTER 2

BACKGROUND

2.1 Turbopump State of the Art

There is considerable history behind pumps in the rocket industry. Most of the background dates back to the early development of rockets but only relates to the larger class of rocket engines. Recent attempts to develop pumps for small rockets have taken different, less traditional approaches. Thus, the subject of the current study is not the first, nor is it likely to be the last of its kind. If further performance improvements are to be realized in the small rocket propulsion industry, then the advent of pumped rockets needs to occur. The other studies combined with this study can continue to apply incentives for the industry to further advance the state of the art in small bipropellant propulsion systems.

Robert Goddard began the modern era of rocket propulsion [31]. In his efforts to develop rockets, Goddard spent a considerable amount of time trying to develop turbomachinery for his rocket studies [13]. His efforts resulted in over two hundred patents [13]. In spite of his early recognition of the need for turbomachinery to provide pressurized propellants, it was not until the advent of World War II that the turbopump was developed for production. Wernher von Braun is generally credited with bringing the turbopump into the modern production era by developing the turbopump used for rockets between 1935 and 1942 for the German V-2 missile [31]. Shortly after Werner von Braun's successful efforts, Aerojet developed the first American turbopump in 1949 based on the German design [32].

Other turbopump efforts of the time are best illustrated through patent filings [13]. Early turbopumps [33], [34] are less complex than modern turbopumps [35], [36]. Early patents describe turbopumps where fuel and oxidizer mix together and burn. The combustion mixture then exits through a turbine. The turbine provides shaft power to a simple impeller for an oxidizer and a simple impeller for a fuel. The exhaust from the turbine dumps overboard and the two main propellant streams enter the rocket engine.

From the initial basic concept, improvements evolved over time. The improvements progressed over the course of thirty years with major advancements grouped around development efforts during the Apollo and Space Shuttle programs [4], [32]. Both programs created large research efforts with vast resources supplied for development purposes. Arguably, the pinnacle of the development effort is the turbopump for the Space Shuttle Main Engine (SSME) [1]. The Space Shuttle Main Engine turbopumps have a high pressure ratio and must be reliable, so a great deal of effort was put into their development [2].

Since the development of the Space Shuttle Main Engine, advances in turbopumps have been limited to changes in how turbopumps integrate with the engine cycle. The culmination of these further developments was the RL-10 engine developed in the 1960's [2]. The RL-10 is possibly the most fuel-efficient rocket engine ever built, due in large part to the high degree of integration between the pump and the rocket. The RL-10 achieves this efficiency by pressurizing both propellants to different pressures. The fuel is pressurized to a higher pressure than the oxidizer [2]. The higher pressure fuel continues to a cooling circuit around the nozzle and chamber [2]. There it picks up heat from the combustion process [2]. The heat transferred to the fuel is normally lost to the surroundings, but in the case of the RL-10, the heat drives the pump system and preheats the fuel. As a result, more of the combustion heat is used to generate thrust.

Since the development of the RL-10 and SSME, improvements in turbopumps have not progressed significantly with the exception of the XLR-132 program [1], [15], [19]. Rocketdyne and Aerojet concurrently developed separate versions of the XLR-132 engine for the Air Force [1]. The Aerojet version called Transtar led to the development of the OMS-E upgrade engine for the Space Shuttle [15], [19]. It was never implemented, but it did show promise. The Rocketdyne version likewise showed a great deal of promise in improved performance [1]. Both programs were for bipropellant rockets slightly larger than those considered in this study. History does show that the turbopumps were successful but required the use of partial admission turbines due to the small turbine flow rate [1].

2.2 Current Efforts

All of the above efforts have been limited to the large rocket engine segment of the industry. In the smaller rocket industry, very little success has been achieved in development of small pumps. However, there have been some efforts of note, especially within the last ten years.

2.2.1 Piston Pump Developed by John Whitehead

One of the pioneers in the pump field for small bipropellant or monopropellant rockets is John Whitehead. He began developing a piston pump system in the 1980's and has developed several prototypes over the years, each one improving upon the last iteration [27]. John Whitehead's pump concept is a positive displacement pump driven by helium or other driver gas [27]. The arrangement is unique and interesting in that he has been able to generate a significant pressure rise while minimizing the loss from the driver gas [27]. One of the major drawbacks in using positive displacement pumps is the ability to provide smooth exit pressure, but John Whitehead's pump has demonstrated that a relatively smooth outlet pressure may be possible since his configuration actually uses four (4) pump elements.

John Whitehead's focus appears to have been on developing an enabling technology for Moon and Mars return missions, among other applications [28]. He has written several papers on his efforts over the years, both in application and development of his concept [17], [27], [28], [37]. The reader is encouraged to review his work, of which only a small portion is referenced in this study, as an example of innovation and persistence in a conservative industry. Unfortunately, the difficulty that John Whitehead has run into in actually implementing his pump is indicative of the overall resistance to change that was described earlier.

2.2.2 Japanese Space Agency Pump Research

Within the past few years, the Japanese Space Agency, JAXA, has begun to show an interest in pumped propulsion systems. In 2006, JAXA funded Advanced

Sciences & Intelligence Research Institute Corp to study and develop a pump using conventional turbopump approaches for a 450 N (101 lbf) thrust bipropellant engine [38]. The pump was built and tested. However, as the authors noted, the performance of the system was not as high as they had predicted it would be, primarily due to leakage across the shaft seals [38]. The proposed solution to provide a buffer gas to improve the seal performance and hence the pump performance provides a clear path for the effort to continue [38]. The pump at best achieved 53% of the predicted efficiency resulting in a pump with an efficiency of 16.2% [38].

The study was a success in many ways, but it also highlights the difficulties facing the development of a pump in this industry for small bipropellant rocket engines. It is not clear if the leakage noted by the authors is the only significant contributor to the low performance. It is likely that a portion of the pump performance decrement is due to tip clearance and small-scale inefficiencies that were beyond what the authors thought they could maintain.

2.2.3 Williams International Turborocket Concept

In March 2000, NASA awarded Williams International with a contract to evaluate the feasibility of their novel turborocket concept. Based on information from their patents [39]-[41], the concept purports to be a low cost rocket engine and turbopump combined into a single device. In 2001, Williams International patented [41] a rocket concept that used a combination of traditional and non-traditional turbomachinery to achieve what appears on paper to be a revolutionary change in rocket propulsion.

Even though the Williams International Turborocket was designed for the large rocket segment of the industry, its principles are unique and can have an impact in the smaller rocket segment of the industry. The basic principles are a large contributor to the current study and provide the basis from which to move forward.

One of the drawbacks to the Williams International Turborocket patent is that it is limited in how small it can be reduced to. As in the Japanese concept, the Williams International Turborocket would suffer from tip clearance and seal leakage issues, as several seals and rotating clearances exist in the concept. Moreover, it is not feasible to make the machinery small enough to fit within a small bipropellant rocket chamber.

2.2.4 Drag Pump Applications

As alluded to earlier in the text, the subject of this study is based on drag pumps. Drag pumps are a pump subclass that uses the friction between rotating elements and fluids to accelerate the fluid to the rotational speed of the pump [14]. The accelerated fluid converts a high level of kinetic energy into pressure. Examples of pumps in this class are regenerative turbines and Reynolds pumps [14]. It is interesting that drag pumps have not found much utility, due primarily to their low efficiencies. As one can imagine, using friction forces to accelerate a flow is not very efficient [42]. In order for a drag pump to be of much utility, the application cannot be overly sensitive to the overall pump performance and the volumetric flow rate has to fall between positive displacement pumps and centrifugal pumps [16].

Drag pumps have been used or proposed for many different applications. However, not much is published about drag pumps. Normally, they are the subject of patents since drag pumps are relatively easy to develop. Thus, the literature about drag pumps resides almost exclusively in patents. The patents on drag pumps range from electric pumps [43], to cryogenic liquid pumps for cooling computers [44], to gas oil separators in oil pipeline applications [45], to fuel injectors in small gas turbine engines [46] – [53], to general pumps [16], [54], [55].

The most applicable example of a drag pump is the injector for some small gas turbine engines. The feature is called a sink trap and slinger arrangement [50]. The fuel feeds into the inside of the rotating shaft where the friction between the rotating shaft and the axial flowing fuel is used to accelerate the fuel to solid body rotation within the rotating shaft [46], [50], [51]. This part of the engine is the drag pump, but is rarely described as anything more than bringing the fuel into solid body rotation. After achieving solid body rotation, the fuel travels through a hydraulic dam commonly referred to as a sink trap, as shown in Figure 2.1, to create isolation between the high pressure combustor gases and the low-pressure fuel feed system [46]. The end of the fuel path is the slinger where the fuel is thrown into the combustor. Often the arrangement is described as a low-pressure fuel system but is really a pump of a less conventional type. The pressure rise is defined by Equation (2.1) and the power consumption is defined by equation (2.2)

$$\Delta P = 0.5 * \rho \omega^2 (R_o^2 - R_i^2) \tag{2.1}$$

$$Pwr = Mdot * V_e^2 \tag{2.2}$$

where ρ is the fuel density, ω is the shaft speed, R_o is the sink trap outer liquid radius, R_i is the sink trap inner liquid radius, Mdot is the fuel mass flow rate and V_e is the tangential exit velocity.

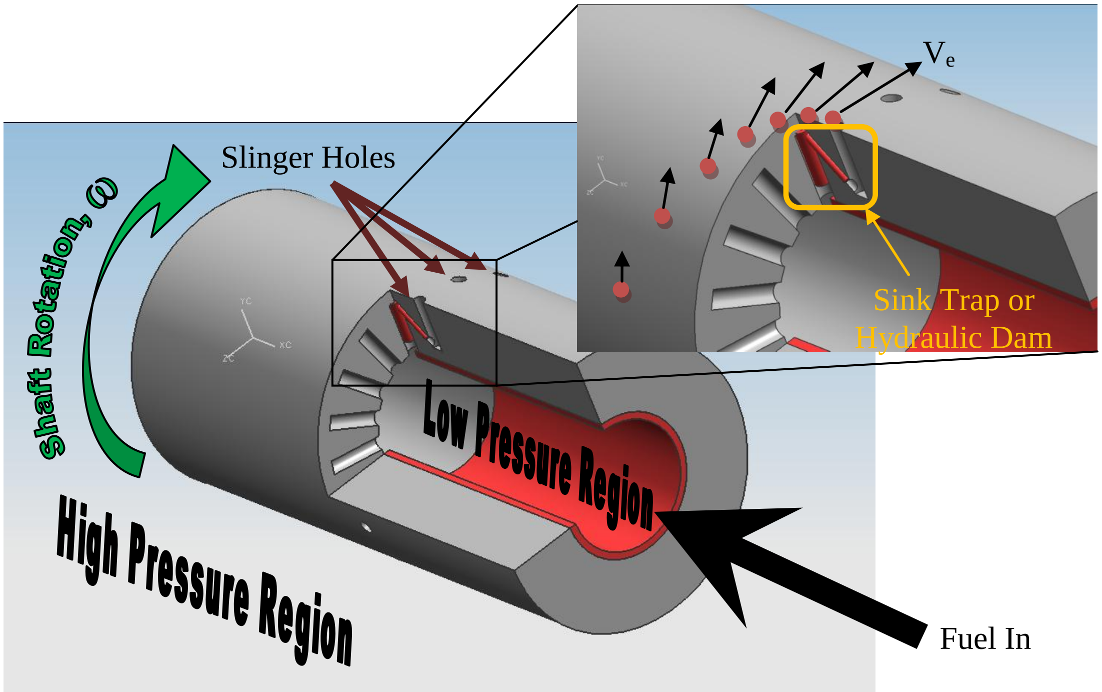


Figure 2.1 Illustration of Sink Trap and Slinger

2.2.5 Other Efforts

In addition to the efforts described so far, a couple of related efforts for larger rockets require mentioning. The first was an effort by A. Knight to develop a non-traditional pump [56]. The concept appears to be a combination wave rotor and positive displacement pump. The reason it is of interest is that the concept appears to be scalable to the size of interest for small bipropellant rockets.

The company XCOR supports the other notable effort. XCOR is one of the companies working on developing a commercial crew vehicle. Under the NASA sponsored program, XCOR has developed a piston or positive displacement pump [29]. The interesting aspect of the XCOR effort is that the pump was initially developed and tested in the size range consistent with small bipropellant rockets. However, it was clear that the end use is for a larger rocket where the driver gas can be heated in a similar fashion as in an expander cycle [29]. It is not clear that it would have any benefits for small bipropellant rockets, but the development path is interesting.

CHAPTER 3

CONCEPT DESCRIPTION

3.1 Initial Concept

Up to this point, the discussion has concentrated on the technical challenges of developing a pump for small bipropellant rockets, the general characteristics of the rocket propulsion industry influencing the design approach and the history of turbopumps for bipropellant rocket propulsion systems. Additionally, a brief discussion of the drag pump was presented. All of the information presented thus far influenced the approach to developing the Combustion Driven Drag Pump. The concept was developed to try to reduce the sensitivity of the pump to the technical challenges and the barriers created by the industry itself.

The key factors driving the design are ease of manufacturing and assembly. The ability to integrate with existing bipropellant propulsion system components to provide stable performance that will not be susceptible to wear, vibration, fatigue or thermal environments are also important factors in the pump design. After considerable investigation and consideration, an approach was adopted using hydraulic dams, a combustor, a turbine and rotary injectors. The pump was also devised to minimize leakage paths where possible or at least make them less important. The resulting initial concept was modeled in Unigraphics NX and is shown in Figure 3.1.

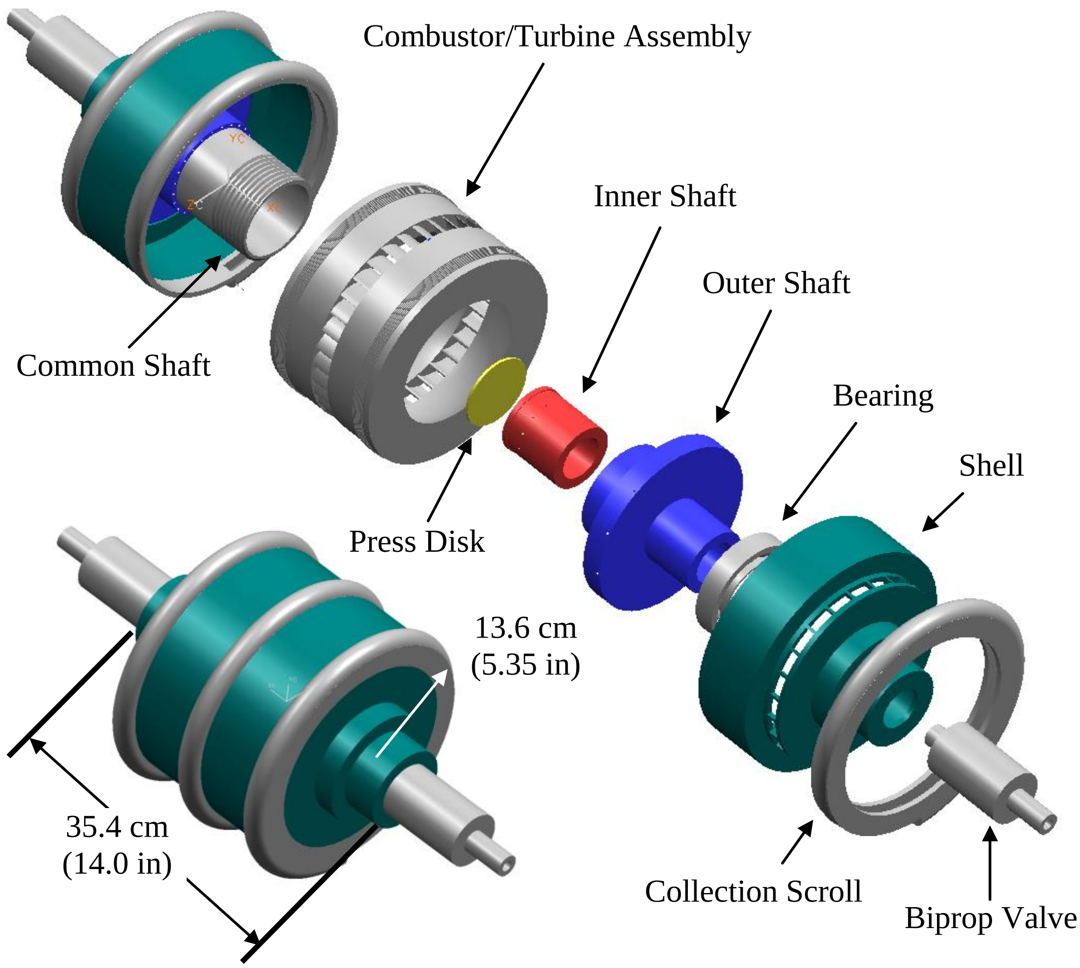


Figure 3.1 Illustration of Initial Combustion Driven Drag Pump Concept

The concept is intended to be simple and uncomplicated, in keeping with the original design intent, such that it will have the characteristics of being reliable and inexpensive. Please note that the initial design was approximate in nature, and subsequent optimizations of the concept do not subtract from its uniqueness, but rather add to it, as will be shown.

3.2 Overview

Due to the desire to keep the device simple, the pumping portion of the concept came from the category of drag pumps where friction is the primary force used to generate pressure. A drag pump was selected because drag pumps do not have sliding seals; such as found in positive displacement pumps, nor do drag pumps have critical tip clearances or the need for tight clearance controls, like those found in centrifugal and axial compressors. Sliding seals and the need for tight clearances pose challenges to pumps in the size range of interest [3]. For the reasons identified above, similar concepts, as the pumping elements, have been in use on gas turbine engines for decades without any known failures [57]. Thus, the drag pump meets the desire of robust operation and simplicity.

The power portion of the concept is also a variation of previously used technology. The power to rotate the shaft comes from burning small amounts of the propellants and then exhausting through a turbine. Usage of a combustor and turbine are derived from turbopumps and turbine engines.

The propellants are metered by traditional bipropellant valves that are free to pulse on and off. The pump is designed to be insensitive to fluctuations in inlet flow rate and/or pressure [51]. Unlike many centrifugal pumps, the Combustion Driven Drag Pump does not have throttling capability [55]. Thus, the valves provide throttling. Conventional bipropellant rocket valves accomplish throttling through pulsing, where the valves open and close repeatedly in a rapid fashion. This method of flow control is another reason to use a drag pump, which smoothes out inlet perturbations.

3.3 Construction and Assembly

As stated earlier, the construction of the pump is simple. Overall, the pump contains one shaft rotating within a shell. The shell supports connections to the inlet valves and outlets from the pump. Additionally, the shell contains the support structure for the two (2) bearings and four (4) seals. The construction of the shell is such that it can withstand the various temperatures and pressures created by the pump without being overly heavy. The two halves of the shell are constructed almost identically as simple turnings that are welded together after they are assembled over the outside of the shaft.

Meanwhile, the assembled shaft is more complicated. The shaft is composed of several elements that are put together to form a more complicated geometry and provide the basic functionality of the pump. The shaft provides the means of accelerating the propellants, isolating the high pressure from the low pressure and distributing propellants to the combustor and rocket. Finally, the combustor and turbine are entirely encapsulated within the shaft.

3.4 Components

3.4.1 Valves

The pump valves are the same valves currently used with bipropellant rockets. Normally, a single bipropellant valve design is used for the oxidizer side and the fuel side. However, a different pressure drop may occur due to the difference in volumetric flow rates between the oxidizer and the fuel. For this study, the valves are sized such that the same valves are used for each flow. One key characteristic of small bipropellant rockets is the ability to pulse the rocket by rapidly turning on and off the valves. The short pulses provide throttling capability to the rocket by only allowing it to fire for short periods. The same valve functionality can be used to throttle the rocket, with a Combustion Driven Drag Pump but in a slightly different manner. When the valves pulsate, the flows going through the pump smooth out [51], which allows pulsating valves to function as throttling valves. Interestingly, the specifics of the valves are not particularly germane to the investigation in that they do not contribute to the pump design other than through the characteristic of pulsing to throttle the flow.

3.4.2 Inlets

The pump inlets are simple in nature but are keys to the success of the pump. The inlets guide the flow from the valves into the inner shaft. Each flow travels through a series of passages that directs the flow to the inside of the rotating shaft. The pump efficiency increases if the flow that impinges on the inside of the shaft is already moving with some tangential velocity. However, the flow also has to be moving axially in order to feed the pumping elements of the shaft. As a result, of the bidirectional inlet injection trajectory, the flow passages in the inlet have to be angled to provide the correct velocity vector. The inlets, shown in Figure 3.2, are slotted cylinders constructed of titanium 6-4 alloy.

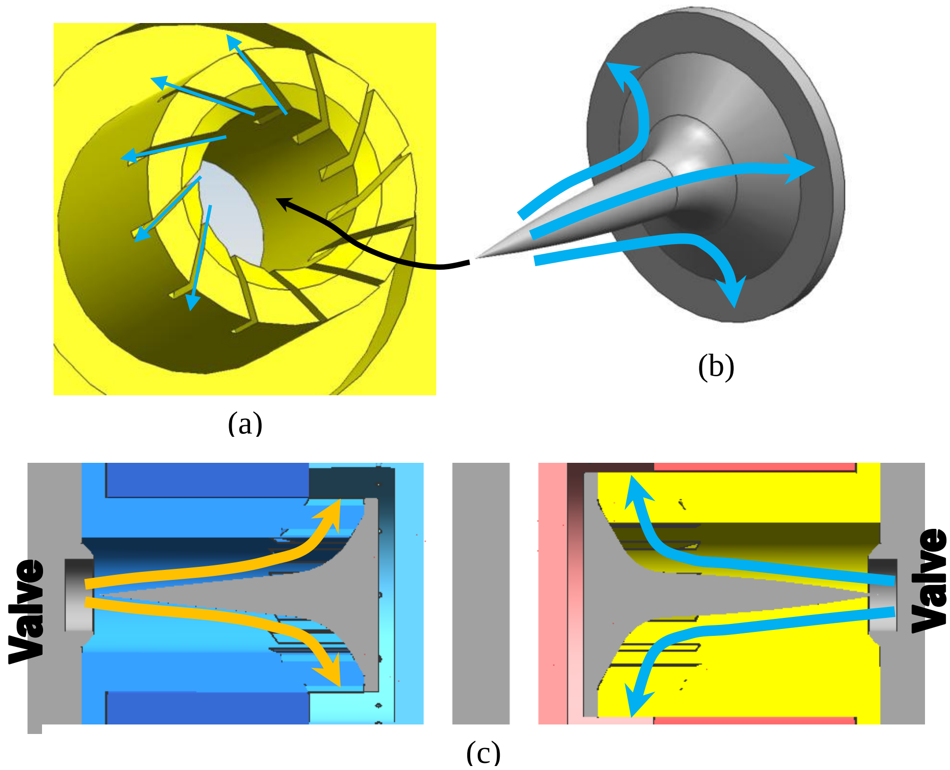


Figure 3.2 Swirl Inlet (a) Angled Slots to Turn Flow in a Tangential Direction, (b) Conical Guide to Turn Flow in a Radial Direction and (c) Conical Guides are Welded into Inlets

3.4.3 Rotating Assembly

The shaft is more complicated than the pump inlets but not to the extent that it cannot be made. By using multiple parts, each being simple to manufacture, and assembling them in a straightforward manner, the complicated geometry of the pumping elements can be constructed. Thus, the shaft consists of several parts to keep the simplicity of the overall pump at a high level. The first piece is the common shaft. It is referred to as such because it combines the oxidizer and the fuel halves into one rotating shaft. The common shaft is a short, hollow cylinder with threads on the outside of the shaft. It also contains a divider that splits the inner portion of the cylinder into two equal volumes. The material selected is Inco 625. As shown in Figure 3.3, the common shaft is a short cylinder with both ends hollowed out. The most complicated aspect of the common shaft is the external threads for assembly with the two outer shafts.

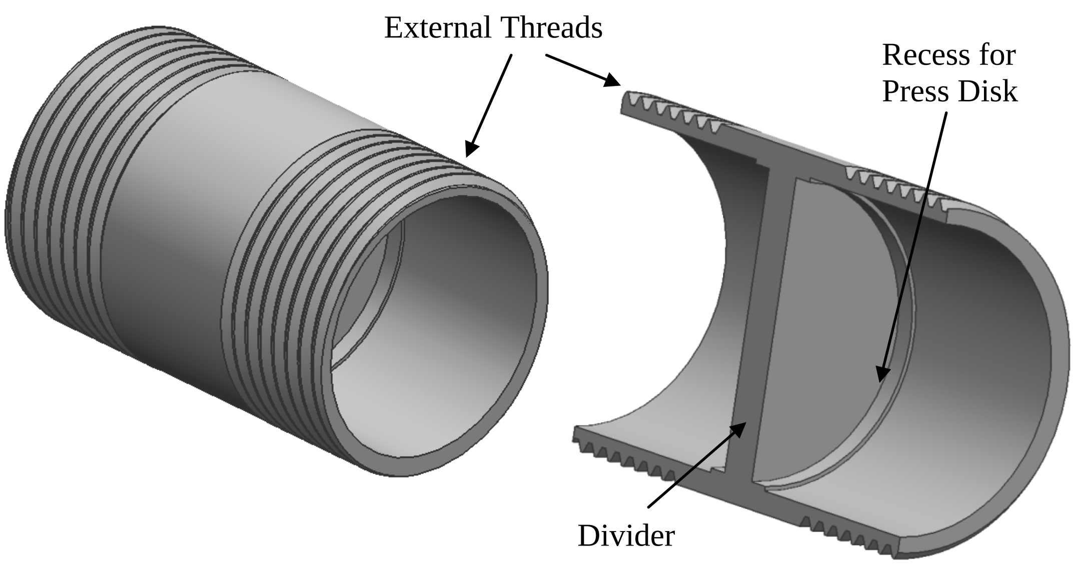


Figure 3.3 Common Shaft

Within the common shaft are two disks called press disks, one on the oxidizer side and one on the fuel side. The press disks deform to act as buffers within the shaft. The press disk allow the design of the shaft elements to be tolerant of machining variations, while simultaneously reducing the volume in the pump where the propellant can be trapped. The volume between the propellant valves and the rocket chamber is referred to as the dribble volume. It is important to minimize the dribble volume on a bipropellant rocket in order to prevent the formation of Fuel Oxidizer Reaction Products or FORP [10]. The initial material selection is a filled Teflon compound that is compliant with the propellants and provides a level of elasticity. As shown in Figure 3.4, the construction is elementary in nature consisting of a basic disk shape. One attribute of concern with the proposed approach is cold flowing of Teflon under constant pressure. Thus, a filled Teflon compound was selected to maintain some rigidity. The other area of concern is swelling of the Teflon after long-term exposure to the propellants. Due to the basic construction, neither concern is expected to be of high significance.

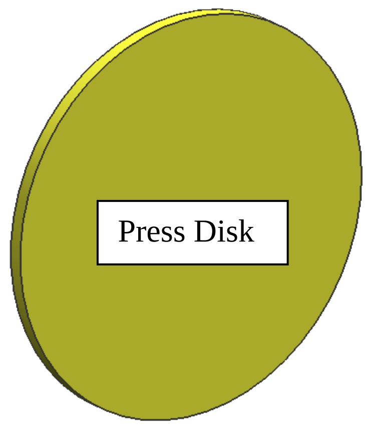


Figure 3.4 Press Disk

Pressed against the press disks are the inner shafts. The purpose of the inner shaft is to accelerate the propellant from axial flow to solid body rotation and then to isolate the high pressure from the low pressure. Each inner shaft contains a hydraulic dam designed to perform the isolation function. The hydraulic dam is created by cross drilling holes into the shaft as illustrated by Figure 3.5.

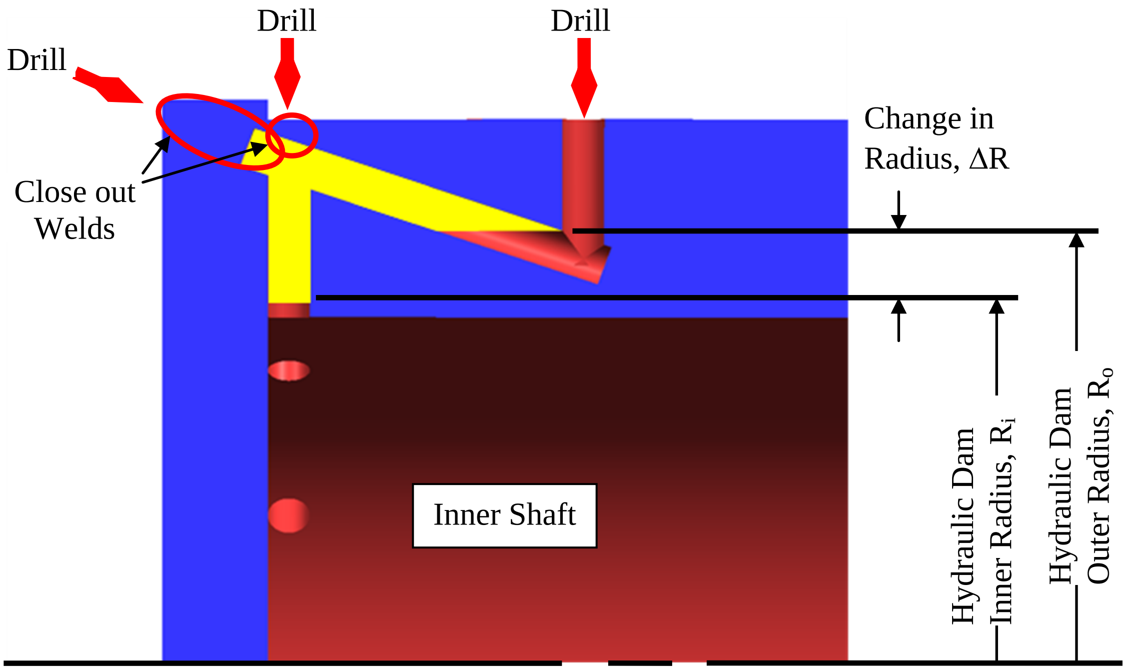


Figure 3.5 Hydraulic Dam

Then the outside holes are welded shut. The end of the inner shaft is capped to prevent the propellant from leaving the shaft in any manner except through the hydraulic dams. Due to its close proximity to the propellant flows, the inner shaft is constructed of Titanium 6-4 alloy. Besides the cross-drilled holes and subsequent sealing of the holes, the inner shafts are simple turnings. The inner shaft is shown in Figure 3.6.

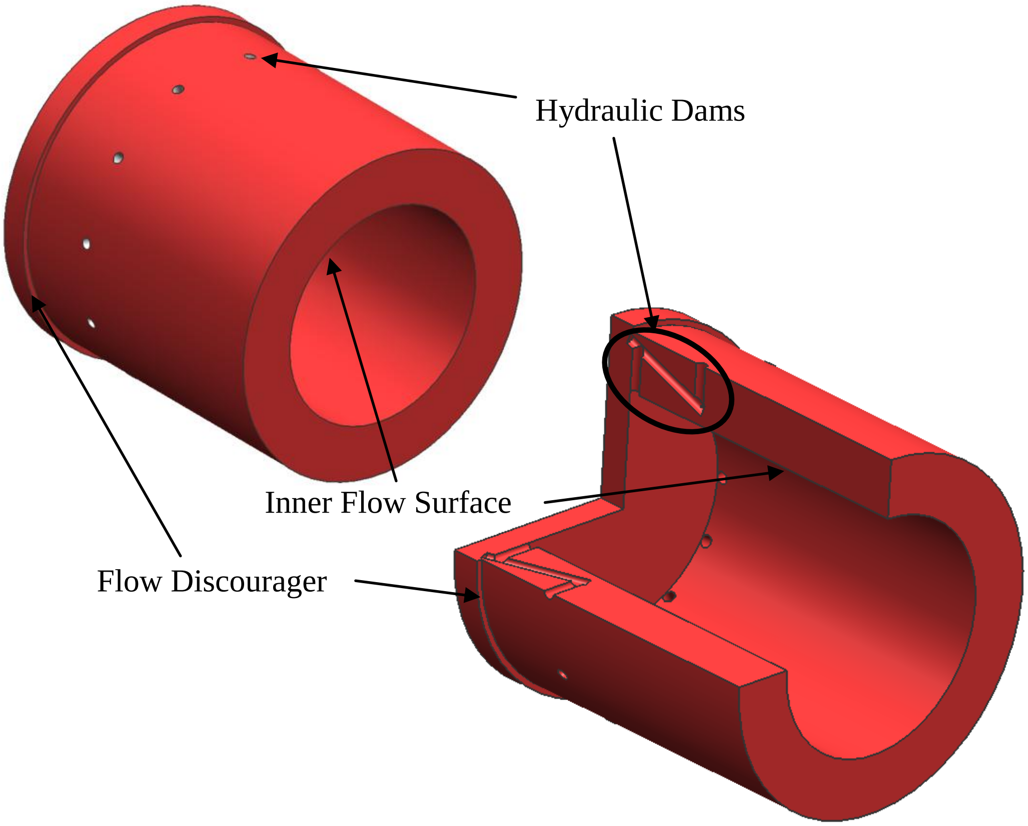


Figure 3.6 Inner Shaft

On the ends of the shaft assembly are the outer shaft elements, which have female threads. The outer shafts serve several functions. The first is that when they are threaded onto the common shaft they clamp the inner shafts in place and form a seal between the high pressure region and the low-pressure region. The second function is that they clamp the turbine/burner element in place for welding. The third function is to interface with the inner diameter of the bearing elements. Finally, the outer shafts distribute the propellants into the collection scrolls. Figure 3.7 shows the outer shaft with bearing elements.

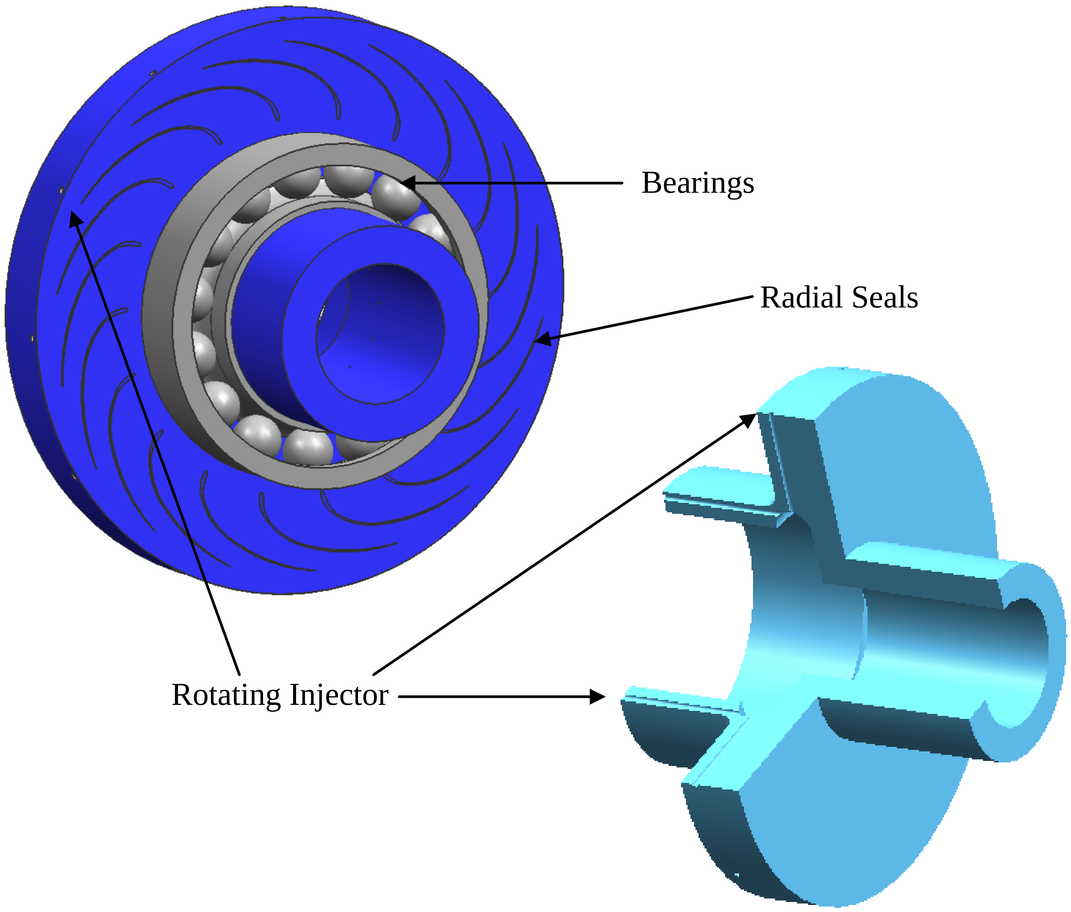


Figure 3.7 Outer Shaft

The rotating injectors distribute the propellants from the shaft as shown in Figure 3.8. There are four (4) rotating injectors in the pump, two (2) for the oxidizer flow and two (2) for the fuel flow. One oxidizer injector distributes the majority of the oxidizer into a collection scroll. The other oxidizer injector distributes a small fixed fraction of the overall oxidizer flow to the pump combustor. The two (2) fuel injectors serve similar functions. The ratio of the fuel flow to the main flow is a fixed physical relationship as is the combustor oxidizer flow. Throttling either the oxidizer or the fuel valves changes the mixture ratio in the rocket. In addition, throttling changes the mixture ratio in the pump combustor.

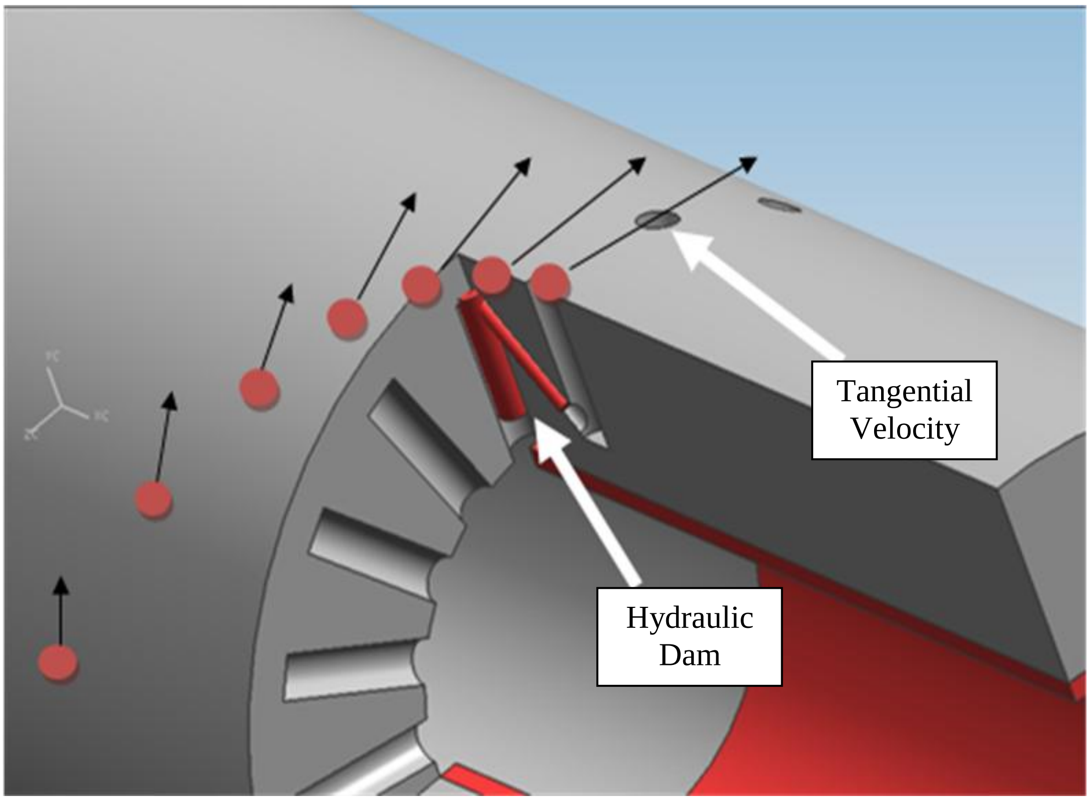


Figure 3.8 Rotating Injector

The material for the outer shaft is INCO 625 because of its proximity to the combustor and turbine. The outer shafts are likely to be the second most complex part in the pump as they have multiple internal passages, and several internal and external features that add complexity. Assembly of the shaft is illustrated in Figure 3.9.

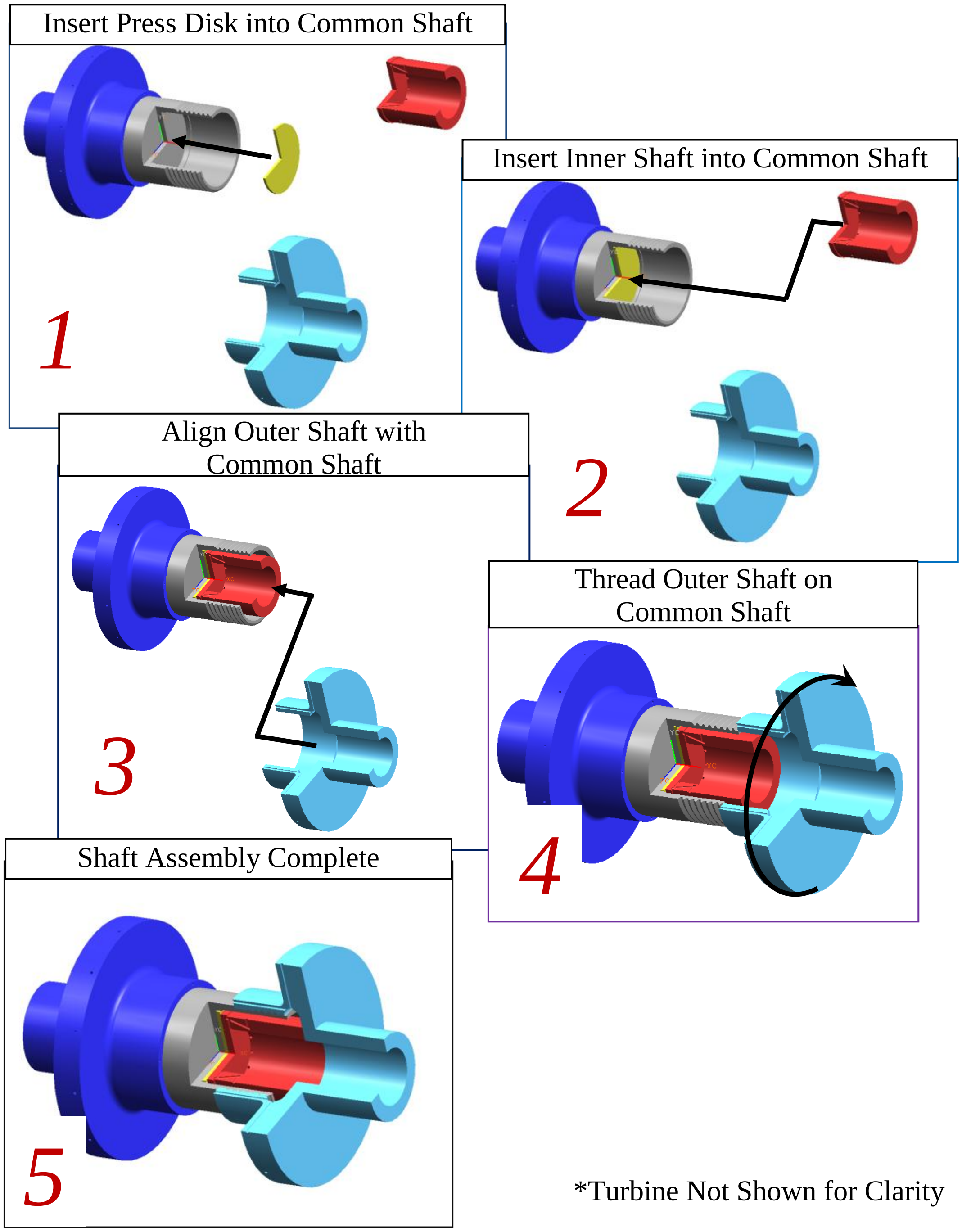


Figure 3.9 Shaft Assembly

3.4.4 Combustor

The combustor is composed of several elements of the rotating assembly as shown in Figure 3.10. The outer diameter of the common shaft, the vertical walls of the two outer shafts and the inner diameter of the turbine element form the combustor. Since the combustor is not an actual physical piece, its construction is composed of the surrounding elements. The initial combustor design provides two important functions. The first is a rapid expansion of the combustion products in the radial and axial directions. Using hypergolic propellants causes a very rapid heat release and density drop [58]. To accommodate this aspect of the hypergolic combustion process, the combustor has a large or expanding volume in the radial direction for the combustion products to fill. The other feature of interest is that the combustor volume is quite large and can be tailored to any geometry. Thus, there is freedom to optimize the combustor geometry based on a successful completion of a more sophisticated analysis.

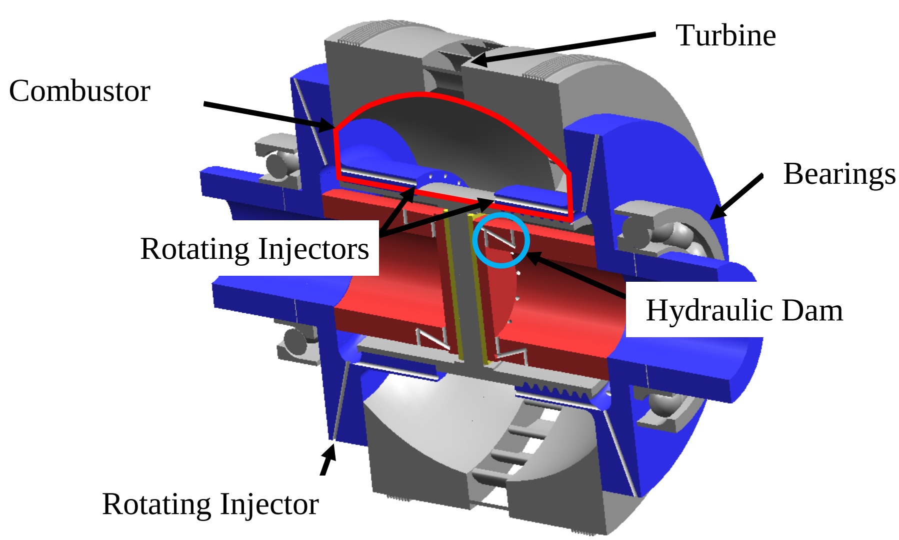


Figure 3.10 Combustor

3.4.5 Turbine

The two outer shaft elements, which thread onto the common shaft, hold the turbine element in place. After the shaft is assembled, the turbine element is welded to the two outer shaft elements so that slippage and leakage are prevented. The turbine element is a simple radial outflow style turbine surrounding the combustor. Around the outside of the turbine are ridges intended to act as seals to isolate the combustion gases from the pressurized propellants. The material is INCO 625. Later analysis indicated that the style of turbine depicted in Figure 3.11 would not meet the needs of the pump. Thus, a different style of turbine was used for the study and is discussed in further detail later. However, the basic construction approach as depicted was not changed.

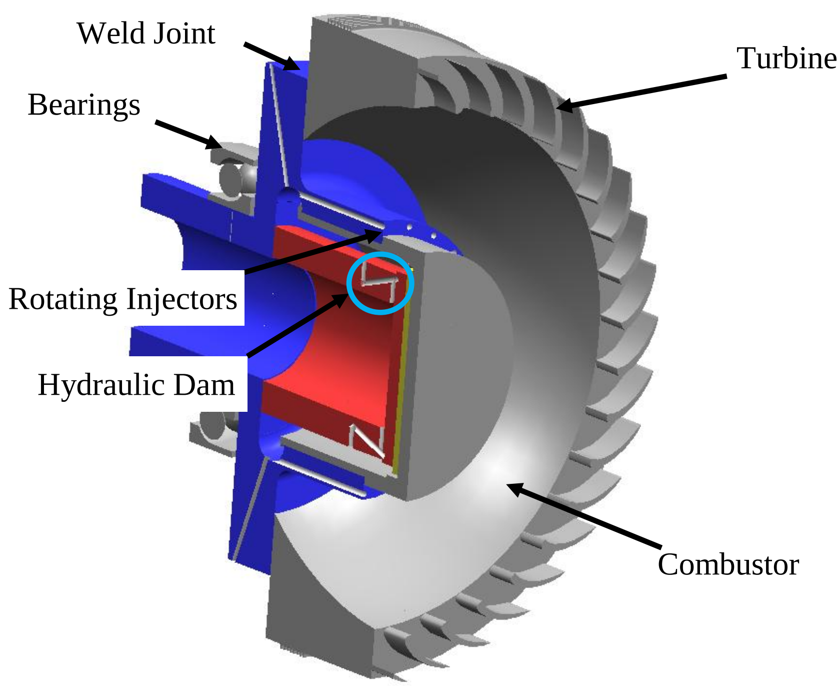


Figure 3.11 Turbine

3.4.6 Scrolls

The collection scrolls for the high pressure propellant reside in the shell. As the high pressure propellant is distributed from the shaft, it enters the scrolls, which are variable area passages shown in Figure 3.12. The collection scrolls are intended to reduce the non-uniform circumferential pressure profile, and recover as much total pressure as possible. Each scroll provides nearly constant mass flow per unit area distribution. The area increases slightly as a function of circumferential distance to account for boundary layer buildup. At the design condition, the area variation works quite well, but at different operating conditions, the scroll experiences additional losses. For instance, when the flow is lower than the design flow, some of the pressure is lost during deceleration of the flow, but when the flow is high, the friction losses increase and reduce the pressure recovery. However, in the initial baseline configuration, it is assumed that none of the dynamic head is recoverable in the scrolls.

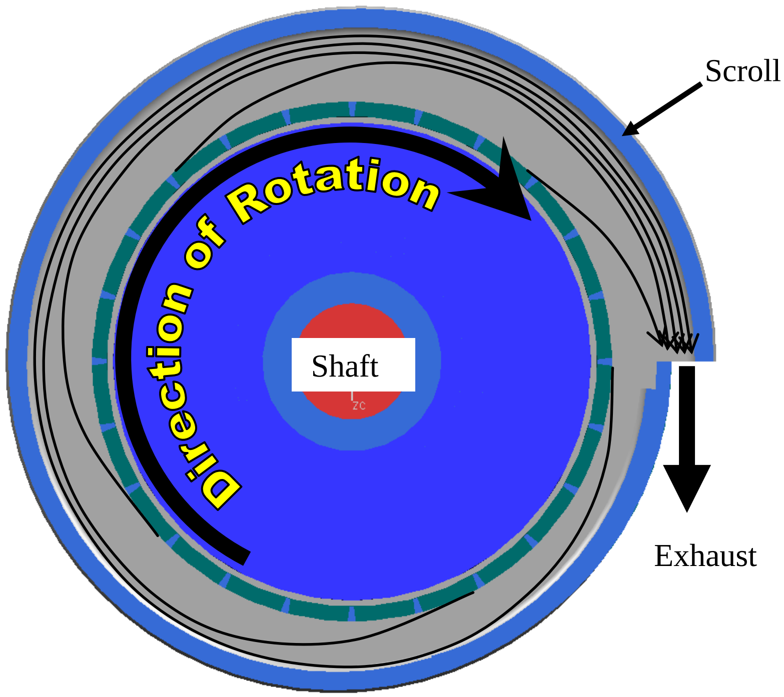


Figure 3.12 Collection Scroll

3.4.7 Shell

The shell is the general-purpose term for describing the pump pressure vessel, structural support, dynamic support and sealing mechanism all wrapped into one. The shell structure can withstand the highest pressures possible from the pump with considerable margin. Additionally, the shell contains the mounting features for holding the pump onto the rocket and against the feed lines. A cross-section of the shell is portrayed in Figure 3.13.

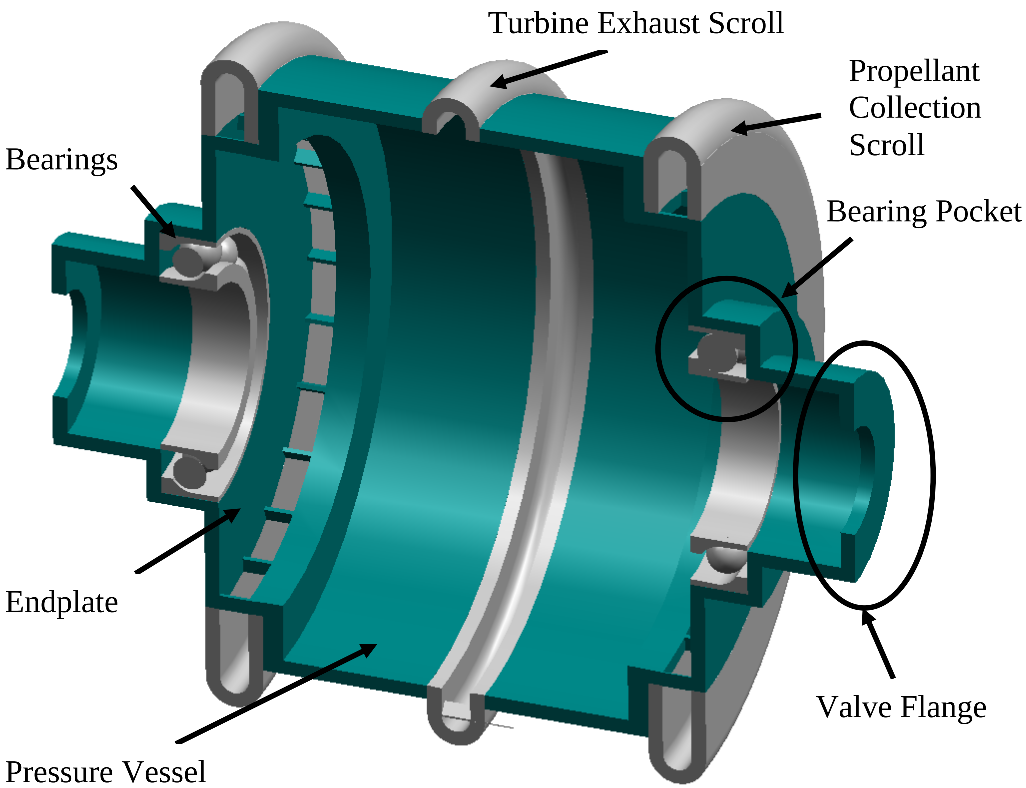


Figure 3.13 Shell

The shell is composed of several separate pieces all welded together with three of them being the collection scrolls. Two of the pieces are flat disks making up the endplates of the pump case with pockets for bearings and inlets. The thickness of the endplates provides considerable margin over the maximum shear stresses. The remaining two pieces are the cases, which are sized to provide margin over the maximum hoop stresses. All static structures are constructed of INCO 625.

3.4.8 Bearings

Two sets of bearings provide the forces necessary to keep the shaft in balance. One bearing set resides on the outer fuel shaft and the other one resides on the outer oxidizer shaft as shown in Figure 3.13. Both bearings are designed to be lubricated, stainless steel bearings as shown in Figure 3.14. Small amounts of the propellants provide the bearing lubrication. However, non-lubricated bearings and foil bearings are considered alternatives. Fortunately, the bearing loads are likely to be low enough to justify the selection of any bearing type as being reasonable.

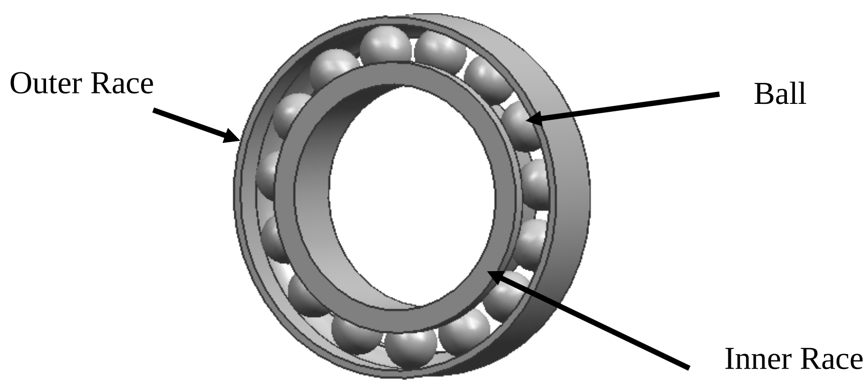


Figure 3.14 Bearing

3.4.9 Seals

Seals are desired in four locations:

- Between the fuel inlet and fuel outlet
- Between the fuel outlet and the turbine outlet
- Between the oxidizer inlet and oxidizer outlet
- Between the oxidizer outlet and turbine outlet

The seals between the propellant inlets and outlets have to isolate high pressure from low pressure. However, since most of the outlet pressure is in the form of dynamic pressure, the actual pressure difference is less severe than might be anticipated. Nevertheless, it is important from a performance standpoint to provide adequate seals. The seal of choice is a hydrodynamic face seal with tangential radial spiral ridges, described in Figure 3.15, to discourage flow from traveling toward the centerline.

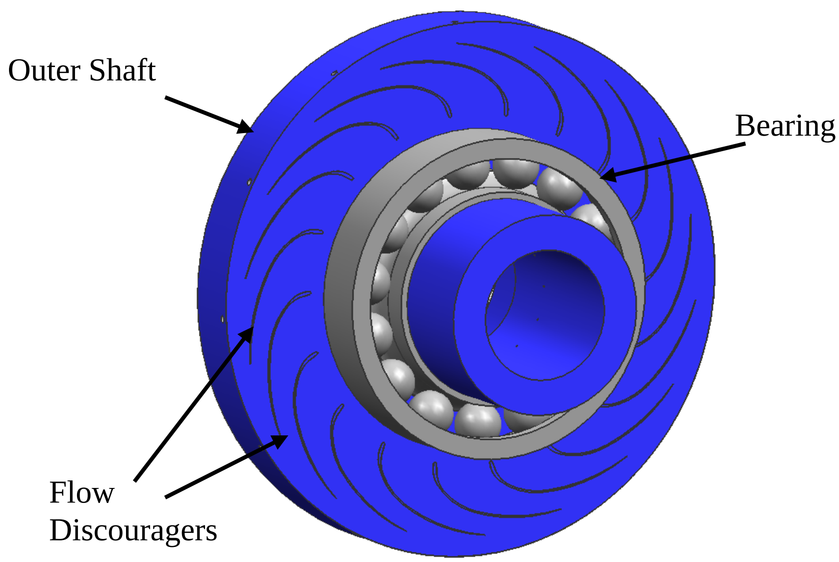


Figure 3.15 Radial Seals

The difference in pressure between the propellant outlets and the turbine outlet is much smaller than between the inlets and outlets, since the static pressures are of a similar magnitude. Regardless of the actual pressure ratios, the design does call for low flow rate sealing in these areas for different operating conditions. The baseline form of the seals is labyrinth seals as shown in Figure 3.16.

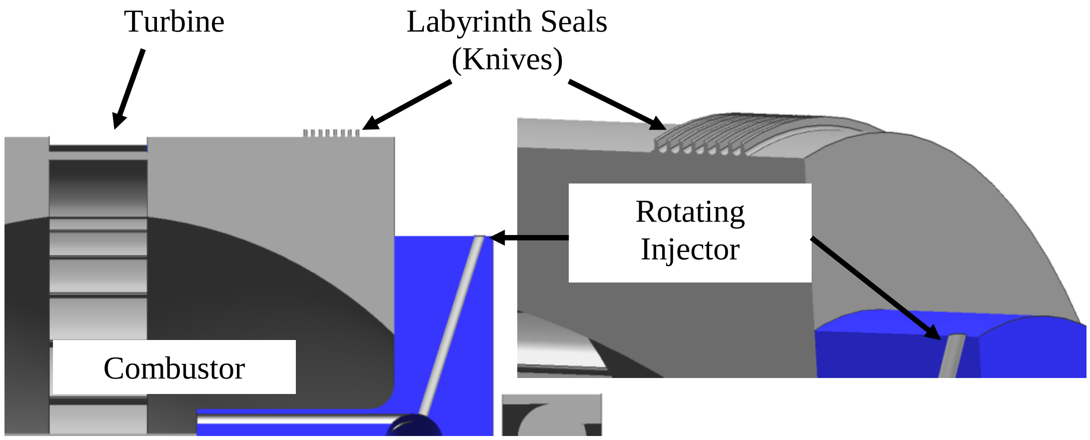


Figure 3.16 Labyrinth Seals

Note that the combustor is operating in a fuel rich manner, which dictates the direction for acceptable seal leakage because the propellants are hypergolic. Flow from the oxidizer stream to the turbine outlet stream is acceptable in very small amounts since large flow rates increase the turbine exit temperatures due to reaction of the MON-3 liquid with MMH rich gas. Excessive leakage would likely thermally choke the turbine exhaust or possibly increase the stresses on the shell to a point where it fails. Conversely, allowing hot fuel rich combustion gases into the oxidizer stream is unacceptable as it would likely result in an unplanned rapid disassembly event commonly known as an explosion. Therefore, the pressure in the oxidizer stream remains slightly higher than the turbine exhaust stream. On the other hand, leakage from the fuel exit to the turbine exhaust or vise-a-versa should not have as catastrophic a result. Thus, limiting leakage in that seal is only necessary from a performance perspective.

CHAPTER 4

MODEL DEVELOPMENT

A model of the concept described in Chapter 3 was developed to aid in the trade studies that were conducted during the design effort. The development of the simulation consumed the majority of the time dedicated to the investigation, but the benefit of developing the simulation is that rapid evaluations of multiple configurations and trades can be conducted. The potential drawback is that any inaccuracies in the simulation with respect to the actual physics may reveal incorrect sensitivities. Therefore, every effort was made to identify the major factors and their relevant physics, while simultaneously neglecting the smaller effects. In some cases, minor or questionable attributes were included in the study to verify that their contribution did not combine with other attributes to magnify the overall impact. Development of the simulation for this study was challenging since test data does not exist for correlating the model.

4.1 NPSS™ Description

The simulation itself was constructed in the Numerical Propulsion System Simulation (NPSS™) architecture, using version 1.6.4, Revision N. NPSS™ is an object-oriented performance modeling code developed jointly between NASA and the propulsion industry [59]. The primary benefit to using NPSS™ is its capability to develop the specialized performance attributes and calculations needed for the pump model and the ability to model physical properties of the fluids involved. Another benefit is the design point/off design point capability in NPSS™ [59]. In coordination with NPSS™, the NASA CEA program is used to predict gas properties of the reaction between MON-3 and MMH and for estimating simple rocket performance [60].

4.2 Design Point/Off Design Simulation

One of the most useful features in NPSS™ is the ability to select the operating mode [59]. In design point mode, the user can specify performance style parameters and have the simulation calculate the geometric properties of the pump. If the developer has correctly modeled the physics, the physical geometry of the pump is generated to achieve those performance parameters [61]. A great deal of effort went into developing this part of the simulation, as it provides the foundation for the off design performance predictions. Running different cases is analogous to evaluating multiple configurations at one condition.

In the off design mode of operation, the simulation holds the physical geometry defined in the design point mode and then calculates the performance at other operating conditions. Multiple cases in off design mode represent running a single configuration to multiple operating conditions. Thus, it is possible to use one simulation to examine performance trades for the design and for overall performance. A simplified example of this process is the design of a pipe. The first step is to define the physical flow rate. Next, the user defines an acceptable pressure loss through the pipe. In design point, the model can calculate the loss factor, K, and define the overall diameter and surface finish of the pipe. In off design mode, the user is free to vary the flow rate and observe what happens to the pressure drop through the pipe element. The Combustion Driven Drag Pump simulation uses the logic in the example but on a much more involved scale.

4.3 Model Description

In model development, it is advantageous to break the model up into discrete but interlocking elements. Treating the simulation as a series of processes simplifies the overall analysis effort. The model contains several flow paths for the propellants and a flow path for the combustor/turbine gas stream. The liquid flow paths are broken up into two sets, one for MON-3 and one for MMH. Each path contains one split where flow from the main stream divides off to enter the pump combustor.

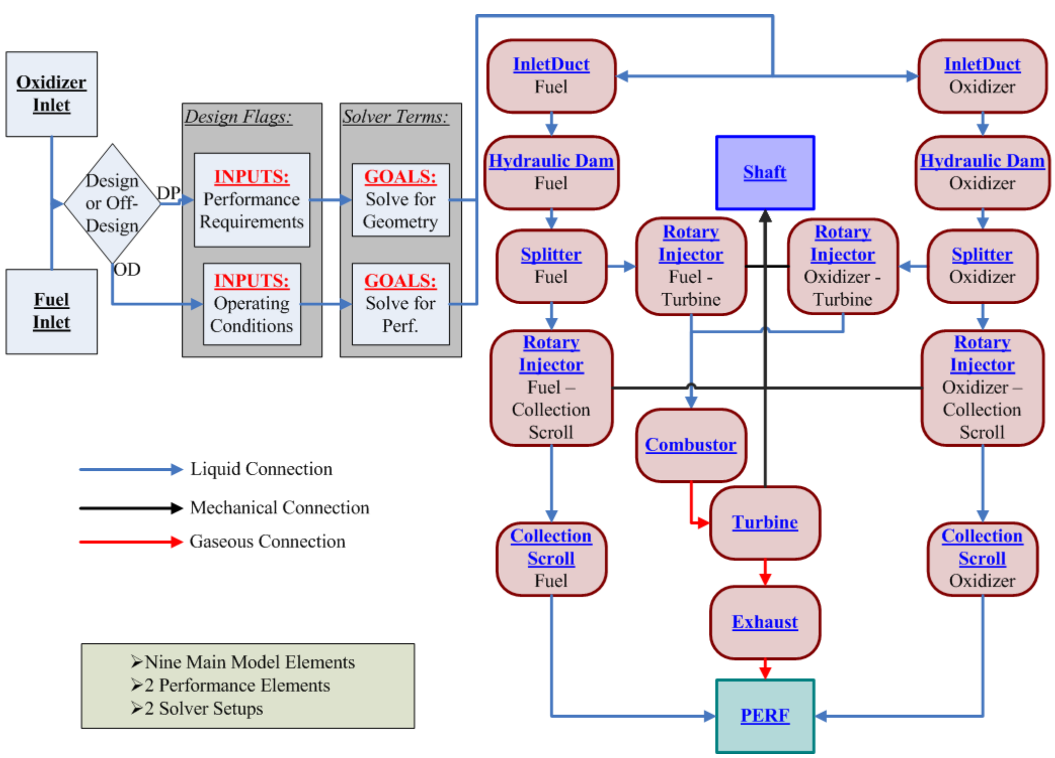


Figure 4.1 Model Schematic

Additionally, there are four (4) leakage paths: one from the main oxidizer flow to the turbine exit, one between the main fuel flow and the turbine exhaust and two (2) leakage paths from the main flow to the propellant inlets. Finally, a performance element calculates overall variables such as weight, length, diameter, pump efficiency, rocket thrust and specific impulse. Next, mechanical linkages between the various elements connect the components in a physical representation. A schematic of the model is shown in Figure 4.1.

4.4 Physics in Each Element

The individual elements represent different processes indicative of a physical design. As such, each element contains a unique model to represent the processes and to carry out calculations within the simulation. Once linked, the elements form the simulation for the pump shown schematically in Figure 4.1. The individual elements are described in the following sections.

4.4.1 Begin Element

The Begin element has the function of defining an initial fluid and the properties of the fluid. The simulation contains two Begin elements, one for the MMH and one for the MON-3. The Begin element requires the definition of pressure and temperature since later elements operate on their initial conditions. Each instance of Begin links to another element through a liquid fluid port. Finally, the fluids must have their mass flow rates defined. Figure 4.2 shows a schematic of the Begin element.

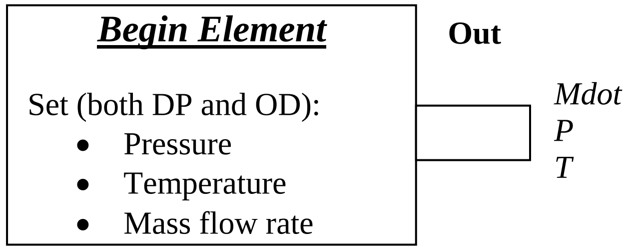


Figure 4.2 Begin Element

4.4.2 Biprop_Valve Element

Metering the flow is the normal function of a valve. However, in the case of a bipropellant valve for bipropellant rockets, the valves behave more like on/off switches. As discussed earlier, the Combustion Driven Drag Pump is intended to be able to use a pulsating (opening and closing) valve as a throttle mechanism. However, in the steady state simulation, the valve element represents the pressure loss through the valve [59]. In the steady state mode, the valve produces a steady state pressure drop. The pressure drop is input in the design point mode, and the valve loss coefficient, Cv, is calculated. Then in off design operation, the valve pressure drop is calculated using the valve Cv and the flow rate through it. The valve element has a liquid inlet port and a liquid exit port. The element is used for sizing the valves and representing various line losses. The definition of the flow rate for steady state operation is defined in the Begin element. In a transient simulation, the element will need to be modified to open and close as a function of time. A schematic is shown below in Figure 4.3.

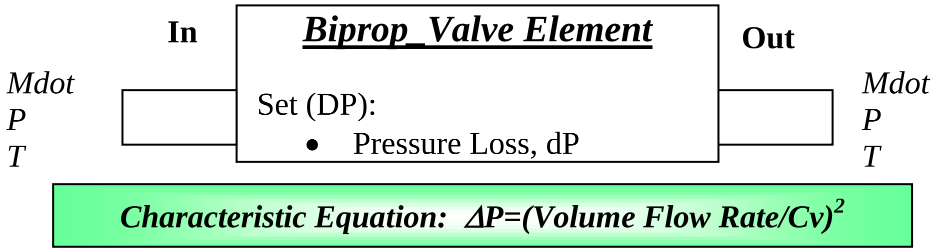


Figure 4.3 Biprop_Valve Element

4.4.3 Inlet Element

The Inlet element to the pump calculates several parameters needed for the Combustion Driven Drag Pump. The first is the pressure drop for the inlet manifold. Defining the pressure drop is accomplished by entering a design point pressure drop and calculating the fluid resistance factor, K. In off design operation, the K factor determines the pressure loss for the specific flow rate [59]. In addition to the pressure loss, the element determines the flow area and orientation of the exit based on an entered fluid velocity and swirl angle. The flow area is normal to the flow velocity vector, so in off design, the actual flow area and its orientation determines the fluid velocity vector for the given mass flow and pressure [62]. Increasing the swirl angle decreases the static pressure since the total velocity has to increase to pass the same amount of propellant through the same cross-sectional area defined by the film thickness. The Inlet element has both an inlet fluid port and an exit fluid port and is shown schematically in Figure 4.4.

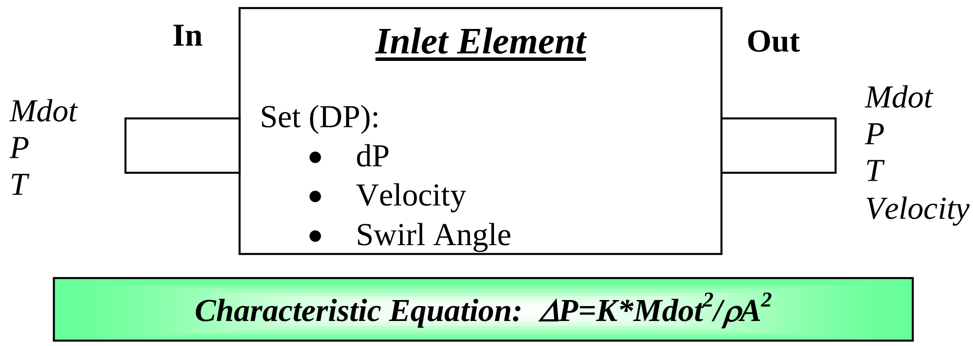


Figure 4.4 Inlet Element

4.4.4 ShaftDuct Element

The ShaftDuct element determines the liquid flow characteristic of a fluid flowing within a rotating duct or more simply on the inside of a shaft. The ShaftDuct element determines the axial length required to accelerate the fluid from the initial velocity to solid body rotation for a desired film thickness[42], [63]. The film thickness is specified in design point mode and then calculated in off design operation. Specifying the film thickness in design point mode leads to the calculation of the inner radius of the shaft needed to pass the inlet mass flow. The film thickness also determines the axial velocity of the fluid as it travels down the length of the shaft [62]. The ShaftDuct element contains a fluid input port, which includes the velocity vector, and a fluid outlet port. In addition to the fluid ports, the ShaftDuct element has a mechanical port for connecting to a Shaft element. The rotation speed passes through the mechanical port. A schematic of the ShaftDuct element is shown in Figure 4.5.

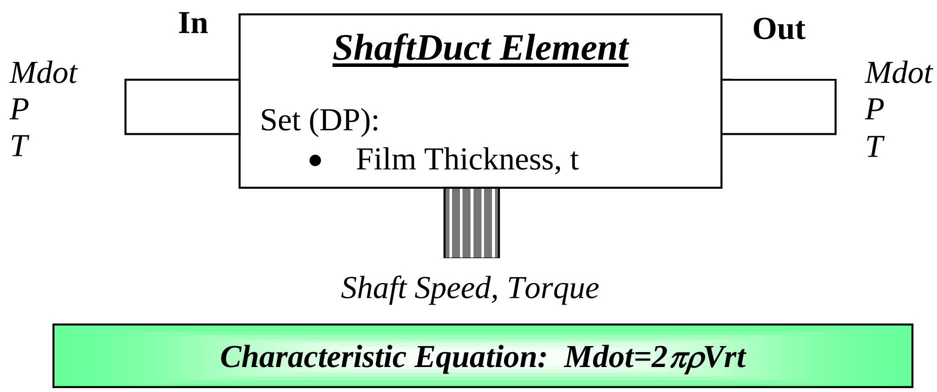


Figure 4.5 ShaftDuct Element

4.4.5 HydraulicDam Element

The HydraulicDam element determines the geometry associated with the hydraulic dam. The physical geometry is determined in design point mode based on the desired pump pressure rise [64], [65]. The geometry in the off design mode represents the liquid level geometries within the hydraulic dam, which are necessary in order to achieve the pressure rise to balance the system [64]. On top of the basic calculations are calculations to add margins to the inner radius and to the outer radius called the inner and outer hydraulic dam margins, respectively. The element contains two fluid ports. One of the ports is the inlet fluid port and the other is the output fluid port. The element also contains a single shaft port to obtain the shaft speed. Figure 4.6 shows the schematic of the HydraulicDam element.

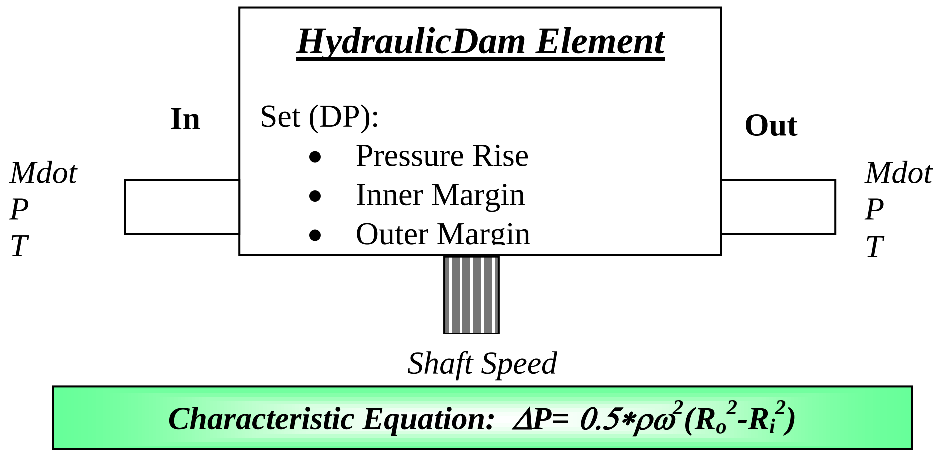


Figure 4.6 HydraulicDam Element

4.4.6 Splitter Element

The Splitter element serves the simple function of dividing the inlet flow into two exit flows. The element behaves the same way in design point and in off design point operation. In design point, the fraction of the inlet flow sent to output stream one is specified. The remainder of the flow goes to output stream two. The element contains one inlet fluid port and two fluid output ports. The Splitter element is schematically represented in Figure 4.7.

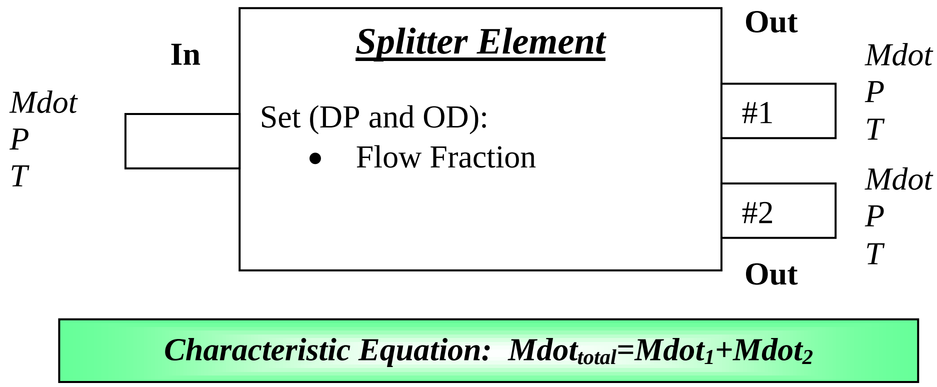


Figure 4.7 Splitter Element

4.4.7 RotaryInjector Element

The RotaryInjector element serves the function of determining the amount of power consumed by the pump. The maximum velocity of the rotary injector surface is supplied in design point mode. With the maximum rim speed selected, the element determines the radius and the work consumed by the pump [57], [66]. In off design mode, the element again determines the power consumed by the pump for each fluid, based on the radius and shaft speed. The element contains a mechanical port for communicating the shaft speed to the rotary injectors and for communicating the torque to the shaft [67]. The two fluid input ports are for input and output, with the output also providing the velocity vector of the fluid leaving the rotary injector [57], [66]. Figure 4.8 shows the schematic of the RotaryInjector element.

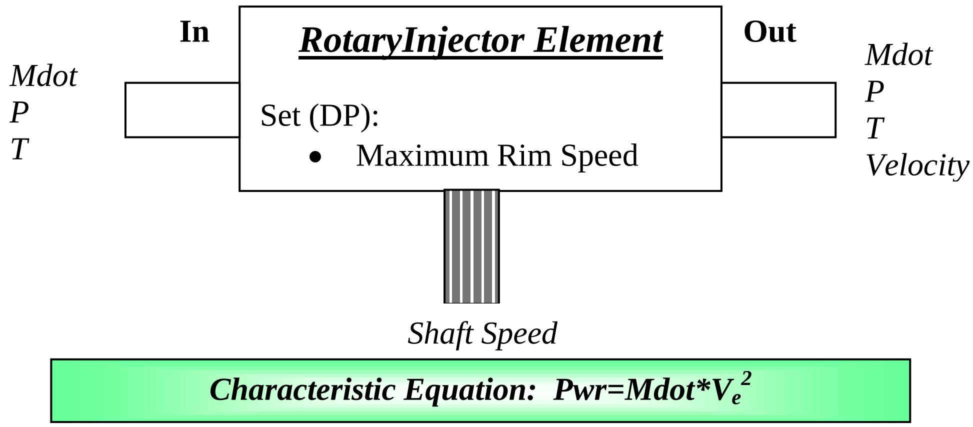


Figure 4.8 RotaryInjector Element

4.4.8 Scroll Element

The Scroll element was developed to estimate the losses in the fluid streams as they leave the pump and are collected for distribution. The design point performance of the scrolls assumes an even distribution of the exit static pressure. Based on having an even distribution, the performance of the scroll requires the input of the loading parameter [68]. The design point also determines the throat area and the exit velocity of the scroll. For off design, the performance decrement for asymmetrically loading the scroll is determined [69]. Next, the impact of throat velocity is determined. If the throat velocity is too high, then the scroll loses performance due to added friction, while if the velocity is too low, the pump loses performance based on decelerating the flow [69]. In both cases, the decrement adds to the asymmetric losses to determine the overall performance. The Scroll element contains an inlet fluid port and an outlet fluid port. Figure 4.9 illustrates the Scroll element schematically. The scroll performance model was primarily based on the paper written by Joseph P. Veres [61].

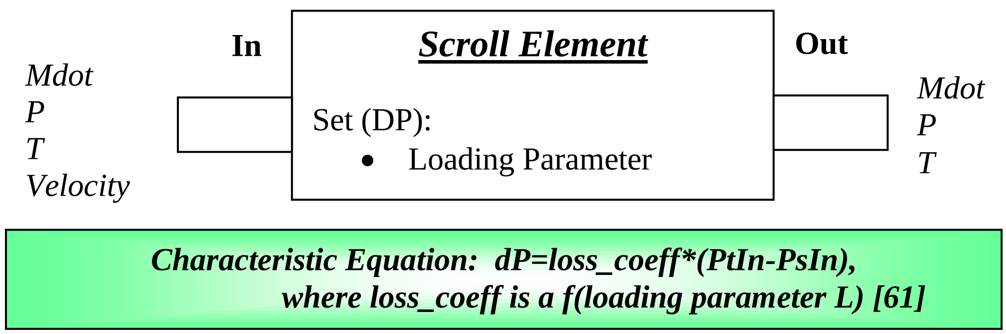


Figure 4.9 Scroll Element

4.4.9 Combustor Element

The Combustor element is the second most complicated element in the simulation. The function of the combustor is to combine small amounts of MMH and MON-3 and allow them to react. This changes the two (2) liquid flows into one high temperature gas flow that is appropriate for driving a power turbine. In the design point mode, the combustor calculates the geometry required to achieve a specified inner radius to outer radius ratio. The pressure drop and the combustion efficiency are specified for the design point and the off design point operation. The combustor uses two (2) calls to CEA, one call determines the gas properties of the perfect combustion process with no losses and a second call determines what the gas properties are after applying a pressure drop and combustion efficiency [60]. The Combustor element has two (2) liquid fluid ports, one for each propellant, and one gaseous port for the combustion products. A schematic of the Combustor element is shown in Figure 4.10.

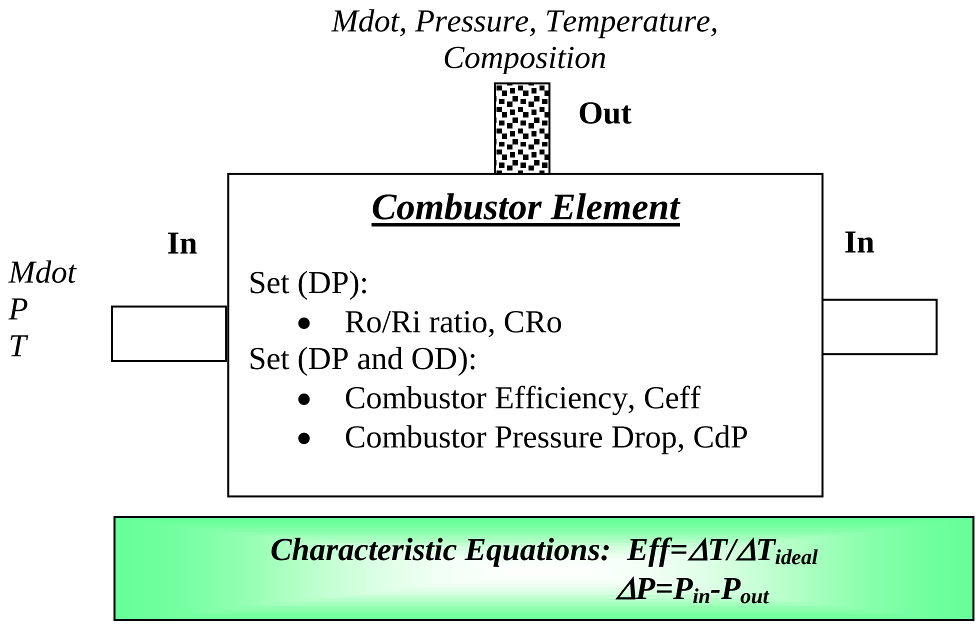


Figure 4.10 Combustor Element

4.4.10 ReactionTurbine Element

The ReactionTurbine element determines the performance of the turbine at the design point and the off design point. The ReactionTurbine is the most complicated element in the simulation. The design point calculations iterate on the efficiency of the turbine based on radius, shaft speed and the power needed from the turbine. The analytical turbine performance model is based on work published by W. J. Comfort III, in 1977 [70]. In off design mode, the turbine does many of the same iterations since the model is not based on a turbine map approach. The complexity of the element stems from the three calls to CEA for the inlet conditions, the isentropic exit conditions and the true exit conditions based on the efficiency iterations [60]. The interesting aspect about the turbine element is that it is not closed form in nature, since the efficiency iterates at the model level. The approach saves unnecessary iterations by simultaneously solving multiple problems. The turbine element contains one fluid port for the turbine inlet and one fluid port for the turbine exit. Additionally, the turbine has one shaft connection to transfer the torque from the turbine to the shaft and to transfer the shaft speed to the turbine [67]. A schematic of the ReactionTurbine is shown in Figure 4.11.

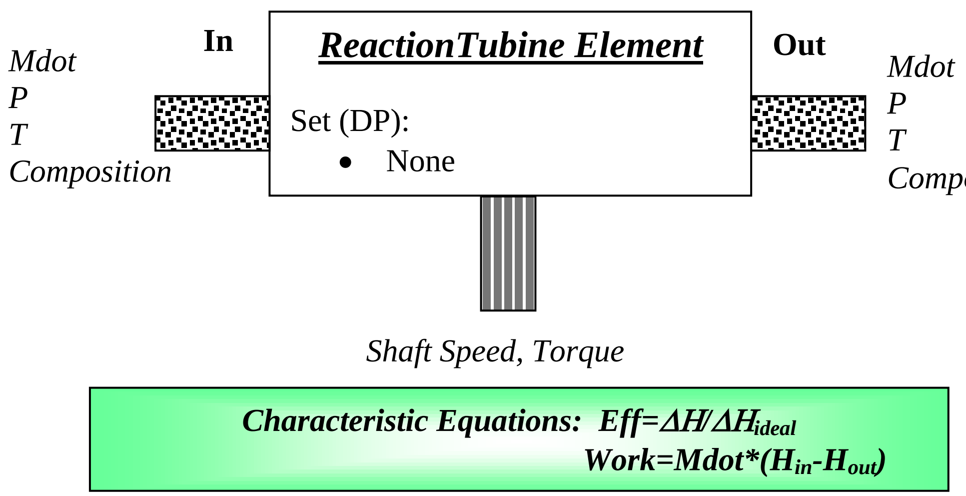


Figure 4.11 ReactionTurbine Element

4.4.11 Bearings Element

The Bearings element extracts power from the shaft to represent the losses associated with bearing friction. The bearing loss defines a fraction of the total power put into the shaft by the turbine. The element has a single mechanical port to connect to the shaft. Additionally, the parasitics for windage losses and seal friction losses are represented using a Bearings element, which is illustrated in Figure 4.12.

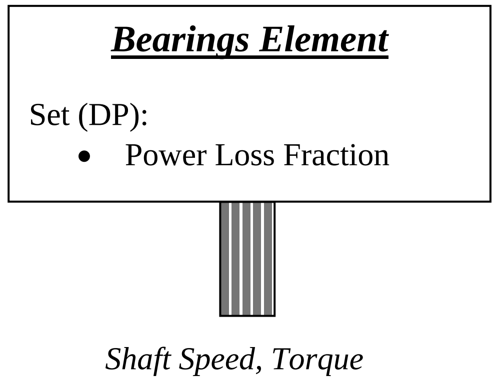


Figure 4.12 Bearings Element

4.4.12 Shaft Element

The Shaft element is a simple element with multiple mechanical connections to all of the different parameters. The Shaft element sums all of the power extractions and inputs to create a net torque term for use with the top-level solver [67].

4.4.13 Performance Element

The Performance element is a collection of overall performance metrics derived from the rest of the simulation. For example, the system weight, length and diameter are determined in the Performance element. Additionally, the Performance element calculates the design point characteristics for the various rocket performance options to be discussed in section 4.7 [60]. Finally, the pump performance parameters are calculated in the Performance element. Table 4.1 summarizes all of the top-level performance calculations done in the Performance element.

Table 4.1 Performance Calculations

Parameter	***Comment***
Weight	The total weight is a summary of all the component weights: Bearings, Scrolls, Shell, Inner Shafts, Press Disks, Common Shaft, Outer Shafts and the Turbine. Plus, it includes increments for changing the valve sizes from the baseline and for changing the rocket size from the baseline.
Diameter	The diameter is the maximum of the turbine diameter or the rotary injector diameter plus the thickness of the shell.
Length	The length is composed of several lengths in the pump: Inlet lengths, Length of the Inner Shaft, Press Disk thicknesses and divider thickness.
Baseline Rocket Thrust	CEA predicts thrust based on the mixture ratio of the simulation, baseline chamber pressure and the baseline expansion ratio.
Baseline Rocket Isp	CEA predicts specific impulse based on the mixture ratio of the simulation, baseline chamber pressure and baseline expansion ratio.
Pump Rocket Thrust	CEA predicts thrust based on the mixture ratio of the simulation, injection of the turbine exhaust, chamber pressure approximately double the baseline and an expansion ratio of 2x the baseline.
Pumped Rocket Isp	CEA predicts specific impulse based on the mixture ratio of the simulation, injection of the turbine exhaust, chamber pressure approximately double the baseline and an expansion ratio of 2x the baseline.
Pump Efficiency	Power provided by the pump outlet streams divided by the ideal power input from the propellant combustion process.

4.5 Weight and Size Parametrics

The weight and size parameters are based on assumptions relating to key geometric parameters. The top-level size parameters are overall length and diameter. In the diameter and length calculations, there are margins built in to account for manufacturing tolerances and clearances.

The length is based on the stack up of several parameters as shown in Figure 4.13. The first parameter is the divider in the common shaft between the two flow paths. In addition to that, is the press disk thickness on each side of the common shaft divider. Next, is the length of the inner shaft ducts required to accelerate the axial flow to solid body rotation. Fourth in the stack up is the length of the outer shaft that presses on the inner shaft. Finally, the thickness of the covers adds to the length, but the valves are not included. Please note that, the length is composed of calculable values and assigned values. For example, the thickness of the common shaft divider can be calculated based on how much stress is placed on it during assembly. An example of an assumed value is the length of the outer shaft. Every effort was made to ensure that the stack up is realistic in nature.

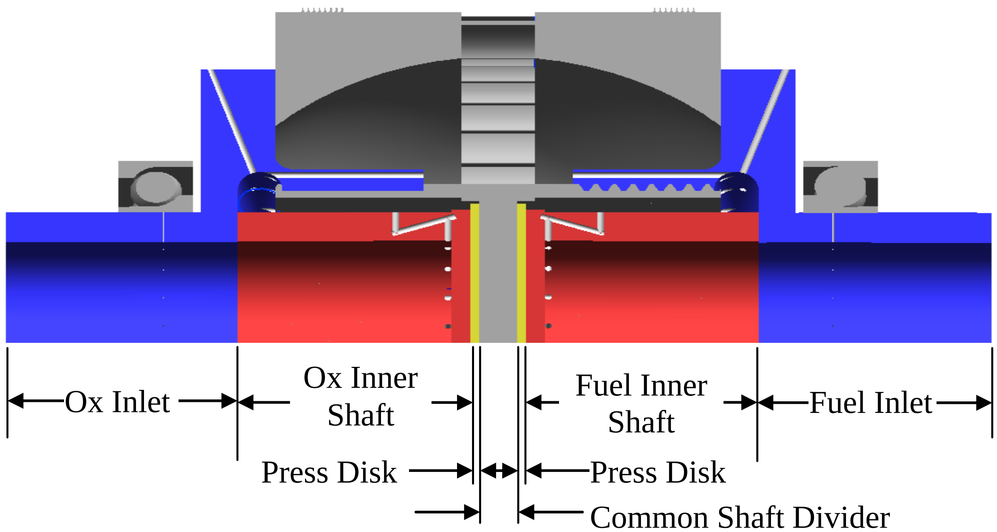


Figure 4.13 Length Stack Up

For the diameter, the maximum of the turbine, the rotating fuel injector and the rotating oxidizer injector is selected. The thickness of the pressure vessel required to contain the pressure created by the pump adds to the maximum shaft diameter. Additionally, a small amount of margin provides for the running clearances between the rotating shaft and the shell. Establishing the value of the turbine outer radius is the additive nature of the inner shaft geometry, the hydraulic dam geometry (including margins) and the combustor geometry. For the rotary injector diameters, the same factors determine their values, except the combustor geometry is replaced with the rotary injector heights. The diameter determination is shown in Figure 4.14 below.

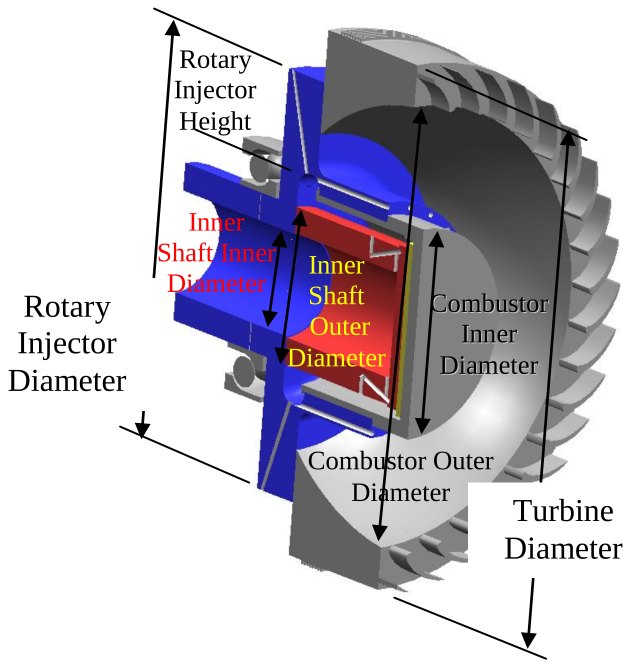


Figure 4.14 Maximum Diameter Determination

The weight estimate for the pump is much more complicated. Each physical component is assigned a density based on its selected material. Then, using the basic geometry calculated by the simulation in design point mode, the volume for each part is estimated. For the propellant valves, a nominal weight for the type of valve used in the application was established. A delta weight based on differences from the baseline flow rate is added to account for changes in the physical size of the valves. The following two tables show the methods used to estimate the weights of each component. Table 4.2 shows the rotating components and Table 4.3 shows the stationary components.

Table 4.2 Weight Approximations for Rotating Components

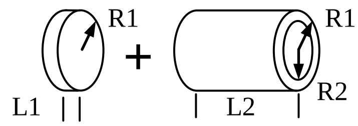
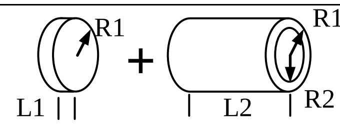
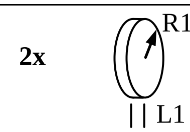
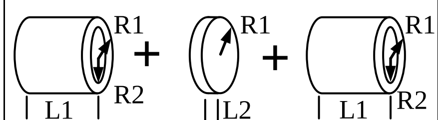
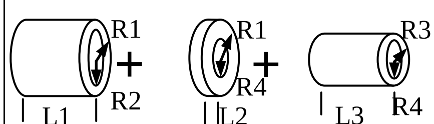
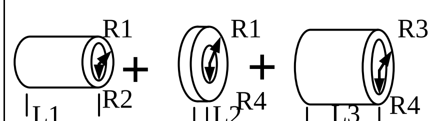
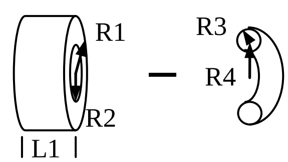
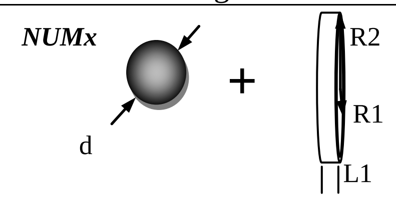
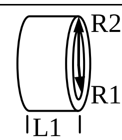
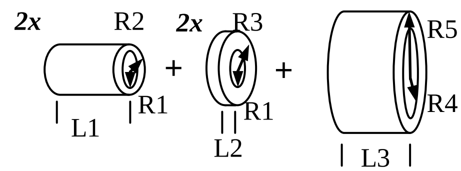
Element	Material	Dimensions	Figure
Oxidizer Inner Shaft	Titanium 6-4	R1=Outer Rad. of Inner Shaft R2=Inner Rad. of Inner Shaft L1=Endcap Thickness L2=Length of Inner Shaft	
Fuel Inner Shaft	Titanium 6-4	R1=Outer Rad. of Inner Shaft R2=Inner Rad. of Inner Shaft L1=Endcap Thickness L2=Length of Inner Shaft	
Press Disks	Polytetra-fluoroethylene (PTFE)	R1=Outer Rad. of Inner Shaft L1=Press Disk Thickness	
Common Shaft	INCO 625	R1=Outer Rad. of Common Shaft R2=Inner Rad. of Common Shaft L1=Length of Common Shaft Cavity L2=Thickness of Divider	
Oxidizer Outer Shaft	INCO 625	R1=Maximum Rad. of Outer Shaft R2=Outer Rad. of Common Shaft R3=Rotary Injector Rad. R4=Inner Rad. of Inner Shaft L1+L2+L3=Length of Outer Shaft	
Fuel Outer Shaft	INCO 625	R1= Rotary Injector Rad. R2=Outer Rad. of Common Shaft R3= Maximum Rad. of Outer Shaft R4=Inner Rad. of Inner Shaft L1+L2+L3=Length of Outer Shaft	
Turbine	INCO 625	R1=Turbine Outer Rad. R2=Combustor Inner Rad. R3=(Combustor Outer Rad.-Combustor Inner Rad.)/2 R4=R3+Combustor Inner Rad. L1=Width of Combustor	

Table 4.3 Weight Approximations for Static Structure

Element	Material	Dimensions	Figure
Bearings	CRES 304	d=Ball Bearing Diameter R1=Inner Race Radius R2=Outer Race Radius L1=2d Num=Number of Ball Bearings	
Scrolls	INCO 625	R1=Rotary Injector Height R2=R1+Shell Thickness L1=Width of Scroll	
Shell	INCO 625	R1=Rotary Injector Height R2=R1+Shell Thickness R3=R4=Turbine Diameter R5=R3+Shell Thickness L1=Length of Outer Shaft L2=Endplate Thickness L3=Width of Combustor	

4.6 Performance Calculations

The performance calculations were limited to pump efficiency and performance of a notional rocket. The pump performance parameters are typical pump characteristics, such as pressure ratio, efficiency and shaft speed for given mass flow rates. In addition to the those parameters are specific component performance parameters, such as turbine rotor inlet temperature, combustor mixture ratio, combustor mass flow, shaft power, turbine pressure ratio and scroll recovery. The performance numbers reported herein have been normalized to the initial baseline parameters for ease of comparison.

4.7 CEA Combustion Properties

In addition to the pump performance calculations, an effort was made to understand the potential rocket performance using CEA [60]. Several different calculations are used for the rocket performance parameters. The first is a baseline calculation of performance. The baseline performance is the CEA calculated rocket performance for a 1,779 N (400 lb) class rocket without a pump. The chamber pressure for the baseline configuration is set at 1.38 MPa (200 psia). The next rocket calculation is to add the pump and calculate the performance of a rocket at the higher pressure, but ignoring the pump combustion gases. This second calculation represents the ideal performance of a rocket operating at twice the chamber pressure. Doubling the chamber pressure is a somewhat arbitrary design requirement for the concept. Since the rocket performance without the pump combustor flow does not have much significance, the next rocket performance calculation assumes that the turbine exhaust provides no thrust benefit. The third calculation has the same thrust as the first calculation but the propellant flow rate is increased to the pump inlet flow rate, resulting in a decrease in the specific impulse. Fourthly, the exhaust from the turbine expands separately from the main rocket, and the overall thrust is calculated by summing the thrust from the rocket and the turbine exhaust. The specific impulse is calculated by dividing the thrust by the total propellant flow rate. Finally, the last rocket performance calculation takes the exhaust from the turbine and injects it into the rocket chamber. The different performance configurations are shown below in Figure 4.15.

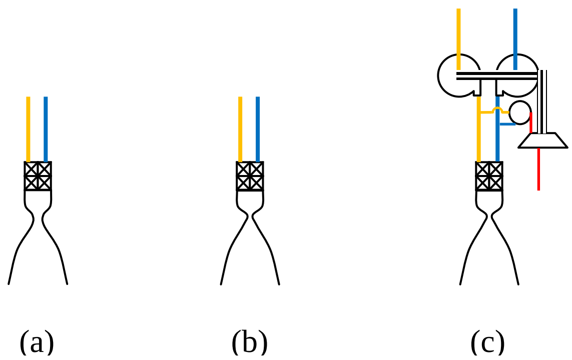


Figure 4.15 Rocket Performance Configurations (a) Baseline, (b) Baseline Pc*2, (c) Staged Combustion, (d) Separate Nozzle and (e) Cooling Flow

It is envisioned that the turbine exhaust is used as a cooling film within the rocket. The cooling flow performance calculation is used in reporting the results relative to the baseline. Each of these performance parameters for thrust and specific impulse are compared to the baseline condition. Additional options that were considered but determined to be outside the scope of the study included the expander cycle, where heated fuel or oxidizer is used to drive the pump, and the gas generator cycle, where a single pump pressurizes propellant for multiple rockets, thrusters or systems.

4.8 Solver Setup

The solver setup is an important part of the operation of the simulation. NPSS™ has a well-defined modified Newton-Rapheson solver. The solver iterates on several interrelated parameters until all of the error terms are brought to closure. The NPSS™ documentation provides more details on the generic solver methodology [59]. The design point solver contains different independents from the off design solver. In the design point solver, Table 4.4 shows the independents and the dependents, where the dependent describes the left and right hand sides to be balanced.

Table 4.4 Design Point Solver Setup

Independents	Dependents	
	Left Hand Side	Right Hand Side
Fuel split between combustor and main fuel flow	Turbine rotor inlet temperature	Desired turbine rotor inlet temperature
Oxidizer flow rate	Rocket inlet oxidizer flow rate	Desired rocket inlet oxidizer flow rate
Fuel flow rate	Rocket inlet fuel flow rate	Desired rocket inlet fuel flow rate
Inner shaft fuel film thickness	Fuel rotating injector radius in combustor	Oxidizer rotating injector radius in combustor
Oxidizer hydraulic dam pressure rise	Oxidizer pressure in rocket chamber	Desired rocket chamber pressure
Fuel hydraulic dam pressure rise	Fuel pressure in rocket chamber	Desired rocket chamber pressure
Turbine pressure ratio	Turbine efficiency error	0.0
Shaft speed	Shaft speed	Desired shaft speed

For the off design calculations, the number of independents and dependents is reduced, resulting in the solver setup shown in Table 4.5.

Table 4.5 Off Design Solver Setup

Independents	Dependents	
	Left Hand Side	Right Hand Side
Oxidizer hydraulic dam pressure rise	Oxidizer injector exit pressure	Rocket chamber pressure
Fuel hydraulic dam pressure rise	Fuel injector exit pressure	Rocket chamber pressure
Rocket chamber pressure	Rocket throat area error	0.0
Turbine pressure ratio	Turbine efficiency error	0.0
Shaft speed	Turbine flow area error	0.0

The tolerance for the dependent parameters is set to 1.0e-4 or 0.01% difference for design and off design solvers. Ideally, solver tolerance levels are less than 1.0 e-6 or 0.0001% difference [59], but since CEA is being called as an external program the full sensitivity of the parameters is limited to only four significant digits on some parameters due to having to read the ASCII output of CEA. Thus, setting the tolerance to smaller values does not have the sensitivity required to solve the perturbation matrix. Future efforts should resolve the lack of resolution by obtaining results that are more accurate from CEA.

4.9 Limits

The limitations on the simulation are either common sense logic or typical guidelines used in the rocket propulsion industry. There are no specific requirements for the optimization of the pump, but limitations were placed on the different design parameters. The goal is to achieve a robust design and ensure that the concept can be made easily and in an inexpensive manner. The initial design and development of a new device often overlooks difficulties or over estimates the potential of creating an innovative design in the first attempt. Therefore, instead of trying to push the envelope, the Combustion Driven Drag Pump design is intended to place all design factors within safe margins to define a realistic device.

4.9.1 Structural

Structurally, the pump design is envisioned to be robust. The margin of safety on the stresses is set at two (2.0). Thus, the actual hoop and shear stresses calculated for the study, place the basic max stresses at one-half of the yield strength. The only stresses that are actually considered are the hoop and longitudinal stresses around the circumference of the pump shell and the shear stresses on the ends of the shell [71]. Two areas of structural design not considered due to the complex nature of the effort are the dynamic loading of the pump under random vibration (launch environment) and shock loads (separation environment). The thermal impacts on the shell were neglected as well, but the material strength was degraded for high temperature usage [71]. It is recognized that further development of the concept requires that the dynamic loading and the thermal loading need to be evaluated to ensure that the design maintains adequate margin for successful development. Both remain for the next stage and are outside the scope of the current study.

4.9.2 Shaft Dynamics

For shaft dynamics, it is assumed that the shaft has to run supercritical, that is faster than the first bending mode. However, the unique shape of the shaft and the design with multiple assembled parts makes it difficult to estimate the modes of the shaft without a detailed analysis and test of the shaft dynamics. Both are beyond the scope of the current effort. Instead, the design incorporates many locations where the shaft can be trimmed or modified in order to tailor the shaft dynamics for the operating range. An example is the location of the bearings. The bearings can be moved either axially outward to make the shaft appear longer or radially outward to allow for shaft stiffening [3].

4.9.3 Seal Performance

Seals are another area where the limitations of the preliminary design process restrict the amount of time dedicated to seal design. Instead of placing a great deal of effort on developing the seals, it is assumed that seals can be included or developed with relative ease that restricts the seal leakage to a fixed percentage of the total flow rate. As a rule, leakage across rotating seals is a function of the pressure differential across the seal [3], [20]. Since that differential does not vary a great deal by design in the Combustion Driven Drag Pump, it is assumed that the constant fraction approach is adequate for this stage of development. However, analysis and design efforts for the labyrinth and face seals are needed at the next step in the development process to verify that the simplified seal model is adequate.

4.9.4 Bearing Limits

In the area of bearing loads, it is regrettable that there was not enough time to address the bearing loads, as that would have been a fascinating topic to explore. However, with the fact that the axial loading is only due to the injector momentum, which is small, the axial loads are likely to be less of a factor on the overall design. Unfortunately, that may not be an overall benefit, as lightly loaded bearings can chatter causing excessive wear [3]. The same cannot be said for the radial loads on the bearings. The pump design is inherently going to put significant radial loads on the bearings. The first load is from the non-uniform pressure loads on the shaft from the three exhaust scrolls. Each scroll is going to have a unique pressure distribution on the surface of the shaft, especially as the pump throttles. In addition to the imbalance is the fact that the machining of the flow passages may allow for the fluids in solid body rotation to pool in an arc in the shaft, causing it to orbit and asymmetrically load up the bearings. Balancing the shaft and using oversized bearings should be enough to create a robust design for the initial development.

4.9.5 Heat Transfer

As was the case for the shaft dynamics, the time constraints on the study prevented in depth study of the heat transfer characteristics and their impacts on overall performance. In light of the restriction, the study is limited to materials that can easily handle the temperatures to be encountered and prevent the temperature limits from exceeding reasonable levels by placing limits on the combustor oxidizer to fuel ratio. The restriction does lead to the potential of having a concept that is conservative in nature from a thermal design perspective and from a weight perspective as high temperature nickel alloys were selected for almost all of the components; where titanium alloys would have saved considerable mass. However, the simplified conservative approach is consistent with the overall design philosophy of trying to keep the concept simple.

4.9.6 Combustion Temperature Limits

The combustion temperature limits are consistent with the goal of developing a concept that is robust from the initial design point. Thus, the baseline temperature limits are set at levels consistent with the material capabilities of a common rocket material, such as INCO 625. The maximum turbine inlet temperature is set at 1900°F. On top of the temperature limit, the pump operates with substantial liquid MMH and MON-3. Neither of them is great at providing cooling, but the relative mass of the main propellant flows can easily absorb any excess heat from the combustor based on the relative flow rates between the combustor flows and the main flows.

4.9.7 Turbine Pressure Ratio Limits

For the turbine, the pressure ratio across the turbine relates directly to the power capability of the turbine. However, since the turbine exhaust generates thrust by injecting the turbine exhaust into the rocket thrust chamber, too large a pressure drop across the turbine reduces the effectiveness of the pump by driving down the chamber pressure. In the performance calculations, the high pressure turbine exhaust provides film coolant for the rocket chamber, so the turbine exhaust gas pressure needs to be approximately twice as high as the chamber pressure. Therefore, a balance needs to be obtained between the turbine pressure ratio, or work generated, versus the overall system size. The turbine pressure ratio is allowed to vary between a lightly loaded turbine with a pressure ratio of 1.1 to a fully loaded turbine with a pressure ratio of 1.8 for a nearly sonic exit velocity.

4.9.8 Hydraulic Dam Flooding

The most interesting limit imposed on the study was the limit for pressure rise within the hydraulic dams. As the pressure rise increases, the inner liquid levels in the hydraulic dams move toward the centerline as shown in Figure 4.16 for a constant shaft speed. The illustration describes a flow with increasing backpressure from (a) where there is no backpressure and no flow, to (d) where the flow floods the hydraulic dam.

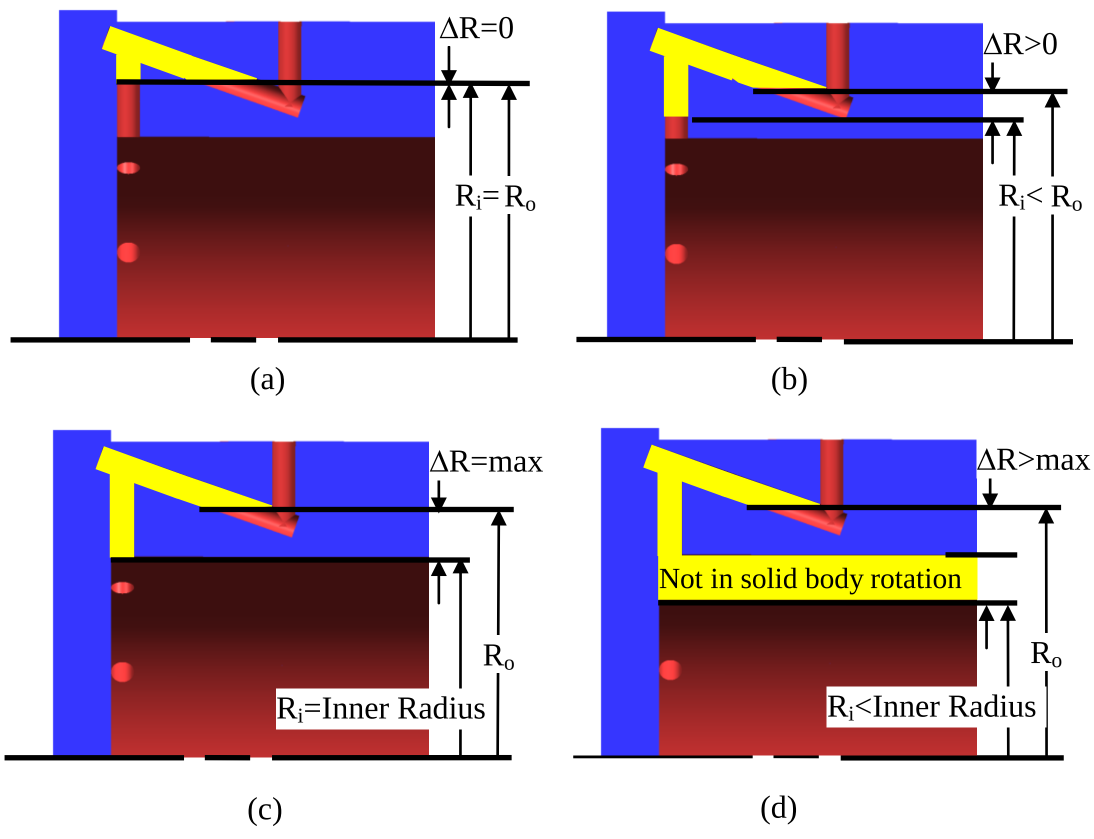


Figure 4.16 Various Operating Conditions for the Hydraulic Dams (a) No Flow, (b) Normal Flow, (c) Maximum Pressure and (d) Over Flow or Flooding

The physics in the hydraulic dams place real limitations on the operability of the concept that encourages investigation in future studies. For the current effort, the liquid level is monitored such that if the inner radius of the fluid is smaller than the inner radius of the shaft, the operating condition is considered unsustainable. Ideally, the simulation would be updated to include a reduction in the flow rate that occurs due to the limitations of the hydraulic dams. Unfortunately, adding that level of fidelity to the simulation requires detailed knowledge of the feed system and the rocket propulsion injection system, which are both beyond the scope of the current effort.

4.9.9 Pressure Limit

The pressure limit for the system is set to provide roughly double the chamber pressure of a baseline rocket. A two to one overall system pressure rise provides a reasonable performance improvement for evaluating the overall performance of the system. Further increases in pressure are attainable, but other factors would grow in importance and might mask the overall level of benefit from a pumped system at this level of study. For example, increasing the chamber pressure by an order of magnitude would certainly provide a performance improvement for the rocket itself, but the increased heat transferred to the structure could require more advanced cooling approaches mitigating the benefit of higher pressure operation. By staying close to the baseline pressure, the same design is able to provide accurate insight into the overall system benefit.

4.9.10 Shaft Speed Limits

The shaft speed limitation is set such that the maximum rim speed of the shaft was 488 m/sec (1600 ft/sec) [3]. The limit is a generally accepted limit for turbine disks in turbine engines and provides a good reference for future structural analysis efforts. In addition to the 488 ms/sec (1600 ft/sec) limit, the dN^2 levels of the bearings are monitored to ensure that a reasonable bearing design is achieved.

4.10 MMH Properties

The properties for MMH are entered into NPSS™ by way of the user specified fluid properties functionality. The properties entered into the tables were obtained from Schmidt’s book on Hydrazine [72]. The fluid properties include temperature, pressure, density, enthalpy, entropy, viscosity and several other variables. Based on the comments and reported properties in several different references, many of the properties of MMH are uncertain [73]-[79]. The reason for the uncertainty relates to the difficulty in measuring various properties of a fluid that tends to break down exothermally when subjected to high temperatures [72]. Additionally, MMH is a toxic propellant, which in itself discourages casual study [72]. The primary difficulty with MMH is that toxic levels can be present prior to the ability to detect MMH, making it a truly difficult substance to work with safely [72].

4.11 MON-3 Properties

The properties for MON-3 are entered into NPSS™ by way of the user specified fluid properties functionality similarly to how the MMH properties are entered. The properties entered into the tables were obtained from several sources, including the

Chemical Propulsion Handbook, CPIA, [80] and the National Institute of Standards and Technology, NIST [81]. The fluid properties include temperature, pressure, density, enthalpy, entropy, viscosity and several others. As is the case for the MMH properties, MON-3 properties are reported as having different characteristics by several different sources [82], [83]. The major parameters, such as temperature pressure and density, are in general agreement. However, properties such as conductivity and entropy showed a considerable amount of uncertainty among the sources [81]-[83]. MON-3 is another substance that is difficult to work with, which might explain the discrepancies. However, it is easily detectable by odor prior to the buildup of toxic levels, so it is unclear as to the exact reason for conflicting reports [81].

CHAPTER 5

TRADE STUDIES

5.1 Assumptions and Limitations

The intent of the study is to investigate the Combustion Driven Drag Pump with the goal of ultimately improving on the baseline design. As with any investigation, developing a solid plan is essential to its success. Naturally, following the plan to its conclusion is equally important to the success of the investigation. The key attributes of the plan for investigating the Combustion Driven Drag Pump are variation, evaluation and evolution. Figure 5.1 shows the design study process.

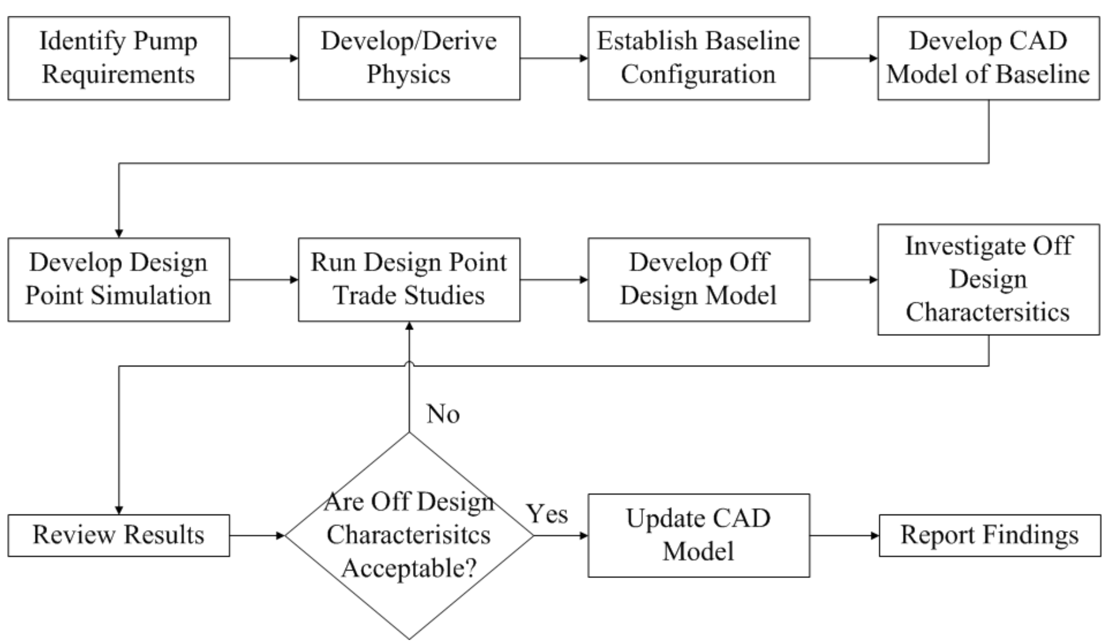


Figure 5.1 Study Process

The plan is best described as a series of trade studies to map out the trade space through variations in the design parameters. After each exploration, there is an effort to evaluate the responses and evolve the design in order to conduct the next series of trade studies.

Several assumptions limit the design space to a reasonable size while still providing insight into the key characteristics of the concept. Each assumption represents a possible avenue for further development and investigation, but it was deemed to be outside the scope of a preliminary design effort on an unproven concept. The assumptions range from the scope of the simulation, to the changes in fluid properties, to simplifications of the design itself. Each assumption is listed below:

1. The propellants are largely incompressible. This assumption is not uniform in nature in that many of the elements do use the small local density changes as functions of pressure. However, the calculations for the pressure rise portion of the simulation ignore the changes in the fluid density between the low-pressure inlet and the high pressure outlet. The assumption is conservative in nature in that as the pressure increases, the density increases slightly for both propellants. The increasing density characteristic implies that the hydraulic dams will be slightly oversized.
2. The liquids do not change temperature significantly between the inlet to the pump and the outlet of the pump. Generally, the assumption is valid, except in extreme cases of pressure rise when the fluid is near its boiling point or is in a high heat transfer region. Any temperature change will have the

primary effect of decreasing the viscosity, which will decrease some of the pressure losses within the pump and collection scrolls.

3. Heat transfer is ignored within the pump, which is possibly the least conservative assumption in simulating the system. With a combustor in close proximity to two liquid fluid flows, it is probable that the heat transfer rate is not negligible. The heat transfer will have the affect of decreasing the turbine inlet temperature and increasing the propellant temperatures. However, with the propellants already pressurized by the time they are significantly impacted by the heat addition, the temperature rise is not likely to play a significant role in the preliminary design trade studies. Future work should verify this assumption, but at the same time include the heat transfer, so that the flow areas are properly sized. Slight variations in the flow areas can have an impact on the overall performance if noticeable changes in temperature, density, pressure and viscosity occur because of heat transfer.

5.2 Design Parameters

Since the design study was conducted to identify an optimum or near optimum configuration for the pump, several of the design parameters are incrementally adjusted to explore the design space. The design space is defined by the limitations placed upon each of the design parameters. The following sections describe the physical meaning of the design parameters.

5.2.1 Combustor Pressure Drop, CdP

The first design parameter is the combustor pressure loss. The pressure loss is independently input rather than being calculated, due to the complex nature of the hypergolic reaction [58], [72] and the complex geometry of the combustor. At this point in the study, the pressure loss is a placeholder for actual analysis and combustor design efforts. The parameter provides insight into the actual impact on the overall pump and rocket performance. Understanding the affect of the combustor pressure drop on the overall performance is critical to understanding which parameters need to be prioritized in the design effort.

5.2.2 Combustor Efficiency, Ceff

Similar to the combustor pressure loss is the combustor efficiency. The actual physics based efficiency is not linked to the physical model. However, during the research phase for the project, it was noted that the reaction of MMH and MON-3 is very thorough as long as the propellants achieve a reasonable level of mixing [58], [72]. The intent of this design parameter is primarily to understand the relationship between the combustor efficiency and overall pump and system performance.

5.2.3 Combustor Radius Ratio, CRo

The combustor rotary injectors set the combustor inner radius. However, the ratio of the outer radius to the inner radius is free to be set. The parameter goes hand in hand with the combustion efficiency, pressure drop and turbine efficiency in that the intent is to evaluate the overall impact of the radius ratio on the weight and diameter of the pump. Unlike the efficiency and the combustor pressure loss, the radius ratio parameter does not have to be limited. There are several options available for making sure the combustor volume and flow characteristics are not directly linked to the actual outer radius of the combustor. Thus, the parameter becomes more of a packaging consideration. Figure 5.2 illustrates the relationship of the combustor geometry to the radius ratio parameter.

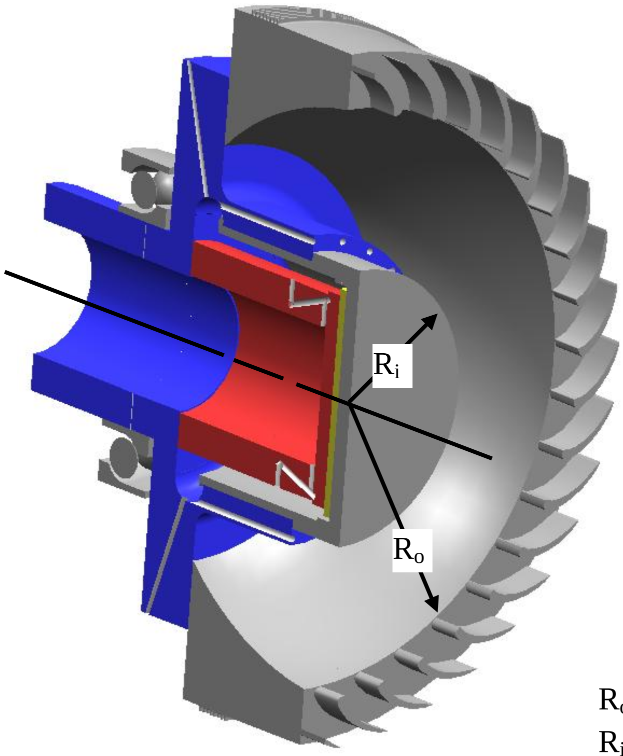


Figure 5.2 Combustor Geometry Factor

5.2.4 Propellant Film Thickness, Film

The film thickness parameter defines the thickness of the film that is created on the inside of the inner shafts for the propellants. The parameter affects the axial velocity of the propellants and the radial size of the inner shaft. The thickness also affects the length of the inner shaft required to accelerate the fluids from purely axial or nearly axial velocity to solid body rotation. The definition of the film thickness is shown in Figure 5.3.

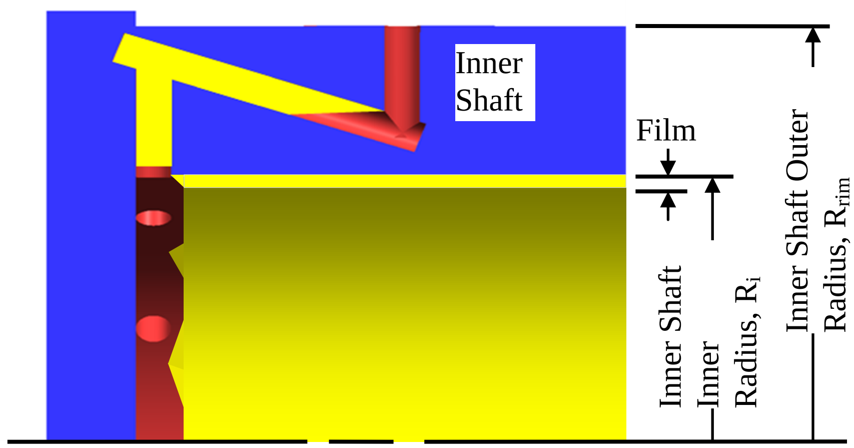


Figure 5.3 Inner Shaft Film Thickness

5.2.5 Pump Shaft Speed, N

The shaft speed of the pump is an important design parameter. Turbine efficiency, scroll recovery, dynamic head from the rotary injectors are all directly affected by the speed of the pump. On top of that, the dimensions for the hydraulic dams relate to the square of the shaft speed. The importance of the design shaft speed makes it a significant design and performance parameter.

5.2.6 Oxidizer Flow Split, OxSplit

Since the design of the overall system is based on a staged combustion system, a certain amount of the propellants entering the pump is diverted to the pump combustor.

The OxSplit design parameter specifies the fraction of the oxidizer that goes directly to the rocket rather than through the pump combustor. Since the release of the chemical energy in the combustor provides the source of power for the turbine, the simulation balances the mass flow rate through the combustor against the turbine pressure ratio required to drive the pump. Additionally, the simulation balances the mixture ratio in the combustor with the turbine rotor inlet temperature, such that controlling the oxidizer split and the turbine rotor inlet temperature will also control the fuel flow split.

5.2.7 Parasitic Losses, Parasitics

The parasitic losses sum up into one parameter termed parasitics. Parasitic losses are not true design parameters, but are byproducts of the design. However, in the simulation, the parasitic losses are treated as design parameters in that different loss fractions represent different design approaches. For example, the difference in the power consumed by foil bearings and roller bearings is significant, so variation in the parasitic parameter represents different design choices. The primary reason for investigating the parasitic variation is to document the sensitivity of the pump to those losses.

5.2.8 Scroll Head Recovery, Recovery

The recovery of the dynamic head in the scroll directly contributes to the performance of the pump. The scrolls convert some of the fluid velocity, due to the rotary injectors, into pressure through diffusion. The design of the scrolls affects the overall pressure rise of the pump and the efficiency of the pump. Hence, it is important to understand how large an impact the scroll recovery has on the overall performance of the system.

5.2.9 Hydraulic Dam Outer Margin, ShaftDuctDelta

Manufacturing the hydraulic dams requires margin in the manufacturing process. How tightly the manufacturing needs to be controlled can sometimes lead to expensive and complex designs. The importance of the margin on the overall performance has to be evaluated to determine the level of complexity needed to manufacture the hydraulic dams. Figure 5.4 shows how the hydraulic dam outer margin or the ShaftDuctDelta is defined physically.

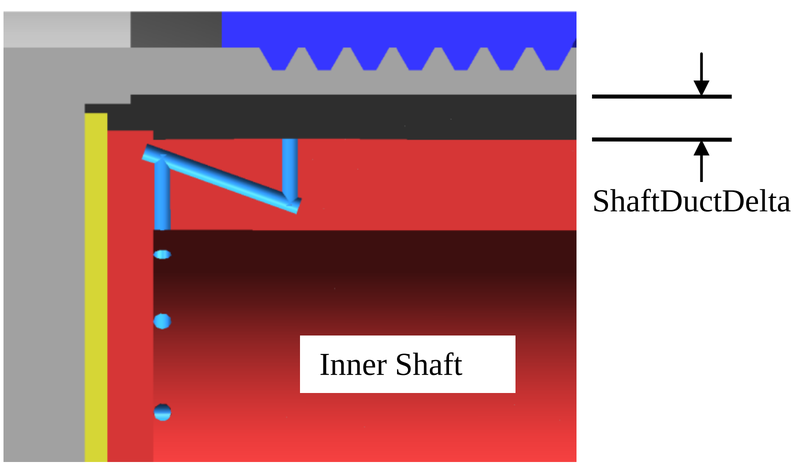


Figure 5.4 ShaftDuctDelta Definition

5.2.10 Hydraulic Dam Inner Margin, HydMargin

The other end of the hydraulic dam also has margin as one of the design parameters. The inner radius of the hydraulic dam has to be larger than the inner radius of the inner shaft in order for the hydraulic dam to work properly. The difference in those two radii in the design point runs constitutes the hydraulic dam inner margin or HydMargin parameter. The hydraulic dam inner margin may influence the sensitivity to manufacturing tolerances and to uncertainties in operating conditions, which makes it important to the robust nature of the pump. However, too much margin negatively affects the size of the pump. Figure 5.5 shows the nature of the hydraulic dam inner margin.

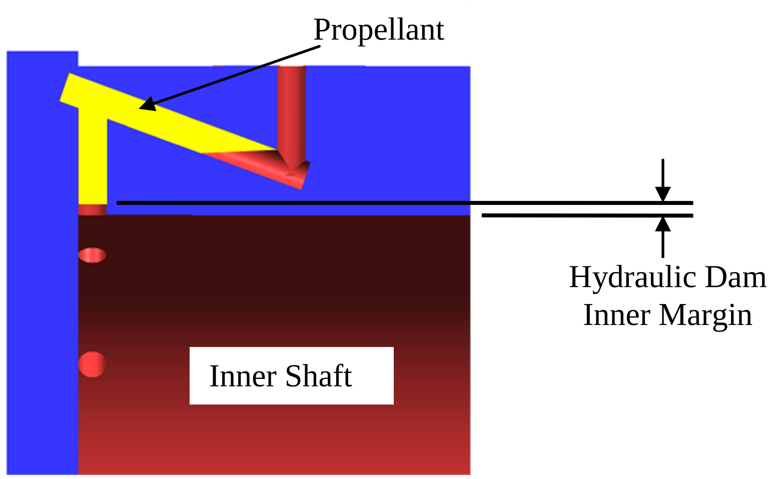


Figure 5.5 Hydraulic Dam Inner Margin Definition

5.2.11 Rotary Injector Height, InjdeltaR

As is the case for the hydraulic dams, the rotary injectors have margin for manufacturing. A larger margin makes the parts more tolerant to manufacturing and assembly variations, but at the same time adds to the diameter of the pump. The rotary injector height is comprised of the difference in radii between where the flow is in the purely axial direction and where the flow leaves the shaft. The difference in those two radii is the injector height and is illustrated in Figure 5.6.

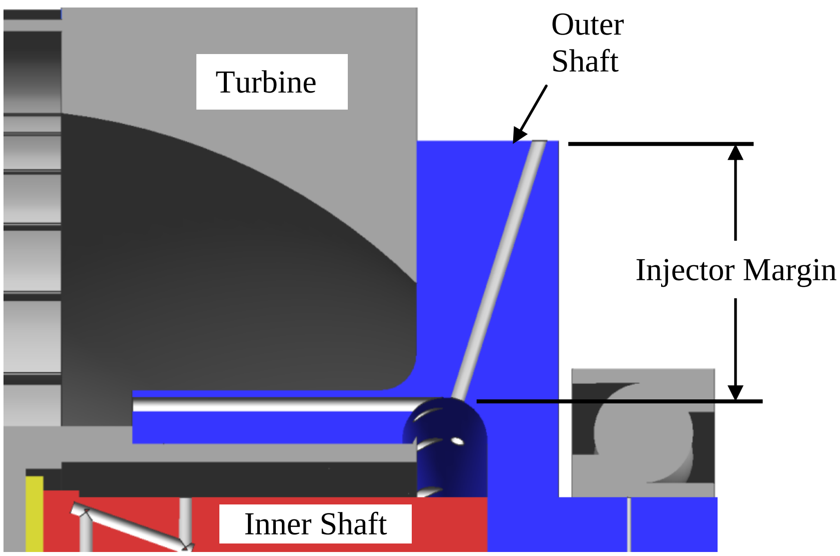


Figure 5.6 Rotary Injector Margin

5.2.12 Inlet Swirl, Swirl

The inlet swirl is a figure that factors into the amount of power the pump consumes. Adding swirl to the inlet flows reduces the initial drag on the shaft at the expense of inlet pressure. Thus, a trade between the initial pressure and the work required from the turbine is represented by the inlet swirl parameter. Positive swirl represents inlet flow in the same direction as the shaft rotation.

5.2.13 Turbine Rotor Inlet Temperature, TRIT

The turbine rotor inlet temperature affects how much work can be extracted from a fixed mass flow rate of combustion gas. Increasing the turbine rotor inlet temperature helps the efficiency of the pump and the system, but it comes at the expense of requiring more exotic materials to withstand the higher temperature. Conversely, decreasing the turbine rotor inlet temperature allows for the use of lighter, less expensive and easier to machine materials, but it requires higher turbine mass flow to generate the same pressure rise within the pump.

5.3 Metrics

The metrics used to gauge the relative value of a change in the design relate to overall performance of the pump itself and for a generic system using the pump. The pump specific metrics, efficiency, power, weight, diameter and length are all considered important in addition to the turbine exit pressure and the fraction of the flow used to drive the power turbine. Since many systems can be developed that can take advantage of a pump, the overall system performance metrics are based on a generic one-engine, staged combustion configuration being fed by one pump. Therefore, the thrust and specific impulse of a generic system are evaluated for each configuration explored. To help understand the responses, the geometric features within the pump, several contributors to the shaft power balance and the mass flow rates are monitored.

5.3.1 Pump Inlet Flow Rates, Wox and Wfuel

The first metrics observed are the mass flow rates entering the pump. Both oxidizer and fuel flow rates are indicative of half the overall system performance equation and are documented accordingly. The flow rates are also an indication of the performance of the pump.

5.3.2 Specific Impulse, Isp

The specific impulse metric is one of the most important metrics in a propulsion system. The specific impulse metric is the combination of the thrust and total flow rate and represents the overall efficiency of the system, not just the pump.

5.3.3 Thrust, F

The thrust is the productive aspect of the system so it is of high importance. The thrust determination is based on the thrust calculation using CEA [60] and assuming the turbine exhaust is input into the thrust chamber for cooling in a staged combustion rocket.

5.3.4 Pump Efficiency, Eff_Pump

Pump efficiency is a natural parameter to use as a metric for a pump. The metric is based on the pressure rise generated by the pump and the power provided by the combustion of the propellants.

5.3.5 System Weight, W

Estimating the weight of the system is another major factor. The weight is determined by adding the weight estimates from the components and the weight delta for sizing the valve to different flow rates. Additionally, a system weight delta is calculated based on the operating pressure achieved in the rocket. The chamber pressure affects the scale of the resulting engine and accounts for increasing the weight as the chamber pressure decreases.

5.3.6 Pump Length, L

The pump length affects the ability to package and mount the pump. Too long a pump and the mounting becomes problematic from a structural point of view in that the mass spans too large a distance to be able to cope with launch vibration loads. Additionally, a larger length lowers the natural frequency of the pump structure and lowers the shaft dynamic modes. Typically, having the highest shaft mode and natural frequency are desirable. Finally, the length of the pump affects the connections to and from the pump and adds to the total volume of the system.

5.3.7 Pump Diameter, D

The pump diameter metric is similar to the pump length in that it affects the ability to package the pump in an efficient manner. Additionally, distributing the mass to larger diameters increases the pumps susceptibility to vibration loads. The pump diameter is of highest importance because the weight of the pump scales with the square of the diameter.

5.3.8 Shaft Inner Radii, Rox_in and Rfl_in

One of the key components of the diameter determination is the inner radius of the inner shaft. The calculation of the inner shaft inner radius is determined by the flow rate and the desired film thickness. The inner shaft inner radii for both the fuel and the oxidizer are potential indications for the effectiveness of the drag pump.

5.3.9 Inner Shaft Rim Radii, Rrim_ox and Rrim_fuel

The rim radii of the inner shafts are major components of the diameter of the pump. Additionally, the rim radii of the inner shafts affect the weight of the pump in that they represent the sizes of the inner shafts. Finally, the inner shafts rim radii are a measure of the compactness of the hydraulic dams.

5.3.10 Outer Radii of the Hydraulic Dams, Ro_ox and Ro_fuel

The outer radii of the hydraulic dams are the primary drivers for the stack up of dimensions establishing the diameter of the pump. Monitoring the outer radii of the hydraulic dams provides insight into the root factors driving the size of the pump.

5.3.11 Inner Radii of the Hydraulic Dams, Ri_ox and Ri_fuel

The inner radii of the hydraulic dams determine the overall size of the hydraulic dam when combined with the outer radii. Thus, monitoring the responses of the hydraulic dams inner radius metrics reveal trends associated with the overall weight. The inner radii of the hydraulic dams affect the weight of the inner shaft.

5.3.12 Inner Shaft Surface Speed, Vrim_ox and Vrim_fuel

Observing the responses of the rim speeds for the inner shaft shows how stressed the shaft will be. Higher shaft speeds indicate an increasing propensity for shaft stresses and creep. Additionally, the rim speeds are an indication of how effective the collection scrolls may be in converting the dynamic head into actual pressure. Finally, the rim speeds provide insight into the power that the pump consumes.

5.3.13 Fuel Flow Ratio, FuelSplit

The FuelSplit metric measures the ratio of fuel directed to the rocket and to the pump combustor. Variations in the FuelSplit parameter stem from changes in the turbine rotor inlet temperature and in the OxSplit design parameters. Monitoring the

FuelSplit parameter provides insight into how efficient the pump is and how aggressive the pump design is.

5.3.14 Combustor Outer Radius, Ro_brn

Keeping track of the outer radius of the combustor illustrates how the various design parameters have stacked up to define the diameter of the pump. Overall, the combustor outer radius is defined by the design parameter relating the inner radius of the combustor to the outer radius of the combustor, as well as, the outer radius of the inner shafts. In observing the combination of the outer radius of the inner shafts and the combustor geometry ratio, the sensitivity of the overall pump diameter can be explained and quantified.

5.3.15 Combustor Inner Radius, Ri_brn

In comparing the combustor inner radius to the inner shafts outer radius, the design efficiency can be monitored. For example, a large difference between the inner shaft outer radii and the combustor inner radius means that there is a large amount of structure between the two, so the design can probably be improved upon. Additionally, the combustor inner radius is an indicator as to the overall effectiveness of the liquid portion of the pump.

5.3.16 Combustor Oxidizer to Fuel Ratio, O/F

One of the metrics that characterizes the combustor performance is the oxidizer to fuel ratio or O/F. The O/F metric shows the ratio of oxidizer to fuel and is normally indicative of the combustor efficiency and the turbine rotor inlet temperature.

Additionally, the O/F metric provides insight into the operating characteristics of the pump.

5.3.17 Total Combustor Mass Flow Rate, Wcomb

The total combustor mass flow rate is an indicator of the effectiveness of the pump to generate high pressure propellants and high pressure turbine exhaust. Since the pump is a staged combustor, either the pressure of the propellants or the pressure of the turbine exhaust gas determines the rocket chamber pressure. Ideally, the two pressures would be matched, such that no energy is wasted over pressurizing the propellants or not extracting enough work out of the turbine. The total combustion mass flow rate is optimized when Wcomb is low.

5.3.18 Turbine Exit Temperature, TET

Observing the turbine exit temperature trend and comparing it with the turbine rotor inlet temperature provides a view into how much work is being provided by the turbine. A large difference between the two temperatures shows that the turbine is extracting a large amount of energy per unit of mass flow. A low temperature difference indicates that a high amount of energy is being extracted by pushing a large amount of gas through the turbine.

5.3.19 Turbine Power, HPturb

The turbine power is an indication of the overall performance of the pump. The power generated is dependent on both mass flow rate and pressure ratio. It is also representative of the combination of mass flow rate and pressure ratio and how much power the pump requires to pressurize the propellants. This parameter shows the input portion, or energy available, for the pump efficiency calculation.

5.3.20 Turbine Efficiency, Eff_Turb

The turbine efficiency is the measure of how well the turbine extracts energy from the combustor exhaust flow. The higher the efficiency, the lower the amount of mass needed for the combustor. Since the turbine extracts some of the thermal energy, the gas flow from the pump does not contain as much potential for thrust as the main rocket engine. Thus, reducing the amount of mass used to drive the pump provides a benefit for the system.

5.3.21 Turbine Pressure Ratio, PRturb

The turbine pressure ratio provides a key metric for understanding the trades between pump performance and system performance. One of the interesting elements of the study is the fact that the turbine exhaust pressure has to be similar in magnitude to the propellant exit pressures, so that the pressures entering the rocket are all of the same order. Ideally, the exact same pressure for all three streams entering the rocket chamber would be best. Thus, understanding how the design parameters affect the turbine pressure ratio leads the way to understanding the system as a whole.

5.3.22 Turbine Exit Pressure, Poturb

Finally, monitoring the turbine exit pressure shows how the turbine and combustor pressure decrease stack up against the pressure rise capability of the pump. When the parameter is compared to the exit pressures in the two propellant streams, it is possible to observe what is likely to happen across the labyrinth seals near the turbine.

5.4 Methodology

As has been stated before, one of the objectives of the study is to investigate the design space regarding the concept and to identify the most important driving factors, while simultaneously optimizing the configuration. In so doing, the first step is to identify general relationships between the design parameters and the metrics. The general relationships are explored by independently running the simulation across a range of values for each of the design parameters. This approach reveals the primary interactions between each of the design parameters and the metrics. In this manner, non-linear, primary relationships are revealed, but secondary interactions of the design parameters are not illustrated. Determining interactions at the secondary and tertiary level are reserved for the final set of iterations.

Based on the first set of sensitivities, the list of parameters is reevaluated to determine if any of the design parameters can be set to specific values or simply ignored entirely. Simultaneously, the variations that seemed to have impacts on the overall design are set to what appears to be their optimum value. Thus, a new configuration is selected for the next set of studies. The reduced set of parameters is again varied to identify further potential for improvements to the design.

Minor adjustments are made to the configuration based on the observable trends from the second round of studies. Therefore, the elimination and optimization process is completed, leaving only a few variables that the concept is sensitive to. Using the local optimums for each parameter, a third configuration is subsequently adopted.

From the third configuration, a reduced set of parameters is run. However, unlike in the previous two iterations, these adjustments are nested such that all combinations of the most influential parameters are run within the reduced trade space to identify the optimum configuration. The process is repeated until the design configuration reaches a stable point. The baseline design parametric values are provided in Table 5.1.

Table 5.1 Baseline Design Parameter Values

Design Parameter	Abbreviation	Initial Value
Combustor Pressure Drop	CdP	2.5%
Combustor Efficiency	Ceff	99.5%
Combustor Radius Ratio	CRo	1.5
Film Thickness	Film	0.1 in
Design Point Shaft Speed	N	50,000 rpm
Oxidizer Flow Split	OxSplit	0.921
Parasitic Loss	Parasitics	2%
Scroll Pressure Recovery	Recovery	0%
Hydraulic Dam Outer Margin	ShaftDuctDelta	0.1 in
Hydraulic Dam Inner Margin	HydMargin	0.1 in
Rotary Injector Height	InjdeltaR	0.1 in
Inlet Swirl Velocity	Swirl	10°
Turbine Rotor Inlet Temperature	TRIT	2350° R

CHAPTER 6

RESULTS

6.1 Trends

As discussed in Chapter 5, the approach taken for this study was an iterative one with multiple design parameter variations per iteration. In this chapter, the results from the study are discussed with an emphasis on the metric sensitivities revealed from exploring each design parameter. The chapter is broken down into five sections. The first section contains a discussion on the metric responses to the design parameters and optimization of the design parameters for the next iteration. Next, a discussion is presented on the first evaluation of the off design operability. The third section presents the design updates and modifications for improving the concept. Following that is the optimization process to arrive at the final configuration. Concluding the chapter is the section on the operability of the final concept.

The initial baseline configuration values are shown in the figures as a solid green circle to remind the reader where the study started. Additionally, the configuration is updated at the end of each iteration, representing an improved design. For the iterations with new design points, symbols are placed in the figures to provide a convenient comparison to the baseline values and the illustrated responses.

The metrics do not always show a response to changes in a given design parameter. Figures where all of the metrics show no sensitivity to the changes in the design parameter can be found in Appendix A for completeness. Short statements in this chapter denote when the figures can be found in Appendix A.

6.1.1 First Iteration

The first iteration consisted of exercising the simulation from the initial baseline by varying each of the design parameters individually. Because of the number of design parameters and metrics, this section is lengthy. The following discussions describe in detail the influences of the design parameters on all of the metrics. The design parameters are presented in the order that they were run.

6.1.1.1 Combustor Pressure Drop, CdP

The first design parameter investigated was the combustor pressure drop. Prior to the investigation, it was believed that large values for the combustor pressure drop would be a detriment to the overall performance of the pump and the system. Thus, the initial assumption was that the combustor pressure drop should be minimized. After running the variation and investigating the responses of the metrics, it appears that the combustor pressure drop does not have a significant influence on the overall system performance parameters of thrust, specific impulse or pump efficiency.

In a similar manner, the overall mass flow rates do not appear to be influenced by changes in the combustor pressure drop. The lack of influence on the mass flow rates is consistent with the fact that the specific impulse of the system and the thrust from the rocket are not affected by the combustor pressure drop parameter. The response figures for the overall performance metrics and the mass flow rates are shown in Appendix A, since they do not show any sensitivity to the combustor pressure drop.

The first indication that the combustor pressure drop influences the system is the response of the overall weight of the system. As the combustor pressure drop increases, the system weight increases linearly. Although the weight increase is small, it is clearly present. The reason for the increase relates to the fact that the turbine exit pressure decreases with a decrease in the combustor exit pressure. The affect on the system is that the rocket chamber pressure is linked to the turbine exit pressure, such that when the turbine exit pressure decreases the chamber pressure decreases and the rocket size, especially the nozzle, increases. The weight of a rocket is directly linked to its chamber pressure, and that delta is accounted for in the weight calculations. The trend is shown in Figure 6.1.

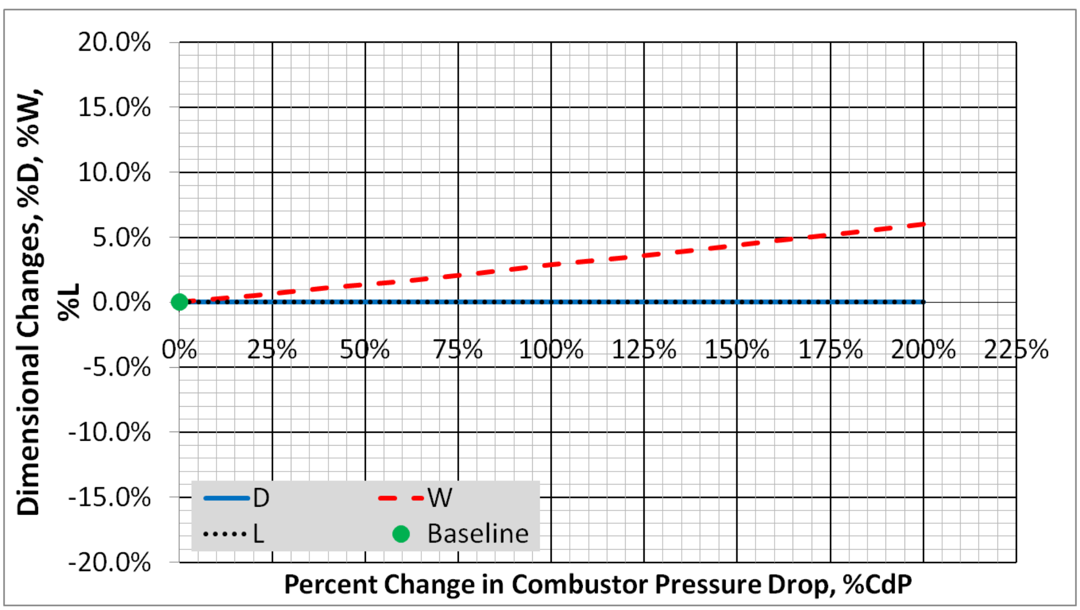


Figure 6.1 Round 1 Combustor Pressure Drop Influence on Overall Dimensions

The internal geometry metrics for the hydraulic dams, the rotary injectors and the combustor all show no sensitivity to the combustor pressure drop. The result agrees with the earlier observation that the pump itself is not affected by the combustor pressure drop, but rather the system level performance is affected. The plots for the geometry metrics can be found in Appendix A.

Finally, a review of the turbine performance illustrates that the only metric that is affected is the turbine exit pressure, confirming that the combustor pressure drop affects the overall system performance. Figure 6.2 shows the turbine related trends for the combustor pressure drop design parameter. The baseline pressure drop was small, so an increase of 100% for this parameter represents doubling of the combustor pressure drop.

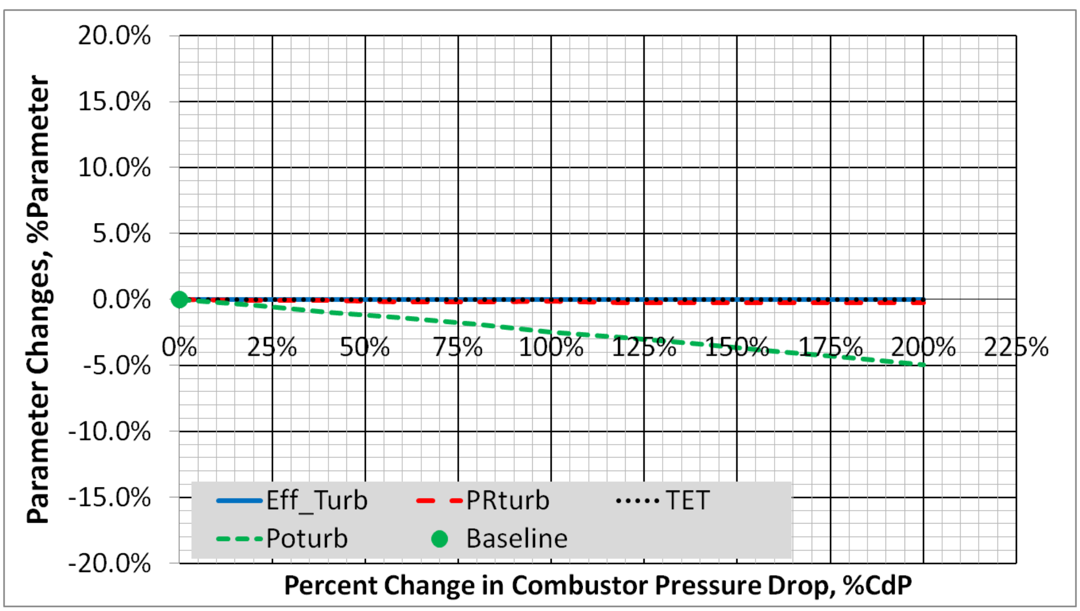


Figure 6.2 Round 1 Combustor Pressure Drop Influence on Turbine Metrics

A detailed inspection of the combustor pressure drop design parameter reveals that the system is affected, but the pump itself is not affected. The influence on the system directly relates to the assumption that the exhaust of the turbine has to be processed through the same combustion chamber as the main flows in a staged combustion system.

Based on the result, the combustor pressure drop can be set at a final value and eliminated from further study as a design parameter. The combustor pressure drop is set at the initial level for the remainder of the study. However, it is possible that the impact of the combustor pressure drop can be eliminated, if the turbine exhaust is expanded separately from the main chamber.

6.1.1.2 Combustor Efficiency, Ceff

Next is combustor efficiency. Like the combustor pressure drop, it was assumed that the combustor efficiency design parameter would affect the metrics for the pump and the overall system. Unlike the combustor pressure drop, there is a noticeable impact on the various metrics when the combustor efficiency changes. The overall performance metrics show that as the combustor efficiency decreases the specific impulse improves, while thrust and pump efficiency decrease, as shown in Figure 6.3.

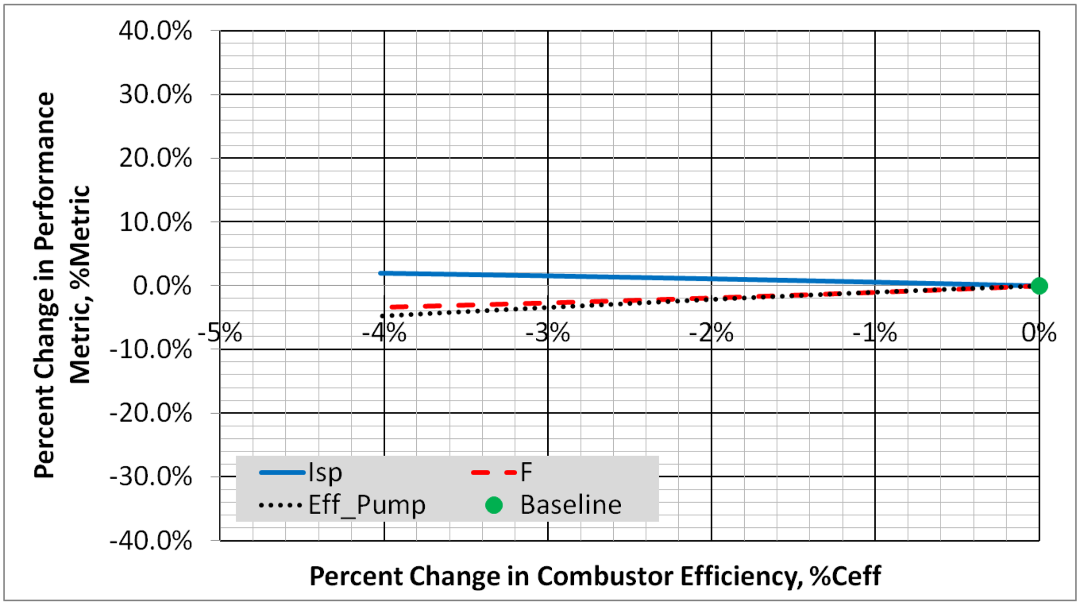


Figure 6.3 Round 1 Combustor Efficiency Influence on Performance Metrics

As the combustor efficiency decreases, the mass flow metrics change slightly. The combustion efficiency reduces the combustion gas temperatures as the efficiency decreases. In order to maintain the specified turbine rotor inlet temperature, the rich burning combustor has to run leaner. Thus, with a fixed oxidizer split, the fuel flow and total flow to the combustor decrease, as shown in Figure 6.4, since it needs to run at a mixture ratio closer to stoichiometric.

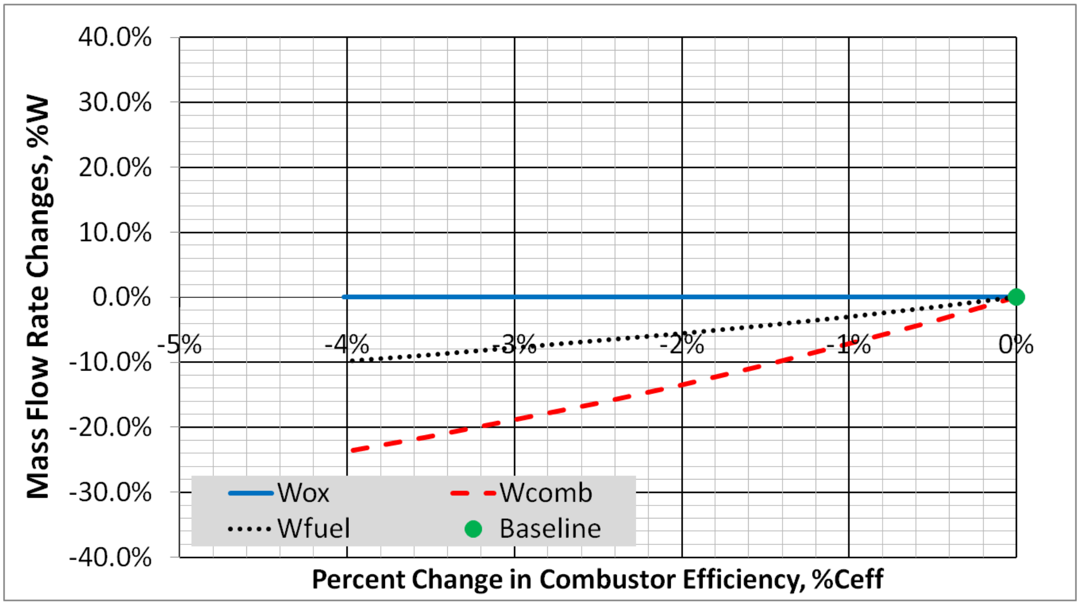


Figure 6.4 Round 1 Combustor Efficiency Influence on Mass Flow Rates

The logical result of reducing the flow through the combustor is that the flow through the turbine also has to decrease, which requires a larger pressure ratio across the turbine to balance the shaft power. The increase in the turbine pressure ratio results in a lower turbine exit pressure and causes the same system weight increase as observed with the increase in the combustor pressure drop described earlier. Interestingly, the overall diameter of the pump decreased slightly. The trends for the overall dimensions are shown in Figure 6.5.

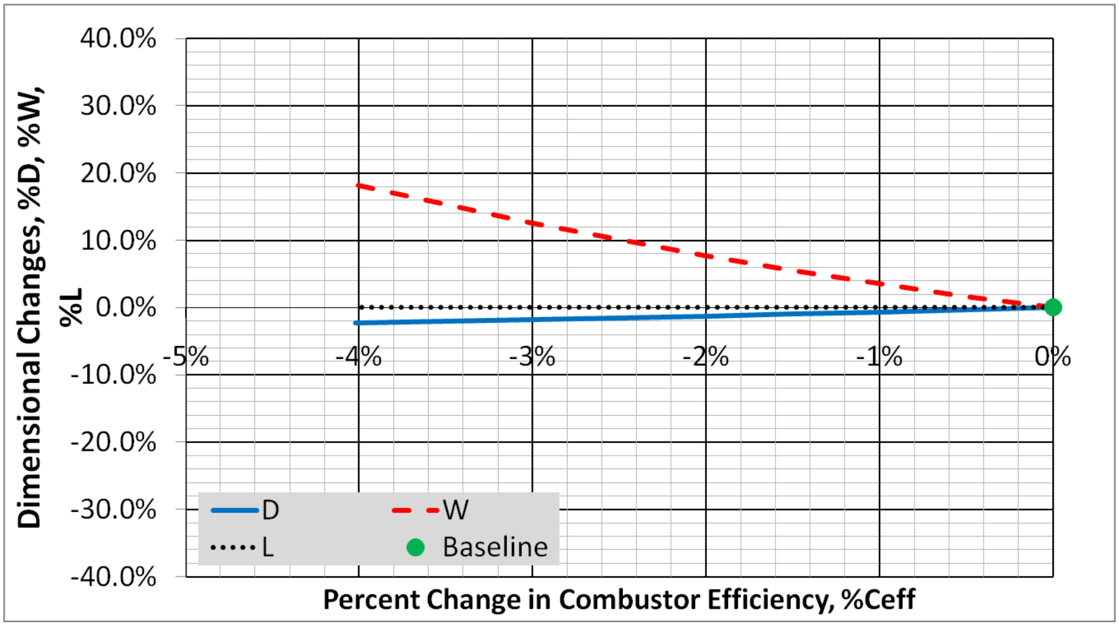


Figure 6.5 Round 1 Combustor Efficiency Influence on Overall Dimensions

In line with the decrease in the overall diameter of the pump is a decrease in all of the geometric features within the pump. In Figures 6.6 and 6.7, the key geometry changes are shown for the oxidizer and fuel systems respectively. It is noted that the pump geometry is dominated by the fuel system geometry due to the lower density of MMH. The shaft geometry for the fuel and the oxidizer flow paths decreases when the fuel flow to the combustor and overall system decreases. The magnitudes of the changes are larger in Figure 6.7, representing the fuel half of the pump.

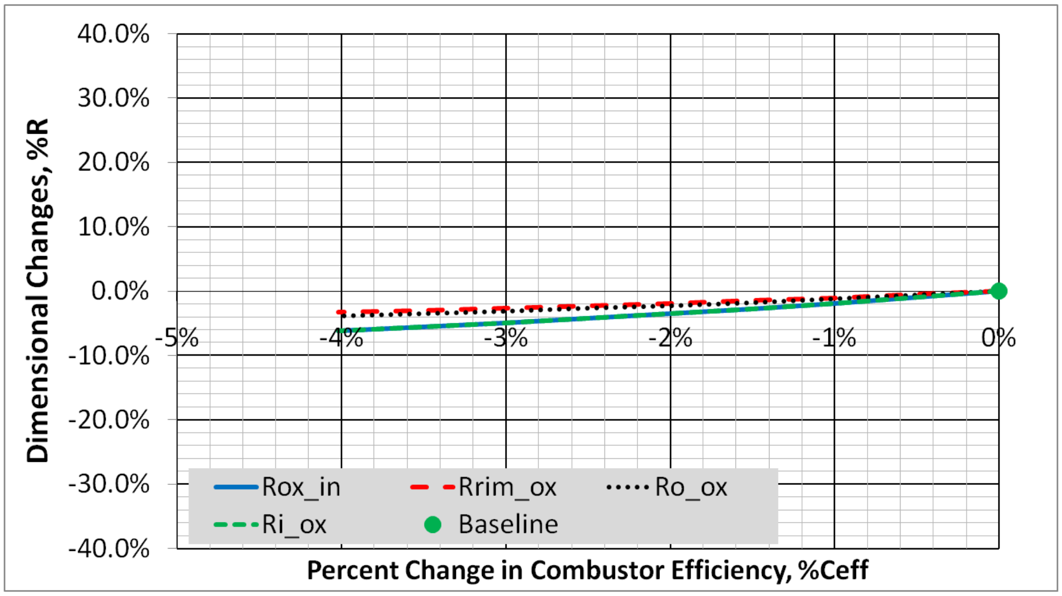


Figure 6.6 Round 1 Combustor Efficiency Influence on Oxidizer System Dimensions

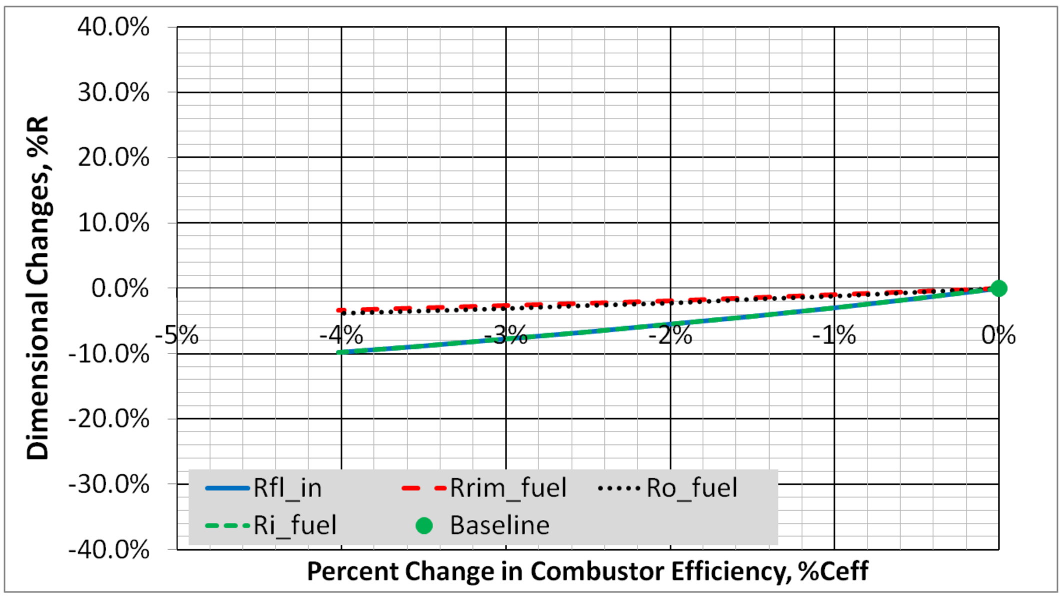


Figure 6.7 Round 1 Combustor Efficiency Influence on Fuel System Dimensions

Decreasing the geometry of the shaft also results in a decrease in the rotating injector geometry and the power required by the turbine, as presented in Figure 6.8.

The overall effect agrees with earlier observations indicating that lower combustion efficiency provides some positive benefits, in that the pump appears to decrease in size as the combustor efficiency decreases.

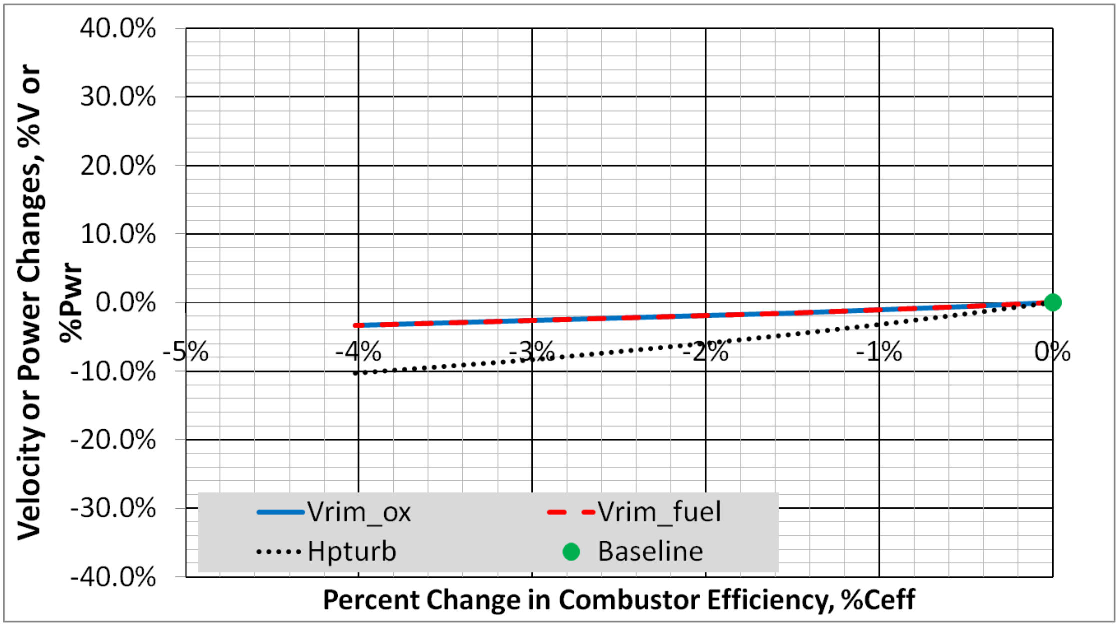


Figure 6.8 Round 1 Combustor Efficiency Influence on Power Metrics

As discussed previously, the fuel flow to the combustor decreases to maintain the specified turbine rotor inlet temperature as the combustor efficiency decreases. Thus, the curves in Figure 6.9 showing an increasing oxidizer to fuel ratio and increasing fuel split are not surprising. Likewise, the decrease of the combustor geometry is consistent with the overall decrease in geometry described earlier.

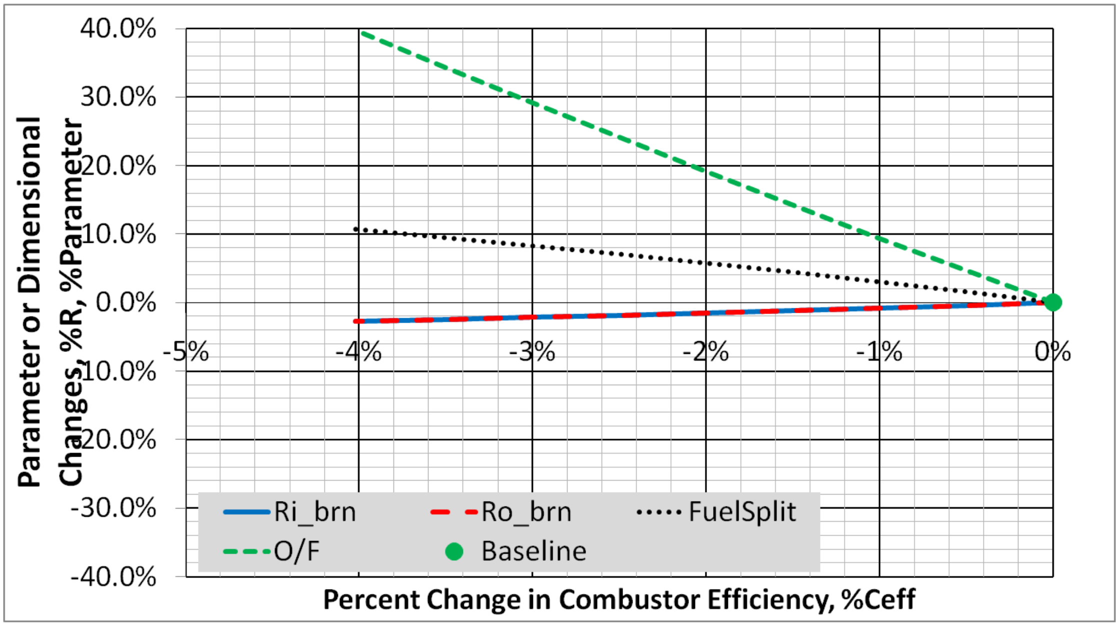


Figure 6.9 Round 1 Combustor Efficiency Influence on Combustor Dimensions

The turbine parameters shown in Figure 6.10 confirm the overall increase in pressure ratio associated with the decrease in combustor mass flow rate. Interestingly, the turbine efficiency also decreases, due to the decrease in the turbine exit diameter. The exit radius drives the performance of a Hero turbine [70], so as the rotor decreases in size, the turbine performance decreases.

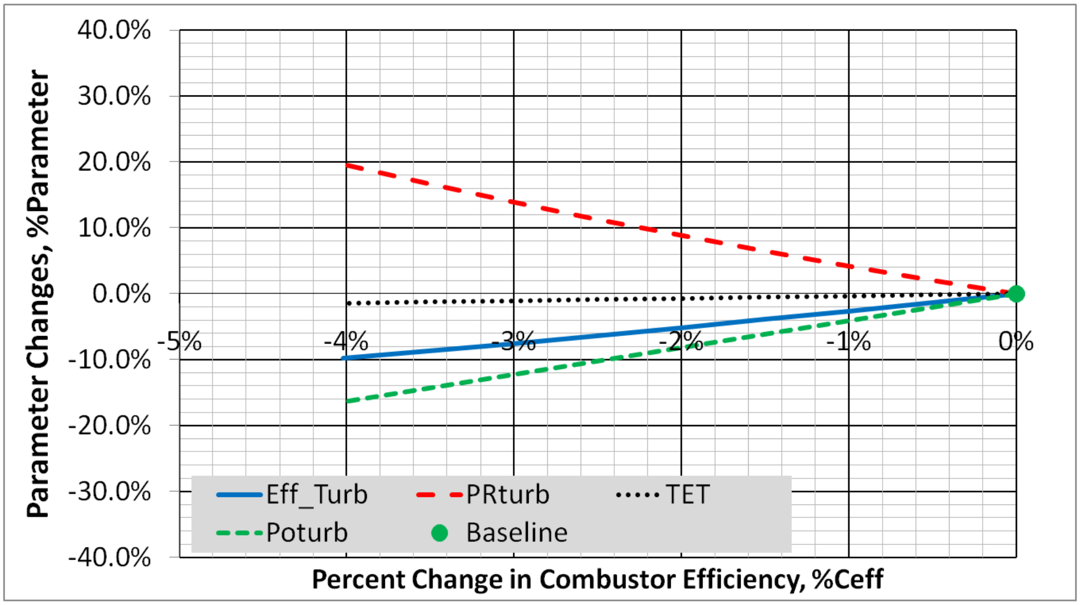


Figure 6.10 Round 1 Combustor Efficiency Influence on Turbine Metrics

The effect of the combustor efficiency on the design of the system is somewhat counter intuitive in that as the combustor efficiency decreases, the pump size decreases and the overall specific impulse increases. Even though the weight of the system increases, a change in how the turbine exhaust is used, i.e. separate exhaust nozzle instead of a staged combustion system, can compensate for most of the detriments. However, it should be noted that if the combustion efficiency decreases, the amount of uncombined oxidizer increases and the risk of hot oxidizer creating a hot oxidizing environment in the combustor, turbine or downstream passages increases, adding risk to the concept. Additionally, MMH and MON-3 are very aggressive reactants, and it could be challenging to create an intentionally low efficiency combustor [58], [72]. Thus, the combustor efficiency is set at the maximum in the survey for the remainder of the study.

6.1.1.3 Combustor Radius Ratio, CRo

The combustor radius ratio refers to how large the outer radius of the combustor is in relation to the inner radius. The ratio controls the radial location of the turbine and the volume of the combustor. Both aspects of the design were expected to have noticeable impacts on the pump and the overall system. In Figure 6.11, the combustor radius ratio influences the efficiency of the pump but not the thrust or the specific impulse of the system. The overall pump efficiency impact is due entirely to the performance of the turbine, which influences the discharge rim speed of the turbine.

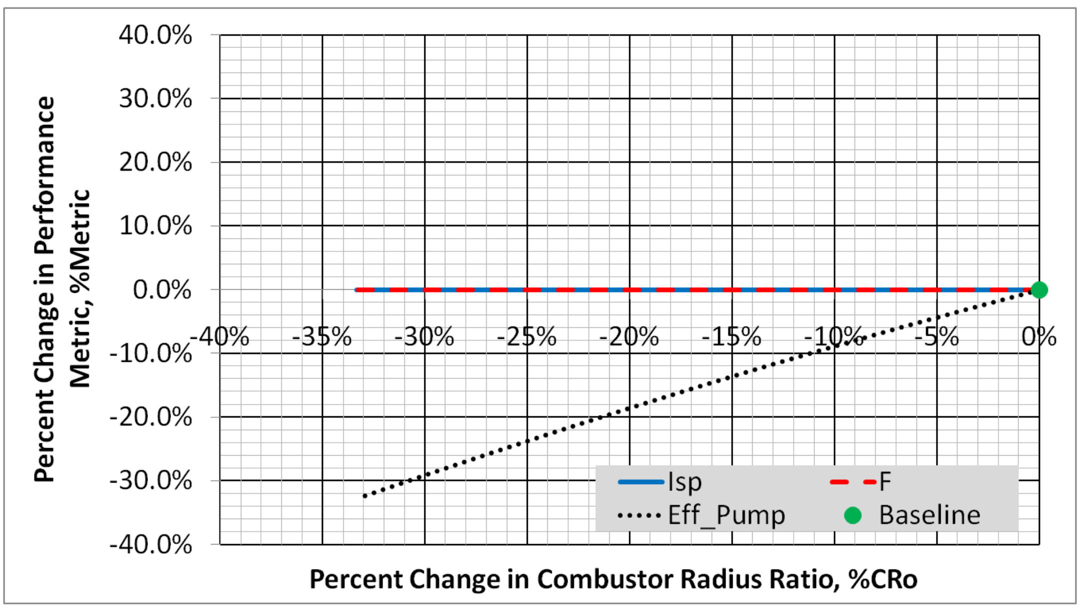


Figure 6.11 Round 1 Combustor Radius Ratio Influence on Performance Metrics

Because the turbine rotor inlet temperature and the oxidizer split are not changing, the overall mass flow rate and the fuel flow rate do not change with changing combustor radius ratio. The mass flow rate responses can be located in Appendix A.

The overall dimension of the pump and the weight of the system are affected. As can be seen in Figure 6.12, the diameter of the pump decreases linearly with the change in the combustor radius ratio as expected, which also decreases the mass of the pump. For small changes, the decrease in the pump mass dominates the overall weight, but as the combustor radius ratio decreases further, the turbine efficiency and by extrapolation the turbine exit pressure decreases. As in the earlier descriptions, decreasing the turbine exit pressure has the effect of increasing the overall system weight. Thus, the system weight starts out decreasing, hits a minimum value at -10% and then starts to increase.

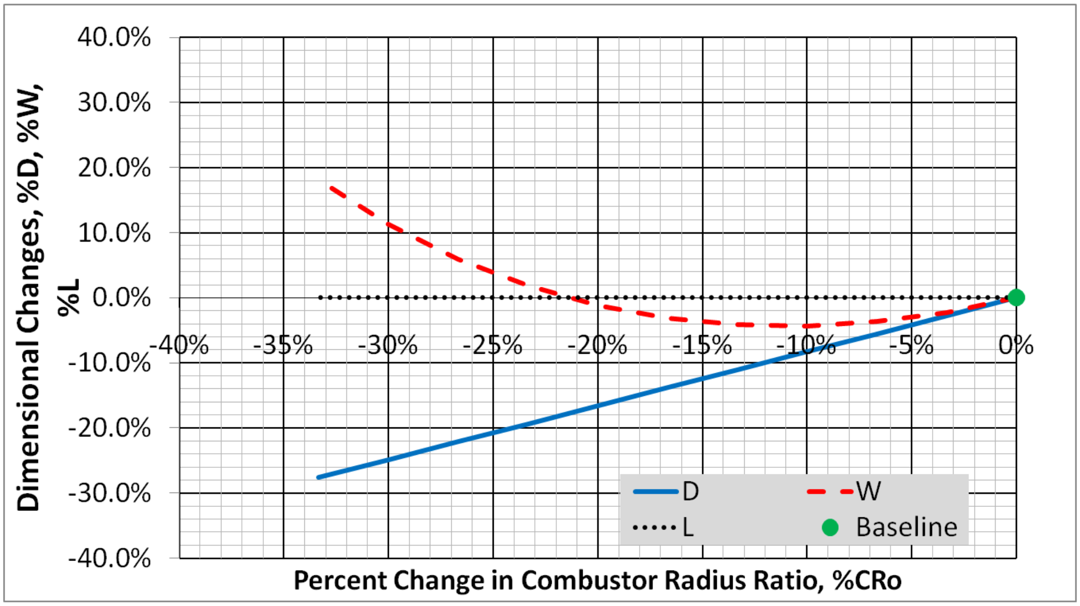


Figure 6.12 Round 1 Combustor Radius Ratio Influence on Overall Dimensions

Since the mass flow rates do not change, the geometry and the power factors do not change. Overall, the pump does the same thing, as in the baseline case. The inner geometry is defined by the pressure ratios and mass flow rates, which do not change. The rotating injectors and the mass flow rates drive the shaft power demand, so no changes in the power factors are observed. The geometry and mass flow rate responses can be found in Appendix A. However, the outer radius of the combustor is clearly affected by the radius ratio of the combustor. Thus, Figure 6.13 shows an expected trend.

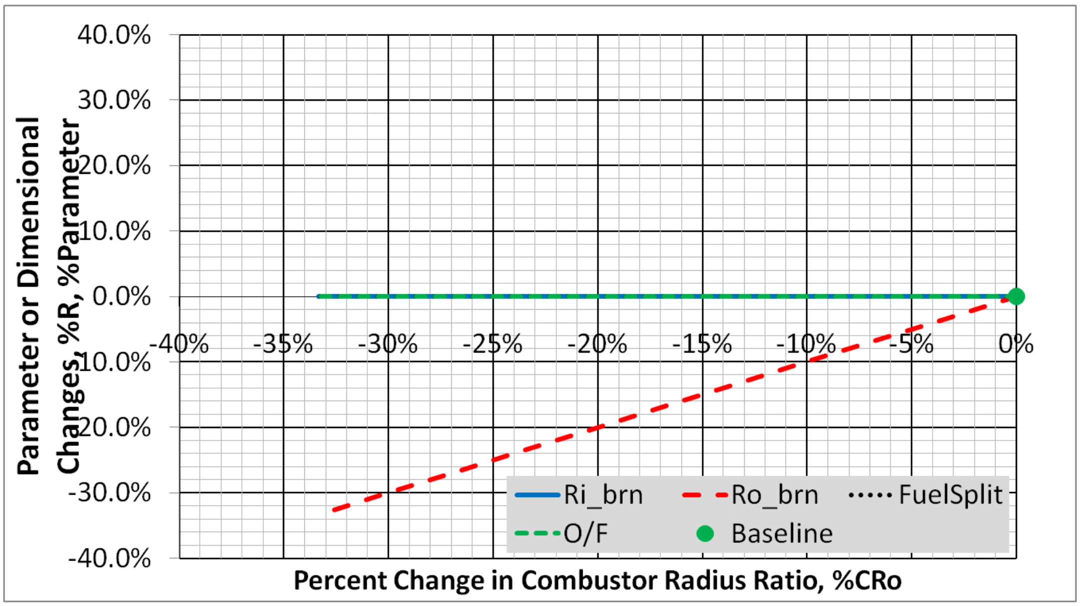


Figure 6.13 Round 1 Combustor Radius Ratio Influence on Combustor Dimensions

The turbine performance metrics shown in Figure 6.14 illustrates the true impact of changing the combustor radius ratio in that the turbine performance drops as the outer radius of the turbine decreases, which is typical for a Hero turbine [70]. As a result of the decrease in the turbine efficiency, the turbine exit pressure drops causing an increase in the overall weight as shown earlier.

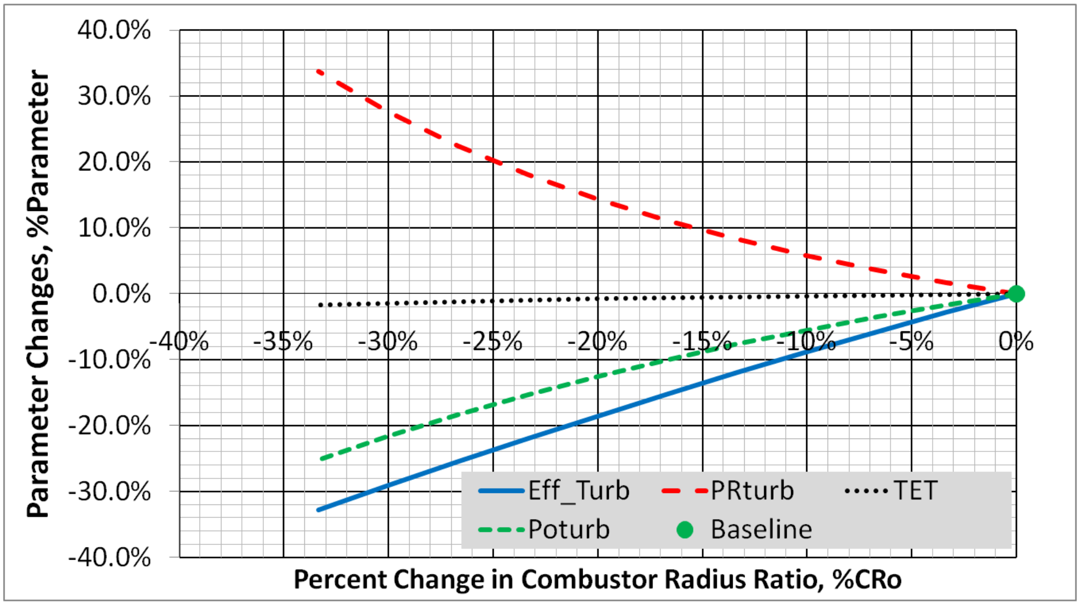


Figure 6.14 Round 1 Combustor Radius Ratio Influence on Turbine Metrics

Clearly, the turbine exit pressure drives the overall system weight. However, there does appear to be an optimum position where the impact of the turbine performance is not as large as the benefit of reducing the pump diameter. The combustor radius ratio is set at the bottom of the weight bucket (-10%) for the next iteration and the combustor radius ratio will be evaluated again in the next iteration.

6.1.1.4 Film Thickness, Film

Adjusting the film thickness was expected to have an effect on the length of the pump and the diameter of the pump, but was not expected to produce any other significant changes in the system. However, it appears that the pump efficiency is significantly affected by the film thickness as shown in Figure 6.15. It shows an increase in pump efficiency as the film thickness increases.

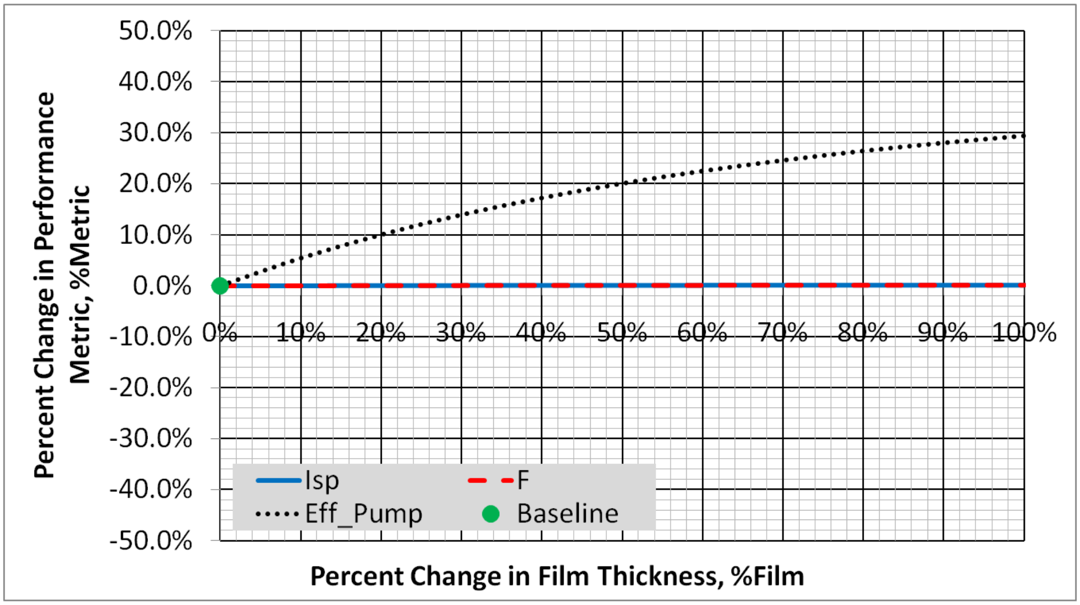


Figure 6.15 Round 1 Film Thickness Influence on Performance Metrics

The overall mass flow rates remain stable with changes in the film thickness, which is expected. The oxidizer split and the turbine rotor inlet temperature remain the same, so the mass flow rates have to remain constant as well. The trends of the mass flow rates are provided in Appendix A.

As shown in Figure 6.16, the film thickness does decrease the diameter of the pump and consequently the weight of the system. However, the length of the pump remains unaffected. It was initially assumed that a thicker film on the inside of the shafts would require a longer distance to establish solid body rotation. Upon closer examination, the distance of the inner shafts required for the flow to achieve solid body rotation does increase. However, the other revelation is that the axial distance required for the oxidizer flow and the fuel flow to achieve solid body rotation within the shaft is much less than the minimum distance required for manufacturing and assembly. Thus, the length difference does not show up in the figure.

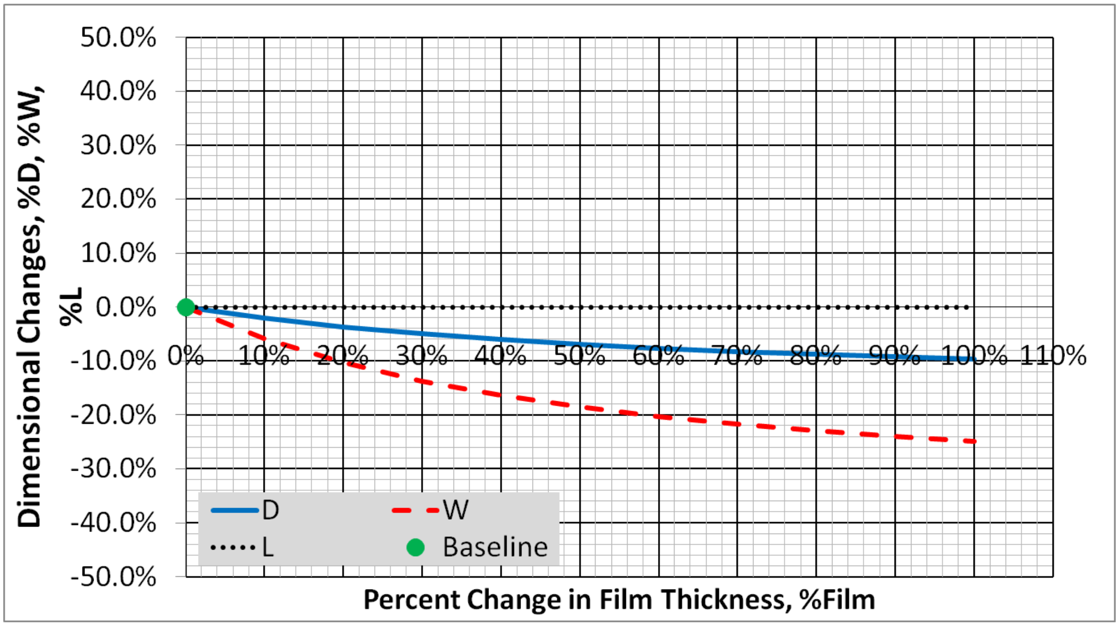


Figure 6.16 Round 1 Film Thickness Influence on Overall Dimensions

In Figures 6.17 and 6.18, the general trend of decreasing radius is illustrated in the hydraulic dams for the fuel and the oxidizer. As the film thickness increases, the minimum shaft diameter decreases, and hence the geometry of the shafts decrease. As can be seen, the hydraulic dam for MMH is affected more significantly by the film thickness parameter, due to the lower density of MMH and correspondingly higher volumetric flow rate.

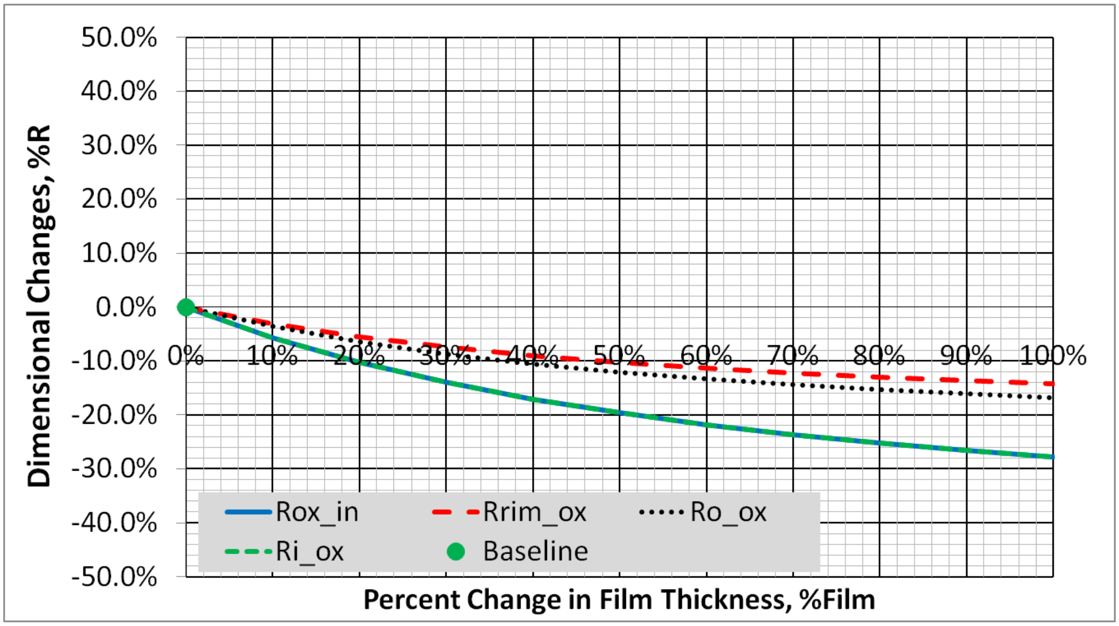


Figure 6.17 Round 1 Film Thickness Influence on Oxidizer System Dimensions

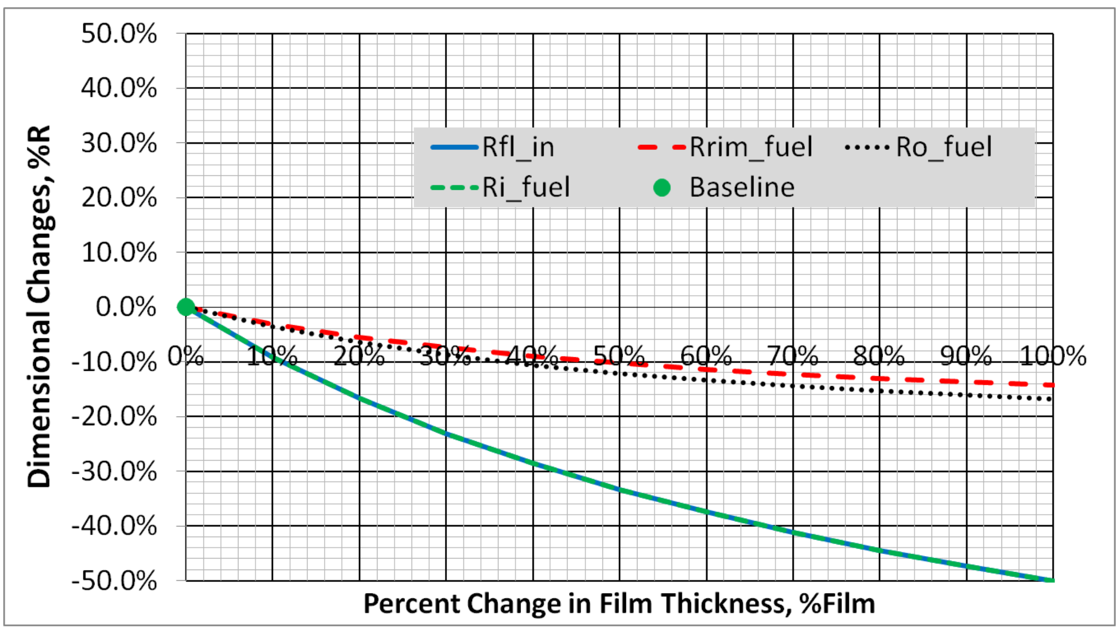


Figure 6.18 Round 1 Film Thickness Influence on Fuel System Dimensions

The reason for the improvement in the pump efficiency is partially illustrated in Figure 6.19. The rim speed velocities of the inner shafts decrease as the film thickness increases due to the decrease in overall shaft radius. Thus, the turbine power is allowed to decrease as well.

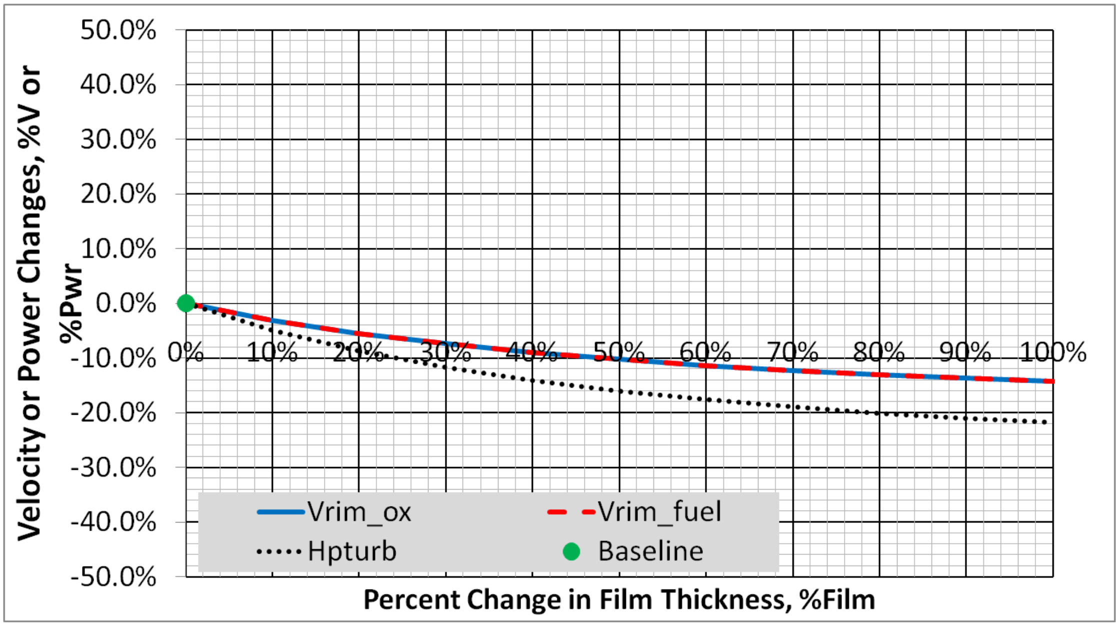


Figure 6.19 Round 1 Film Thickness Influence on Power Metrics

The combustor parameters show the same trends as the hydraulic dams in that the combustor geometry factors both decrease. Changes in the oxidizer to fuel ratio and the fuel split remain constant as indicated by the total mass flow plot. The combustor parameters are illustrated in Figure 6.20.

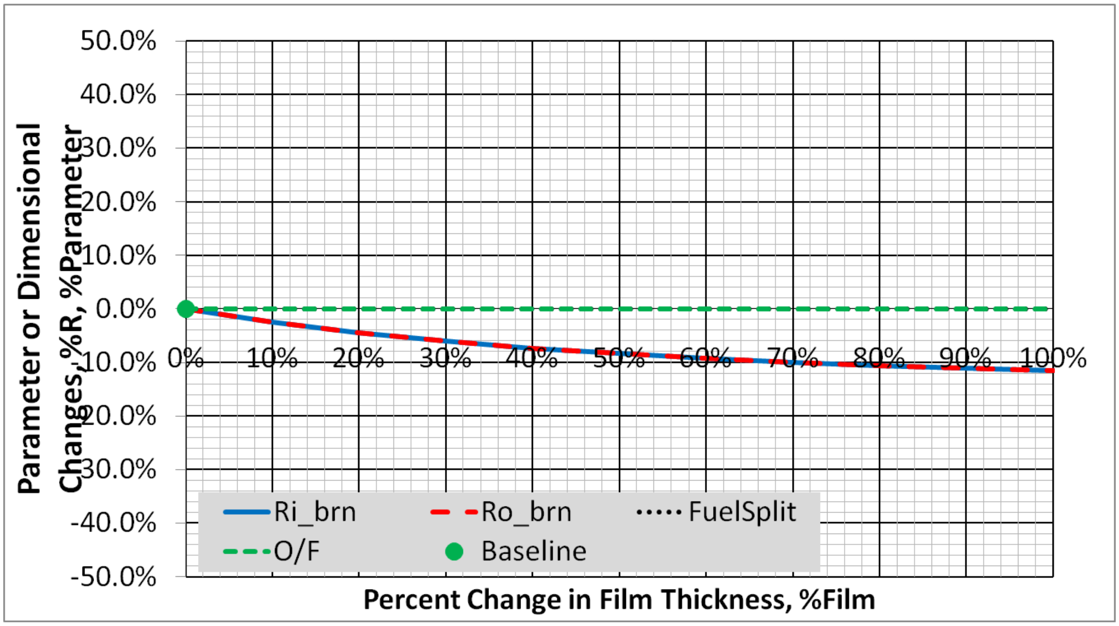


Figure 6.20 Round 1 Film Thickness Influence on Combustor Dimensions

Finally, the turbine metrics confirm the observations made earlier that the turbine work decreases. Figure 6.21 shows that the turbine pressure ratio decreases as the film thickness increases, which causes the turbine exit pressure to increase. Since the turbine exit pressure increases, the overall system weight decreases as the rocket chamber pressure increases.

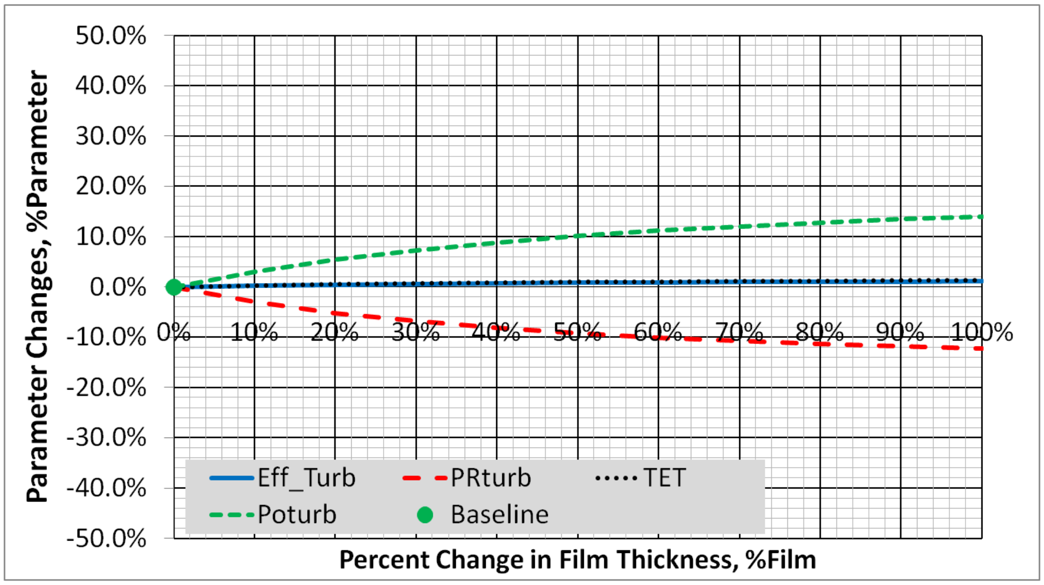


Figure 6.21 Round 1 Film Thickness Influence on Turbine Metrics

The film thickness does have an overall benefit to the packaging of the system and the performance of the pump. However, increasing the film thickness does add risk to the system in that if the film is not allowed to establish a pseudo steady flow by the time the flows enter the hydraulic dams, then the flows within the inner shafts may be turbulent. Turbulent flows may have regions that are not in solid body rotation. Therefore, it was concluded that the film thickness would be set at the baseline value for the next iteration and the film thickness would be reevaluated.

6.1.1.5 Design Point Shaft Speed, N

The design point shaft speed was initially anticipated to have strong influences on most of the geometry metrics. It was also believed that the shaft speed would influence the various performance metrics. However, in Figure 6.22, it appears that the shaft speed influence may be limited to the pump, since the overall thrust and specific impulse are not noticeably affected by changing the shaft speed. Meanwhile, the pump efficiency shows a strong trend with the shaft speed. The pump efficiency appears to increase as the shaft speed decreases.

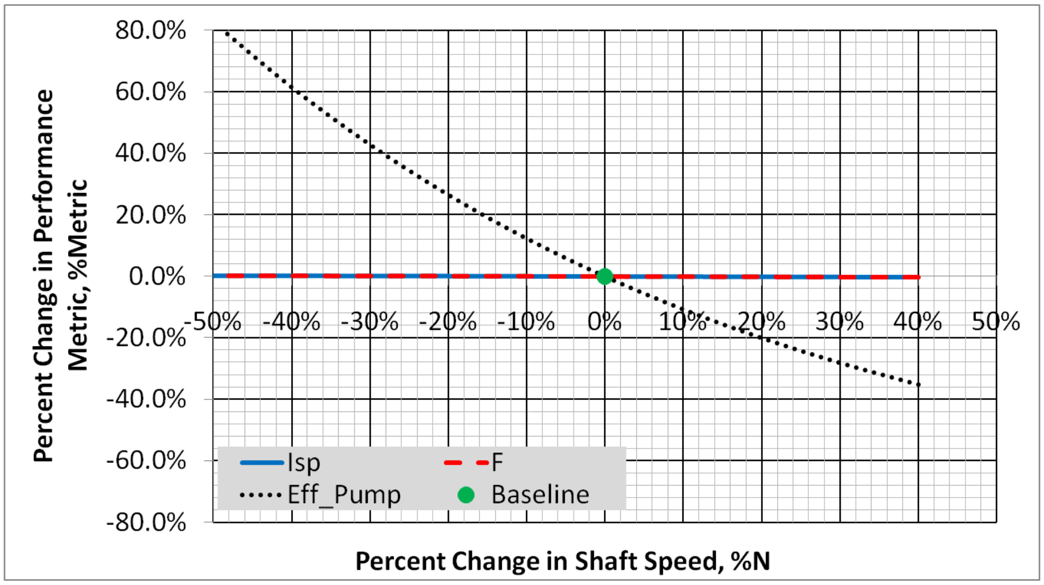


Figure 6.22 Round 1 Design Point Shaft Speed Influence on Performance Metrics

The mass flow rates are unaffected by the changes in design point shaft speed because of the constraint to maintain the fixed oxidizer split and the specified turbine rotor inlet temperature. The static mass flow rate trends are provided in Appendix A.

As expected the geometry of the pump is affected by the shaft speed, as shown in Figure 6.23. The length of the pump is not affected, but the diameter of the pump is affected by the shaft speed. As the shaft speed decreases, the pump diameter increases due to changes in the geometries of the hydraulic dams. Additionally, the weight of the system increases as the shaft speed moves away from the baseline value. The reason for the mass increasing in both directions is that as the shaft speed decreases, the pump increases in weight from the increase in pump diameter. For increasing shaft speed, the weight of the system increases because the turbine exit pressure drops. To the left of the minimum (-6%), the pump weight grows faster than the system weight decreases due to a rise in the turbine exit pressure. On the right hand side of the minimum (-6%), the system weight increases because decreasing turbine exit pressure out paces the improvement in weight from the decreasing diameter of the pump.

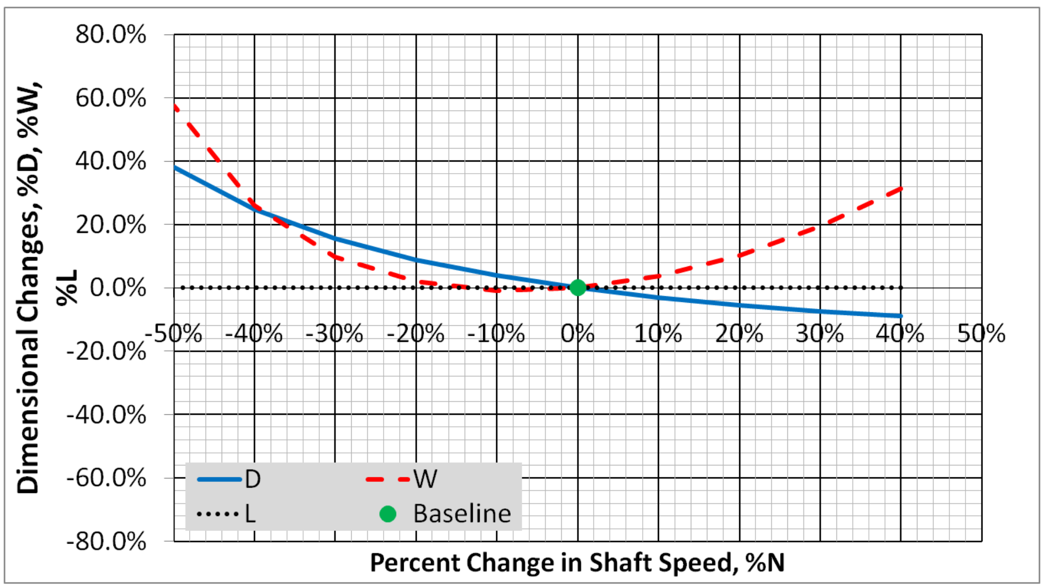


Figure 6.23 Round 1 Design Point Shaft Speed Influence on Overall Dimensions

Changes to the geometries of the hydraulic dams are driven by the fact that the two radii in a hydraulic dam are governed by the square of the shaft speed. As the shaft speed decreases, the distances between the inner and outer radii in the hydraulic dams have to increase, which pushes out the outer radii of the shaft. As the fuel has the lowest density, the fuel inner radius remains fixed while all of the other radii are pushed outward, as shown in Figures 6.24 and 6.25.

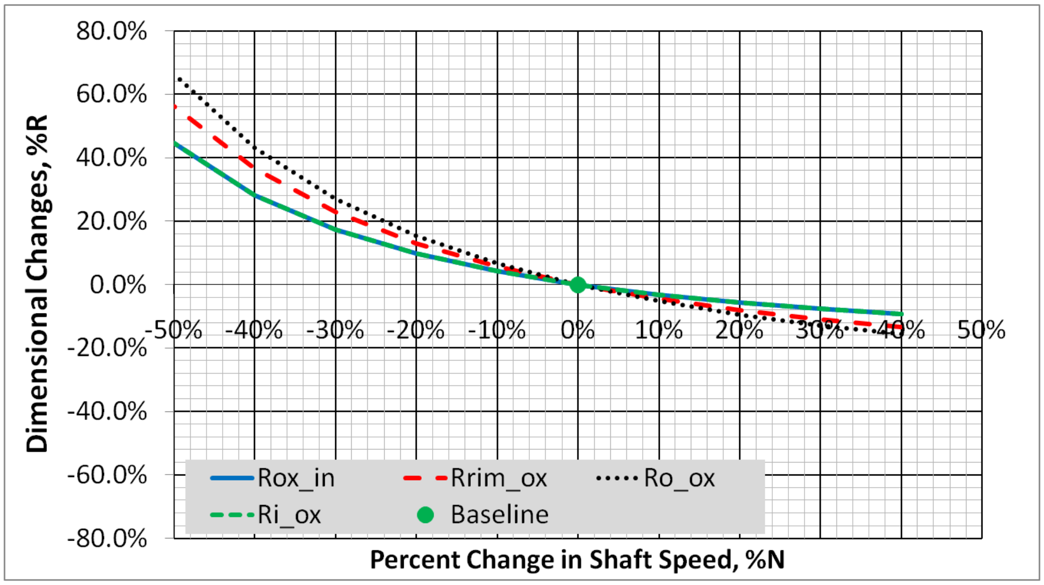


Figure 6.24 Round 1 Design Point Shaft Speed Influence on Oxidizer System Dimensions

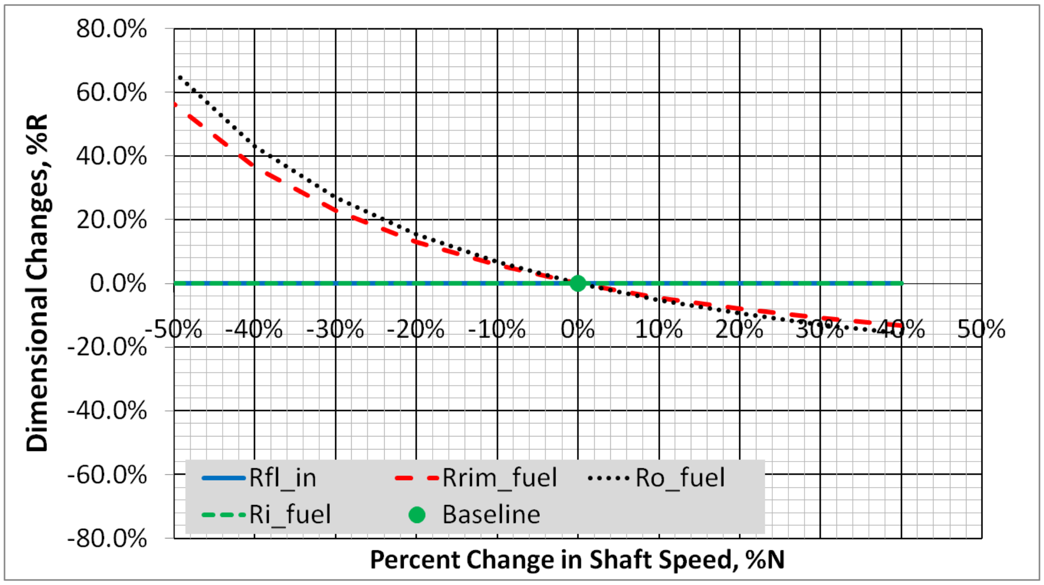


Figure 6.25 Round 1 Design Point Shaft Speed Influence on Fuel System Dimensions

Figure 6.26 shows the trends in the power factors. As the pump shaft speed increases, more power is required to maintain the higher shaft speed. The increases in the rim speeds are a direct result of the increases in the shaft radii caused by the changes in the hydraulic dams and the shaft speed itself. The turbine efficiency and pressure ratio required to meet the shaft speed demands also factor into the overall system metrics.

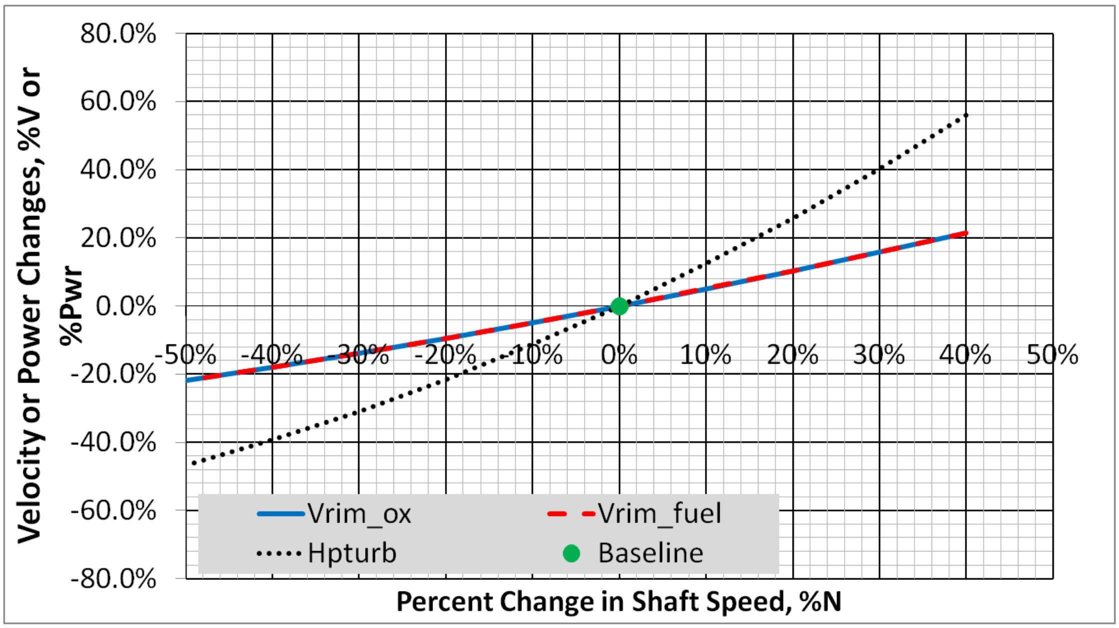


Figure 6.26 Round 1 Design Point Shaft Speed Influence on Power Metrics

Because the combustor resides outside of the hydraulic dams, its geometry is also affected by the changes in the hydraulic dams. As shown in Figure 6.27, the combustor radii increase with decreasing shaft speed.

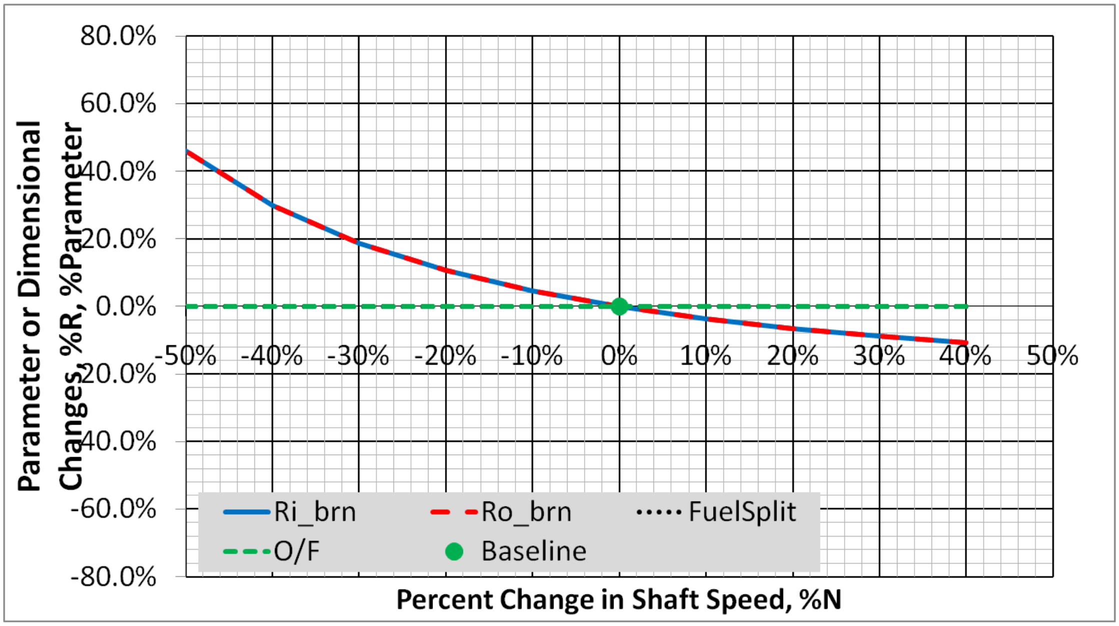


Figure 6.27 Round 1 Design Point Shaft Speed Influence on Combustor Dimensions

The turbine parameters, illustrated in Figure 6.28, show the changes that occur as a result of changing the design point shaft speed. As the shaft speed increases the demand on the turbine to provide more power increases. The demand is somewhat offset by increases in the turbine efficiency, but not enough to prevent the turbine pressure ratio from increasing.

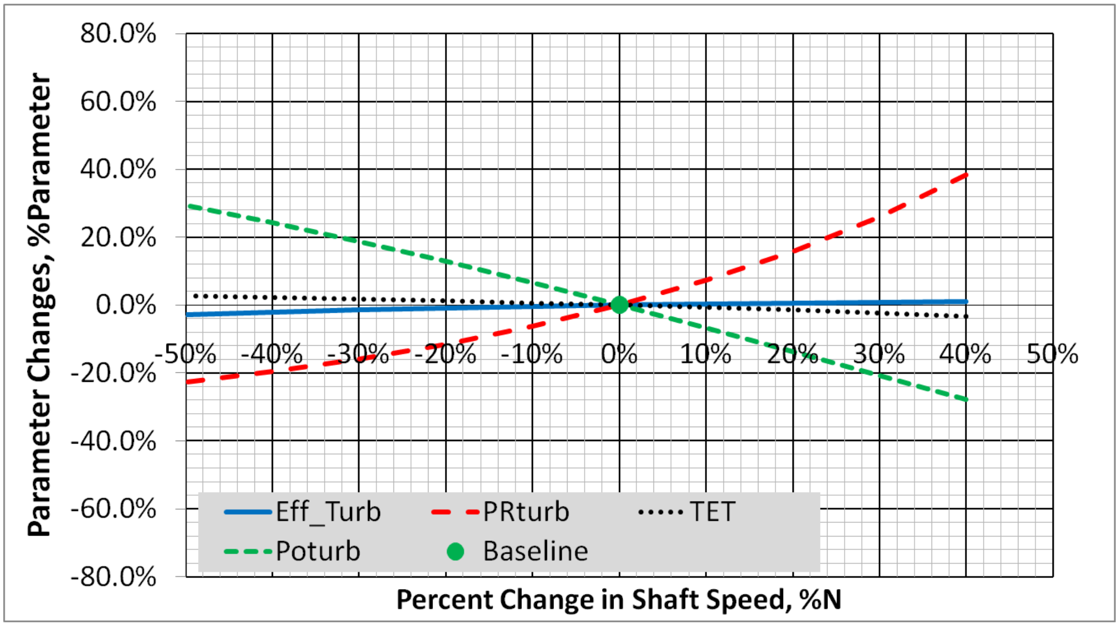


Figure 6.28 Round 1 Design Point Shaft Speed Influence on Turbine Metrics

The design point shaft speed has a strong influence on a number of geometric parameters. However, the overall performance metrics are not strongly affected by the shaft speed. Interestingly, there is a trade off between system weight and pump weight that points to the optimum overall setting for the pump design shaft speed. Therefore, the pump design point speed was set slightly lower than the bottom of the weight bucket at -10% for the next set of iterations.

6.1.1.6 Oxidizer Flow Split, OxSplit

Adjusting the oxidizer flow split changes the amount of flow that goes to the pump combustor instead of directly to the rocket. The parameter is setup such that increasing its value reduces the amount of oxidizer that goes into the pump combustor. The oxidizer split design parameter was initially believed to be an important factor in that it would affect the oxidizer mass flow rate into the pump combustor, which would also affect the fuel flow rate into the combustor in order to maintain the same combustion temperature. As can be seen in Figure 6.29, all three overall performance metrics are affected by changing the oxidizer flow split. At the lower oxidizer flow splits the total mass flow rate and thrust increase, but the specific impulse decreases. A higher fraction of the flow going through the pump combustor reflects taking energy out of the propellants to drive the pump. The pump efficiency trends upward as the flow split decreases but then starts to decrease.

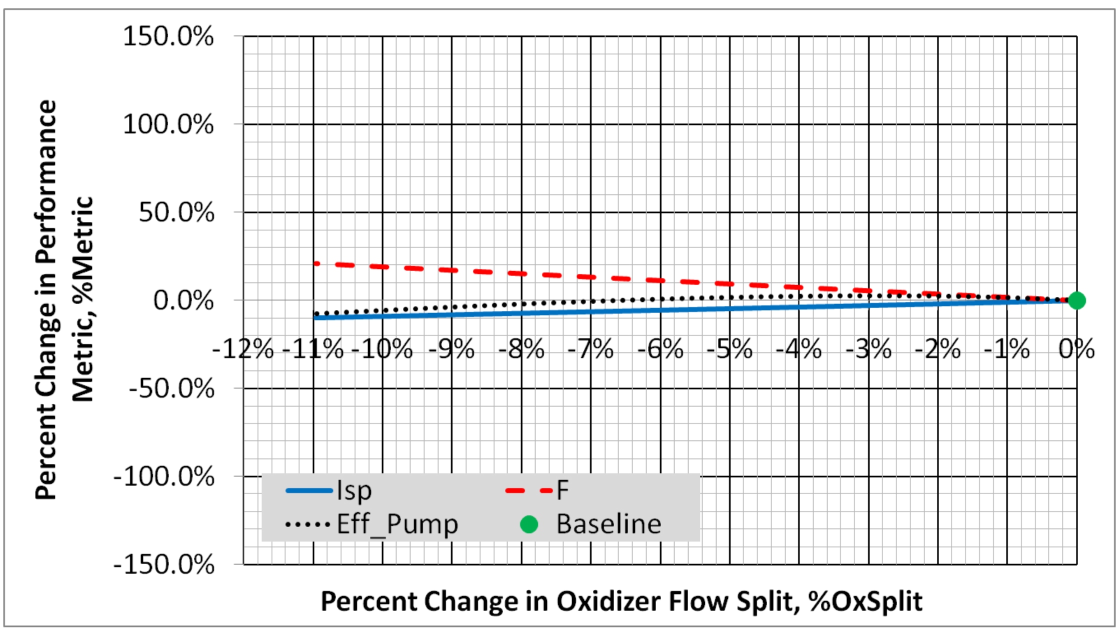


Figure 6.29 Round 1 Oxidizer Flow Split Influence on Performance Metrics

Figure 6.30 shows that the overall flows must increase when the flow split decreases since more oxidizer flow goes to the combustor. The shift in flow occurs in order to maintain the specified turbine rotor inlet temperature.

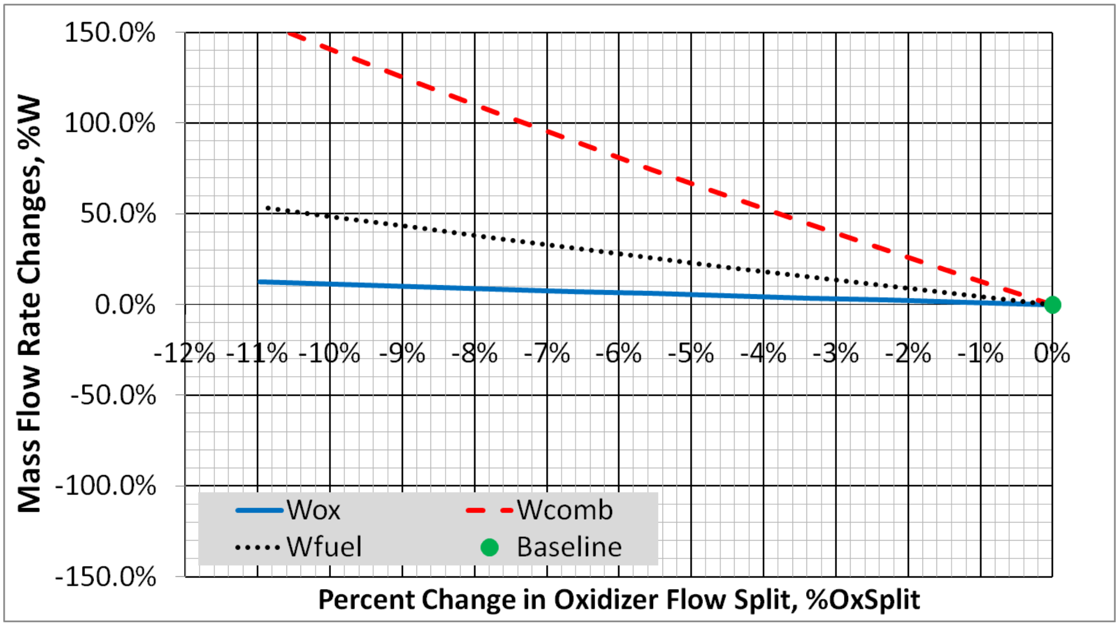


Figure 6.30 Round 1 Oxidizer Flow Split Influence on Mass Flow Rates

Interestingly, the system size did not show a strong dependence on the change in the oxidizer split design parameter, as shown in Figure 6.31. There is a slight increase in the pump diameter, which is associated with maintaining the film thickness for an increased fuel flow rate. The design pushes out the inner shaft inner radius to accommodate the small increase in flow rate. The pump weight trends down as the flow split decreases but then starts to increase, similar to the inverse of the changes in the pump efficiency.

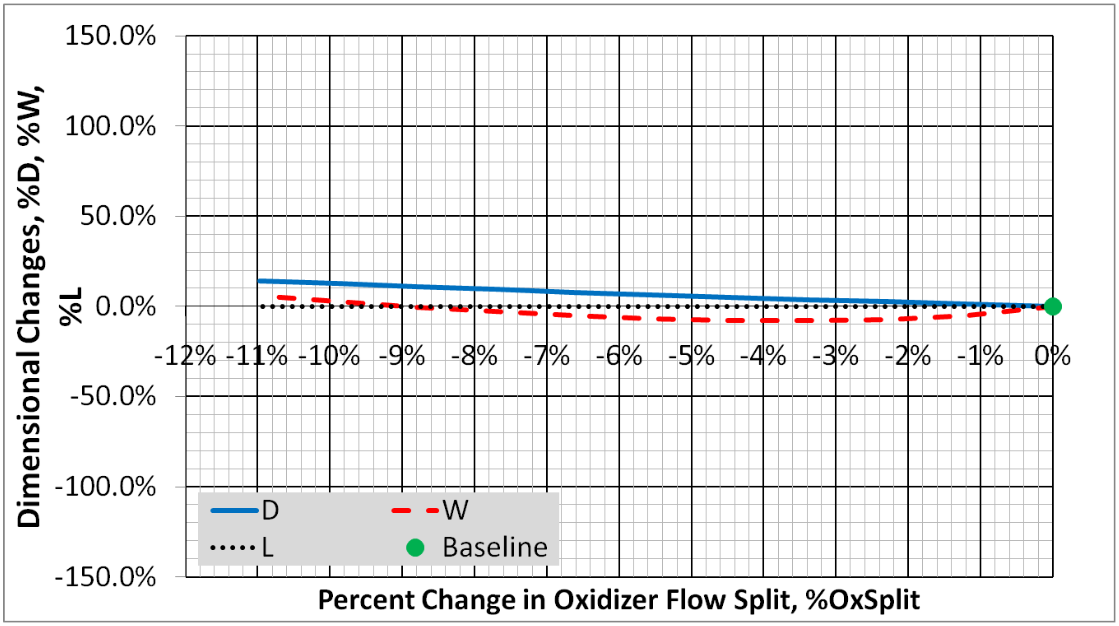


Figure 6.31 Round 1 Oxidizer Flow Split Influence on Overall Dimensions

The geometries of the hydraulic dams, Figures 6.32 and 6.33, do show an increase in the overall diameter of the shaft. However, the rim radii are not increased as much as the internal dimensions, which helps to keep the pump from growing in diameter. The growth in the hydraulic geometry is necessary to accommodate the increase in the mass flow and still maintain the specified film thickness on the inside of the inner shaft.

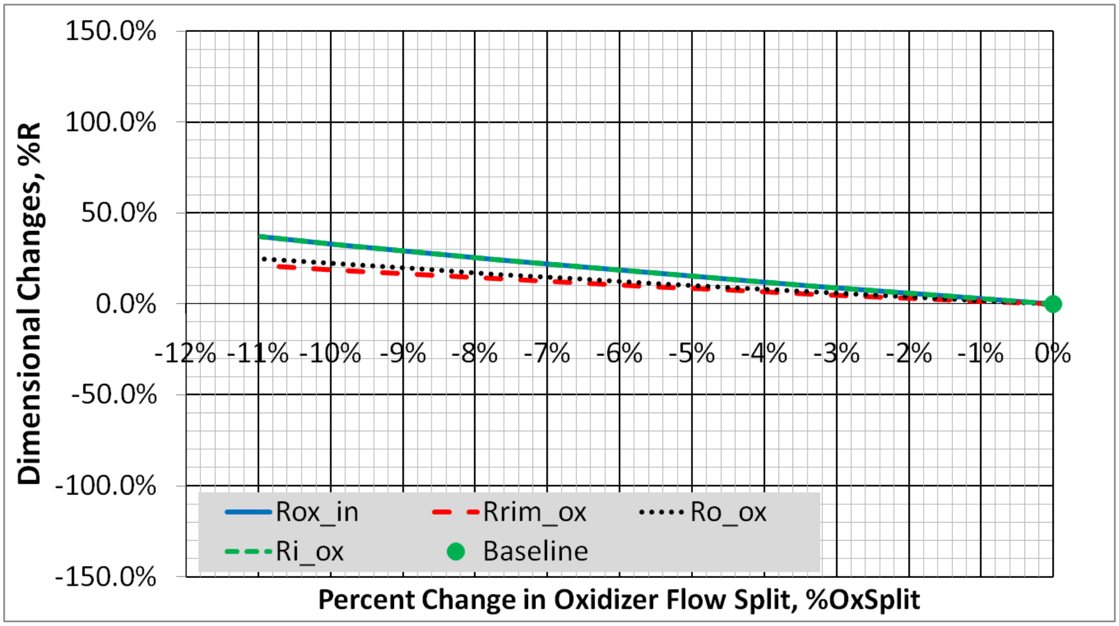


Figure 6.32 Round 1 Oxidizer Flow Split Influence on Oxidizer System Dimensions

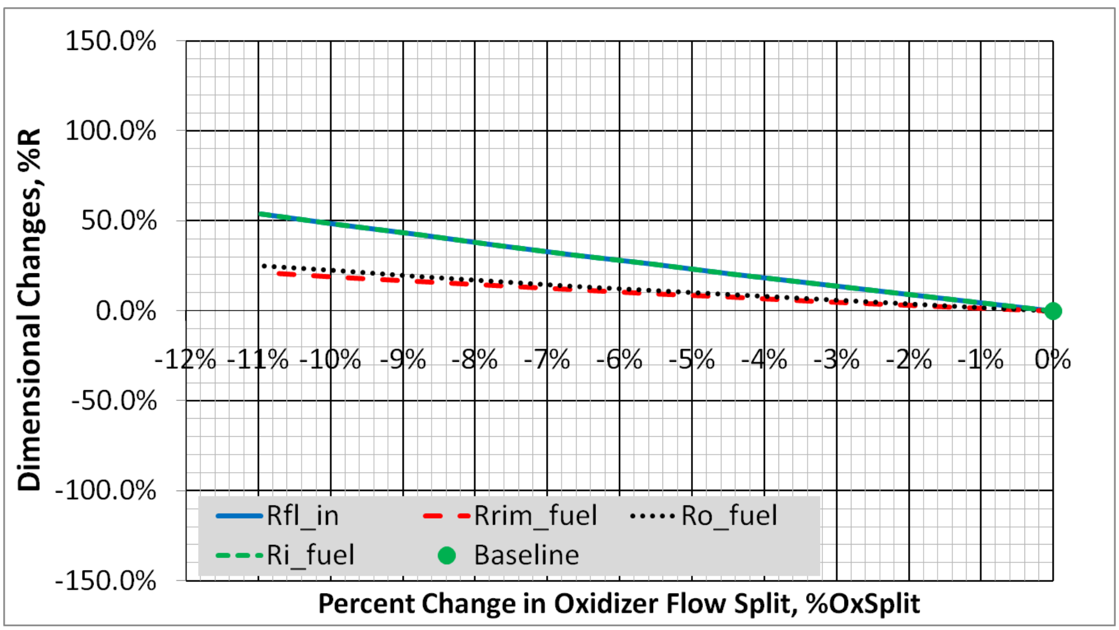


Figure 6.33 Round 1 Oxidizer Flow Split Influence on Fuel System Dimensions

In keeping with the changes in the radii of the hydraulic dams, the rim speeds also increase, which drives a higher power output from the turbine. Figure 6.34 shows how the shaft power factors increase with increases in the amount of flow going through the combustor.

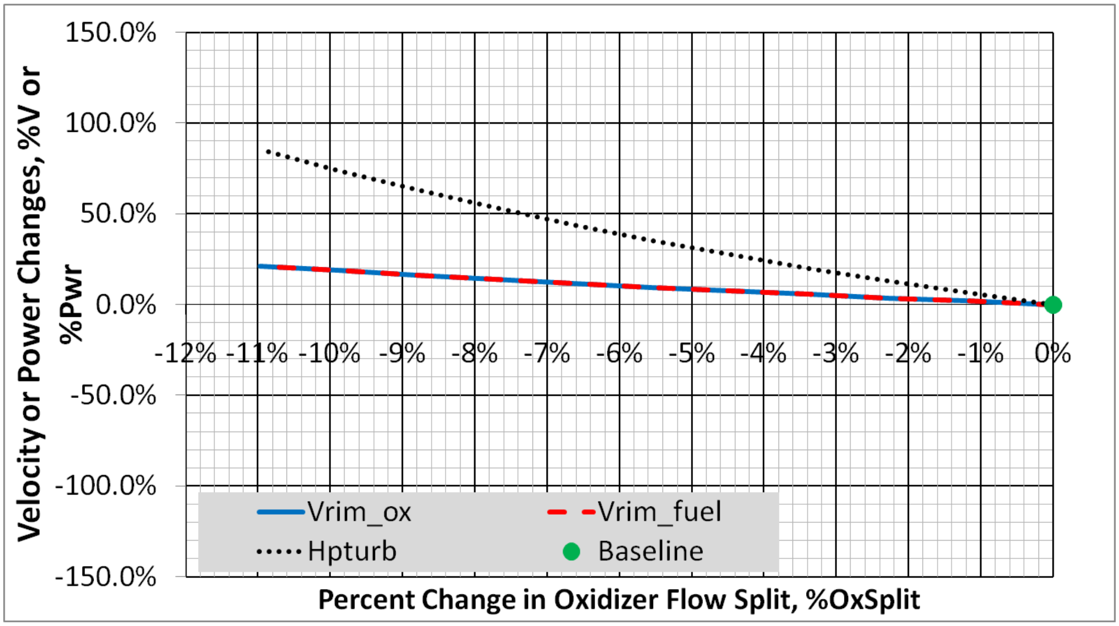


Figure 6.34 Round 1 Oxidizer Flow Split Influence on Power Metrics

Figure 6.35 also offers no surprises. The fuel split increases to maintain turbine rotor inlet temperature, while the combustor geometry increases slightly to accommodate the shaft radius growth. As would be expected, the mixture ratio does not change.

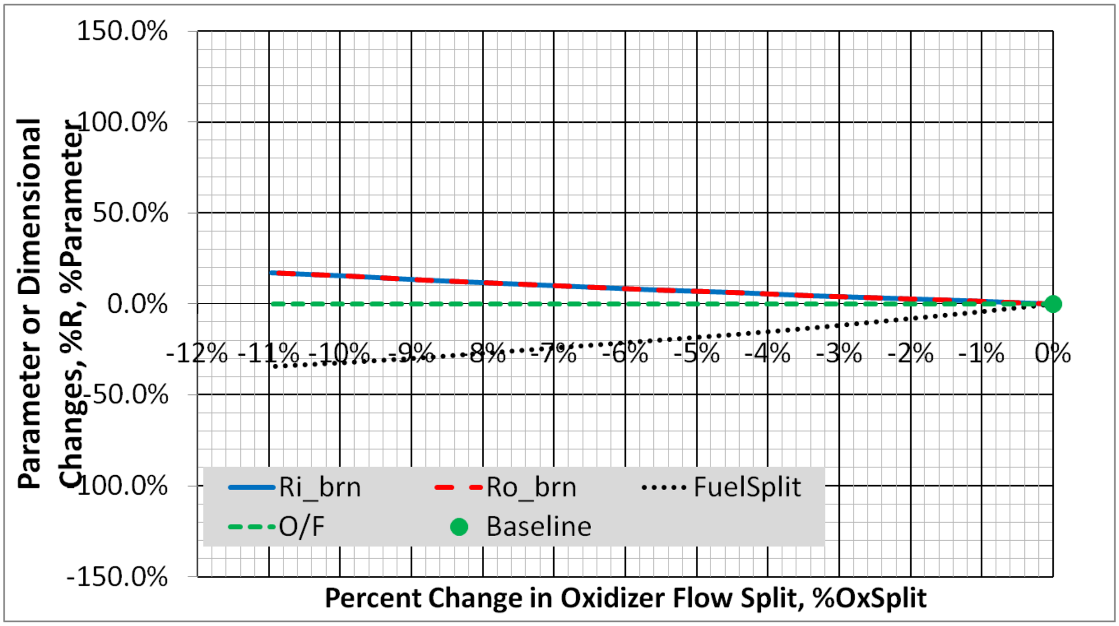


Figure 6.35 Round 1 Oxidizer Flow Split Influence on Combustor Dimensions

Review of the turbine metrics confirms that the changes in the oxidizer split design parameter do not drive major overall system weight changes. In Figure 6.36, the turbine exit pressure actually increases as the split decreases, which should have decreased the weight of the system. However, the weight of the pump also increases because of the increase in the overall diameter of the system. The two trends appear to cancel each other out. It is also interesting to observe that the turbine efficiency increased because of the turbine exhausting at a higher radius as the pump diameter increases.

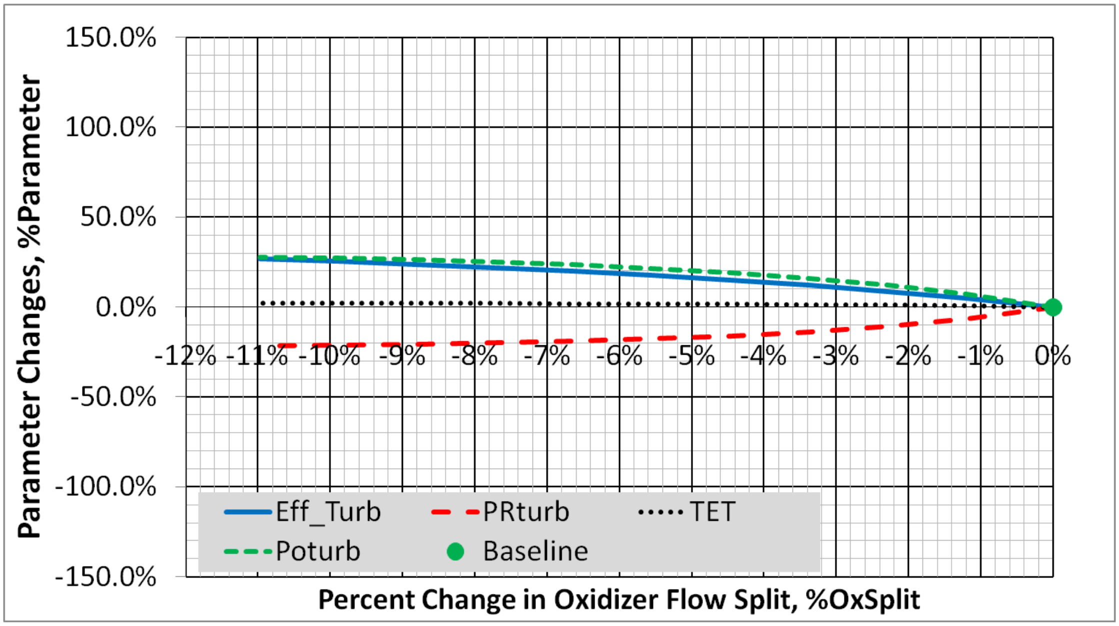


Figure 6.36 Round 1 Oxidizer Flow Split Influence on Turbine Metrics

As expected, the oxidizer flow split did affect the overall design metrics. Although, the impact on the geometry and the weight were not as significant as expected. As a result, the OxSplit will be carried forward to the next iteration with the value set at the minimum weight point (-3.3%).

6.1.1.7 Parasitic Losses, Parasitics

Parasitic losses by their nature consist of losses that have a secondary effect on the overall performance of a system. The parasitic design parameter was believed to be of minor importance in the system. However, the effort needing to minimize the parasitic losses can be estimated by evaluating their impacts on the performance. As can be seen in Figure 6.37, the parasitic losses do not noticeably affect the overall thrust or specific impulse but do affect the pump efficiency. The efficiency is affected because the turbine produces more power to accomplish the same end affect.

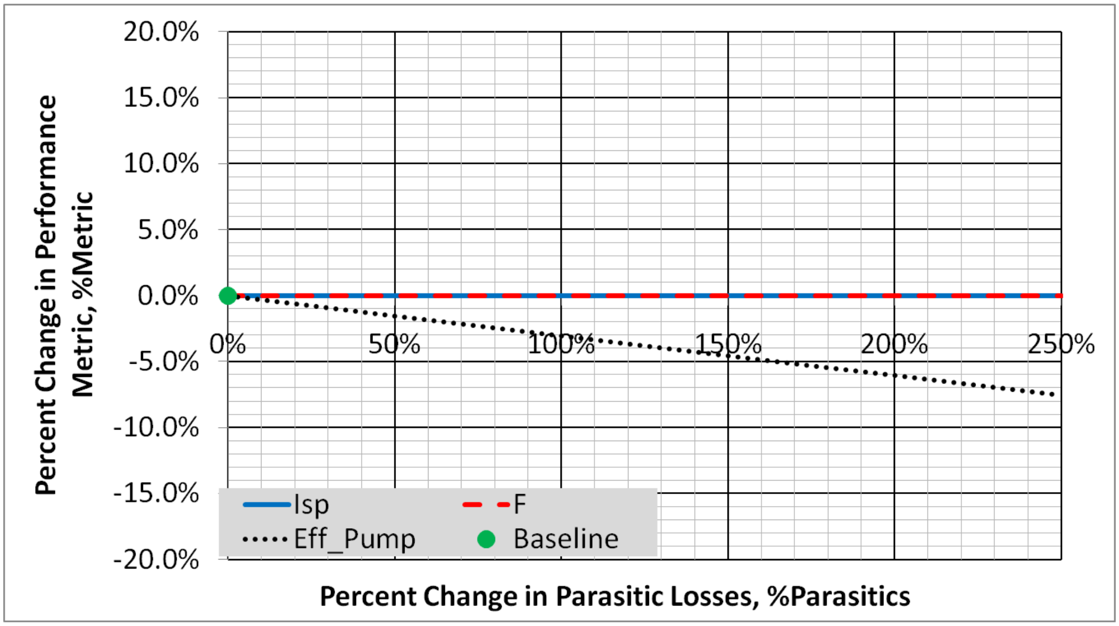


Figure 6.37 Round 1 Parasitic Loss Influence on Performance Metrics

Since the oxidizer flow split and the turbine rotor inlet temperature limits remain the same, the overall mass flow rates are unaffected by changes in the parasitic losses. The mass flow rate insensitivity can be found in Appendix A.

As discussed earlier, the weight of the system relates directly to the amount of power the turbine has to do per unit mass flow rate. Since the parasitic losses consume power from the turbine, the turbine pressure ratio increases resulting in lower turbine exit pressures, which increases the size of the system. The change in the system weight is shown in Figure 6.38, which also shows that the diameter and length of the pump are not affected by the parasitic losses.

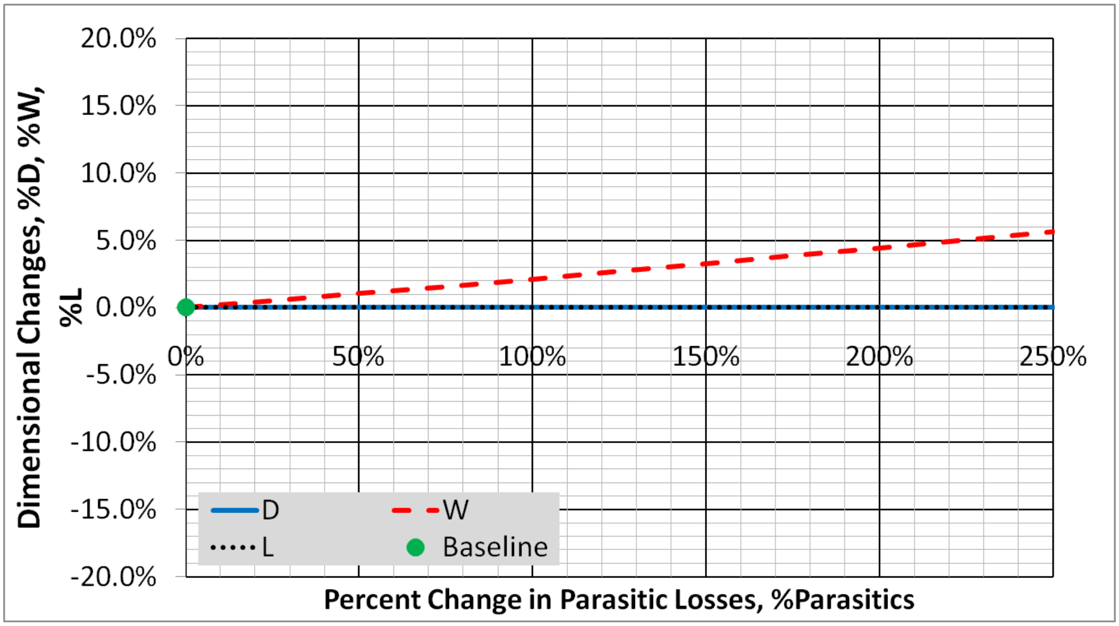


Figure 6.38 Round 1 Parasitic Loss Influence on Overall Dimensions

Both hydraulic dam geometries remain unaffected by the changes in the parasitic losses. The result is understood as the parasitic losses only extract additional power from the turbine. The geometric responses are shown in Appendix A.

Figure 6.39 confirms that the turbine work changes in response to an increase in the parasitic losses without affecting the geometry of the rotary injectors. No change in the inner shaft rim speed is a direct reflection of the fact that the shaft geometry did not change since the shaft speed remains constant.

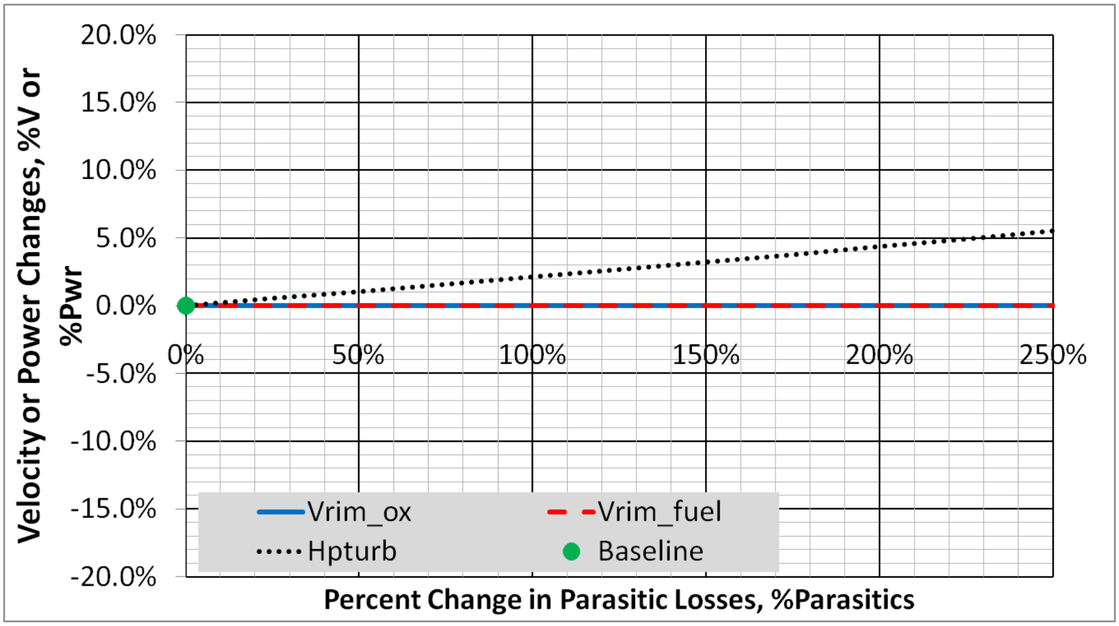


Figure 6.39 Round 1 Parasitic Loss Influence on Power Metrics

As with the geometries of the hydraulic dams and the rotary injector geometries, the combustor geometry does not change. Nor did the fuel split or oxidizer to fuel ratio change, since those two parameters are controlled by the oxidizer split and the turbine rotor inlet temperature parameters. The combustor dimension responses are provided in Appendix A.

The turbine parameters provide the most direct observation as to what is occurring in the pump. Figure 6.40 shows that the turbine pressure ratio increases with increasing parasitic losses in order to provide the additional power required to maintain the specified shaft speed. As the pressure ratio increases, the turbine exit pressure decreases, driving up the weight of the system. Interestingly, the turbine efficiency also decreases making the turbine pressure ratio increase even further.

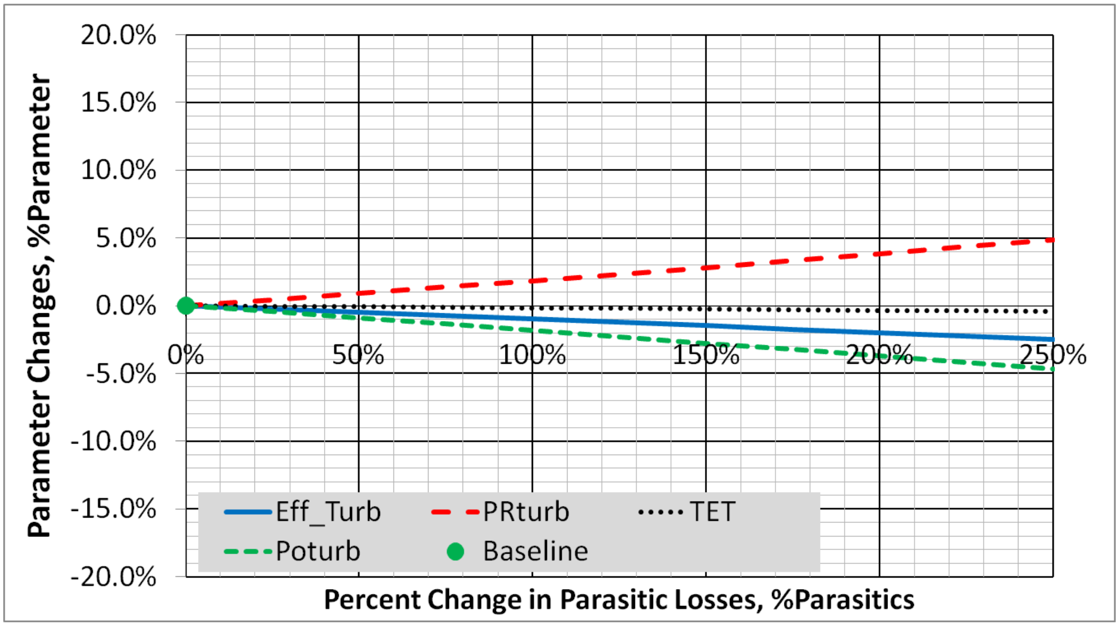


Figure 6.40 Round 1 Parasitic Loss Influence on Turbine Metrics

Based on the observed metric responses, the parasitic losses are important to minimize. Thus, their value is set to the minimum that is reasonable to achieve without extraordinary efforts. It should be noted that if the turbine exhaust is expanded separately from the main rocket exhaust, then the system sensitivity to the parasitic losses can be reduced.

6.1.1.8 Scroll Pressure Recovery, Recovery

Intrinsic to the operation of the Combustion Driven Drag Pump is the fact that the liquid discharges are at a high tangential velocity. The baseline configuration used the assumption that the velocity could not be recovered as pressure. However, it was believed that if the dynamic head or any portion of it could be recovered, then the pump efficiency could be improved, which would have an effect on the overall system. As can be seen in Figure 6.41, recovery does have a noticeable effect on the pump efficiency and a modest effect on the thrust and specific impulse. As the recovery increases, the pump efficiency and specific impulse both increase, while the thrust drops slightly.

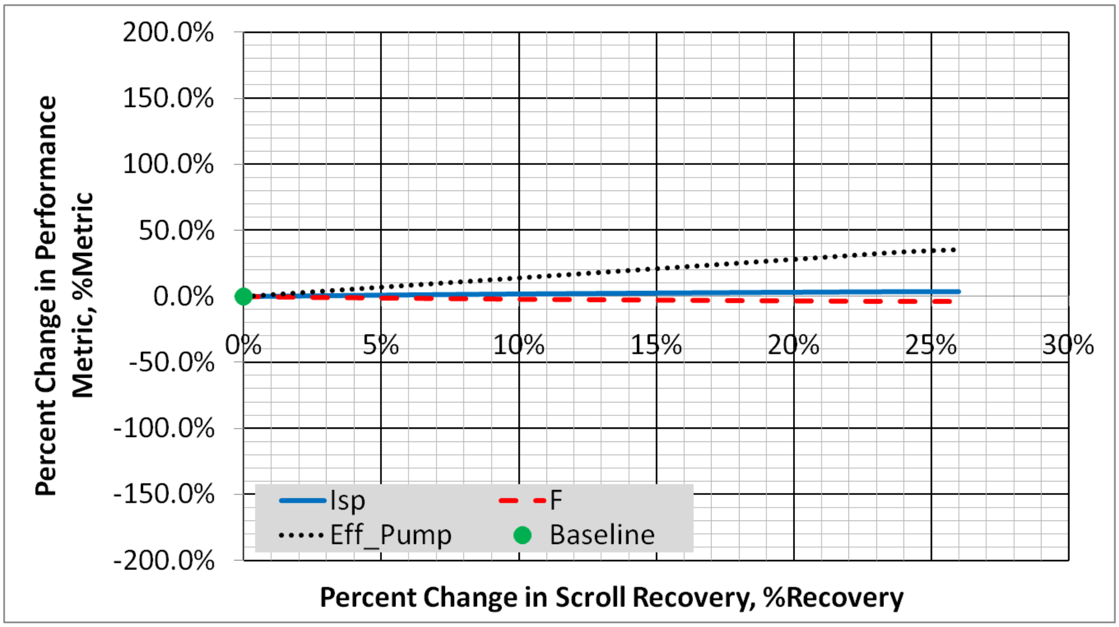


Figure 6.41 Round 1 Scroll Pressure Recovery Influence on Performance Metrics

Up until this point, all the design parameters have had the same overall effect on the mass flow rates. Essentially, only the turbine rotor inlet temperature or the oxidizer flow split should have an impact. However, it has been observed that when the recovery of the system increases, the amount of pressure rise and propellant heating decreases. At the lower inlet temperatures and pressures, the mixture ratio required to hold a constant turbine rotor inlet temperature changes, so the fuel flow rate to the combustor decreases, which reduces the total combustor flow rate and the total fuel flow rate, as shown in Figure 6.42.

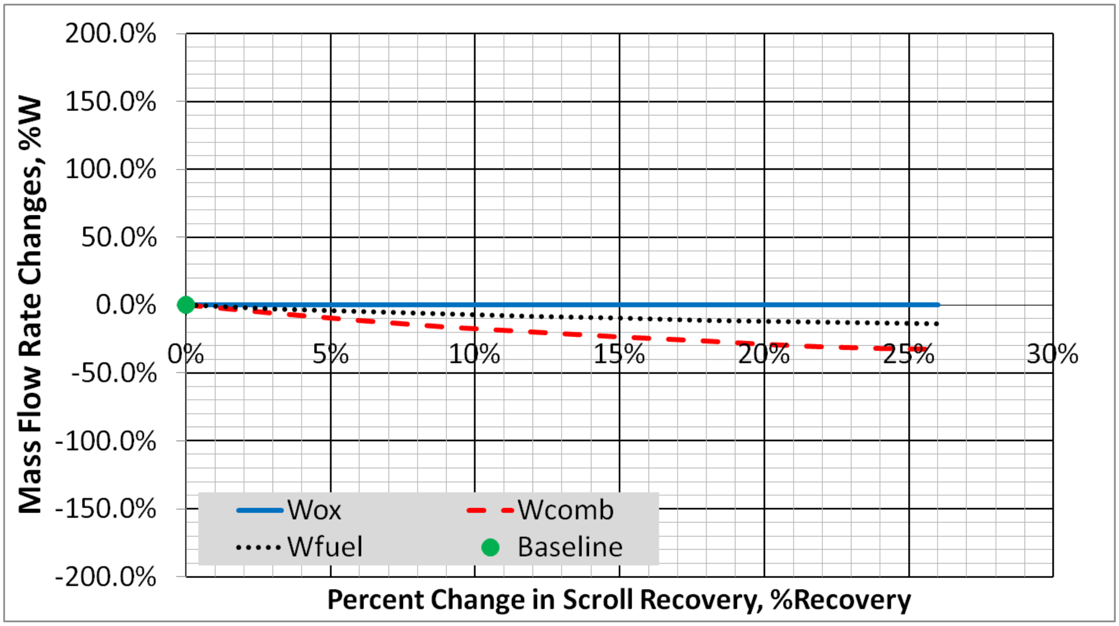


Figure 6.42 Round 1 Scroll Pressure Recovery Influence on Mass Flow Rates

The change in the overall weight of the system is notable. As the recovery increases, the pressure in the pump combustor drops and decreases the turbine exit pressure, which pushes down the rocket chamber pressure. Thus, the system increases in weight, as shown in Figure 6.43. The weight gain would be even greater except for the fact that improving the scroll recovery allows the pump to decrease in diameter and hence reduce the pump portion of the weight.

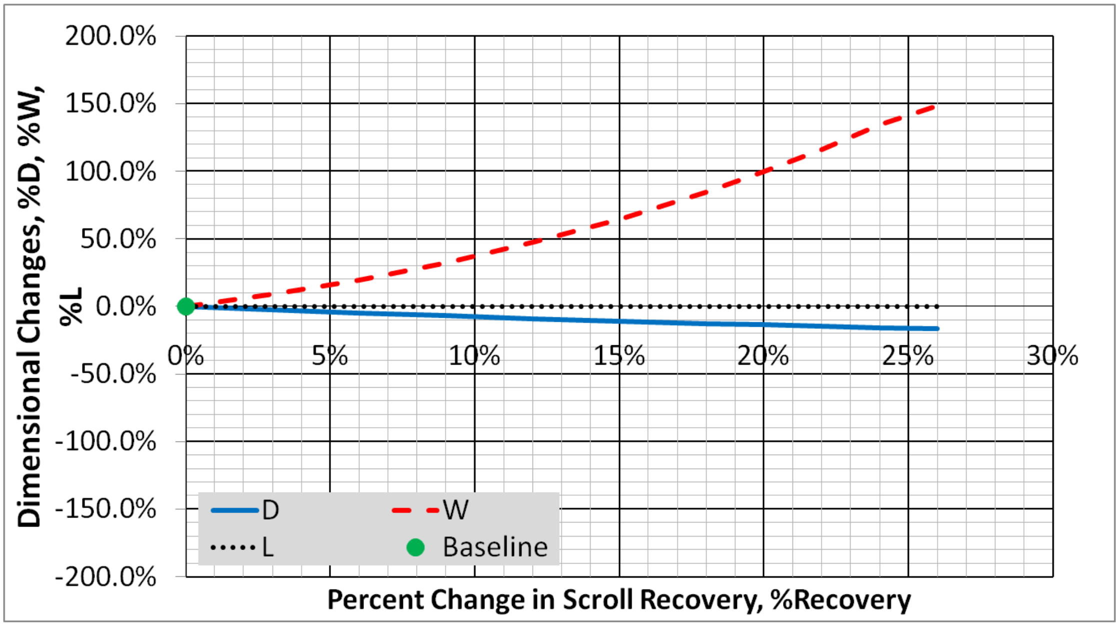


Figure 6.43 Round 1 Scroll Pressure Recovery Influence on Overall Dimensions

Since the total pressure rise is accomplished in two stages with scroll recovery, the amount of pressure rise from the hydraulic dams decreases. With the decrease in demand, the geometry of the hydraulic dams decreases, as shown in Figures 6.44 and 6.45. The effect is amplified slightly because of the decrease in fuel flow rate discussed earlier.

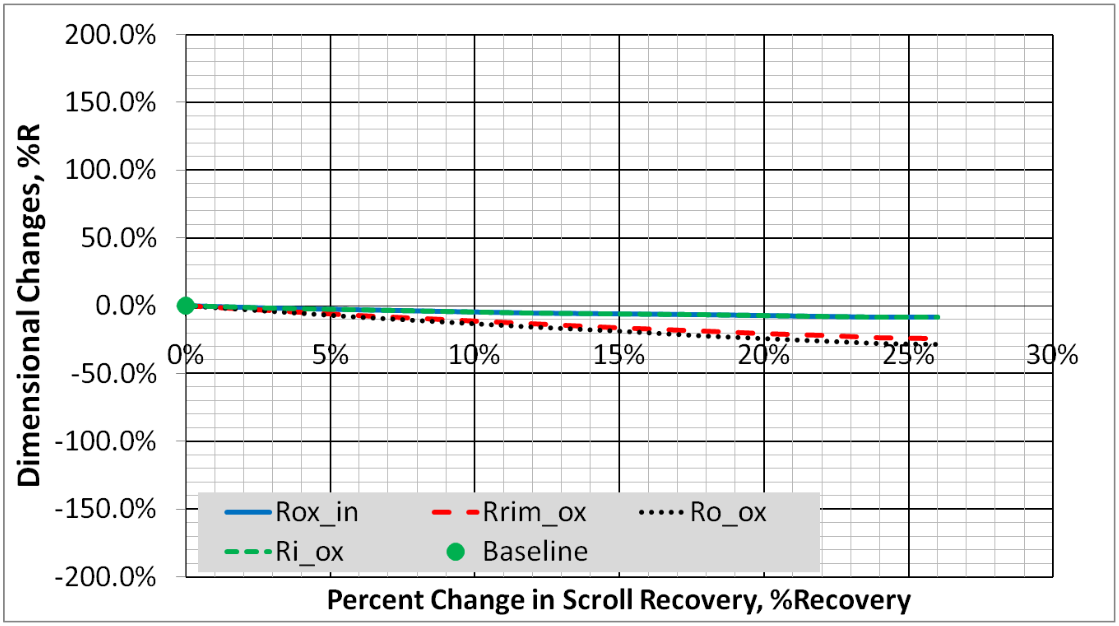


Figure 6.44 Round 1 Scroll Pressure Recovery Influence on Oxidizer System Dimensions

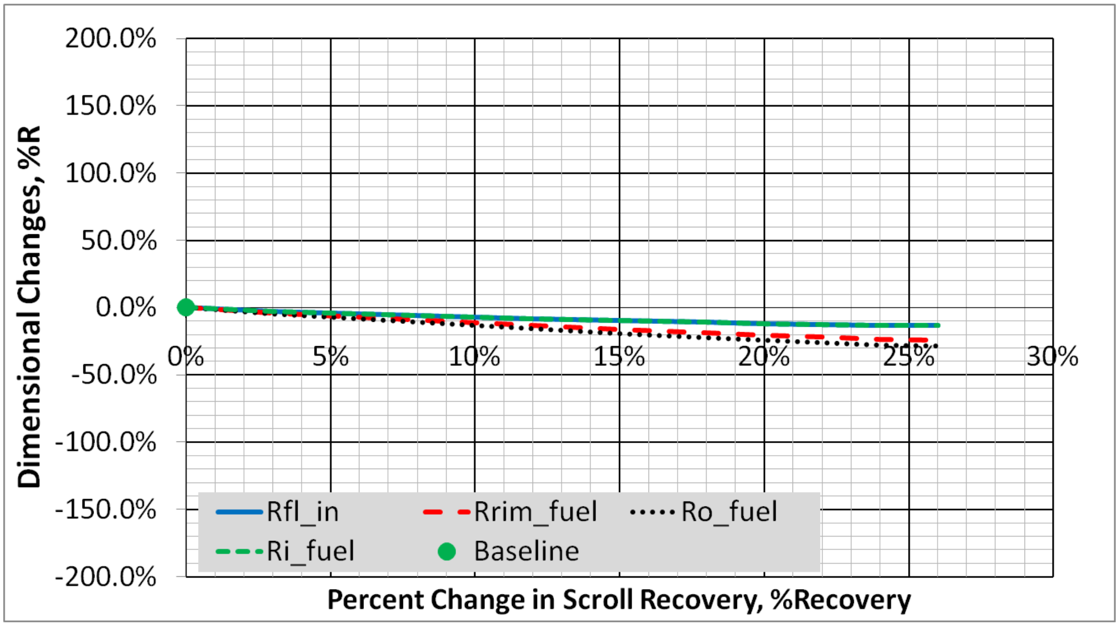


Figure 6.45 Round 1 Scroll Pressure Recovery Influence on Fuel System Dimensions

With the decrease in the geometry, the rotary injectors have a smaller radius, which decreases the power required to maintain the constant shaft speed. Therefore, the power provided by the turbine drops, as shown in Figure 6.46.

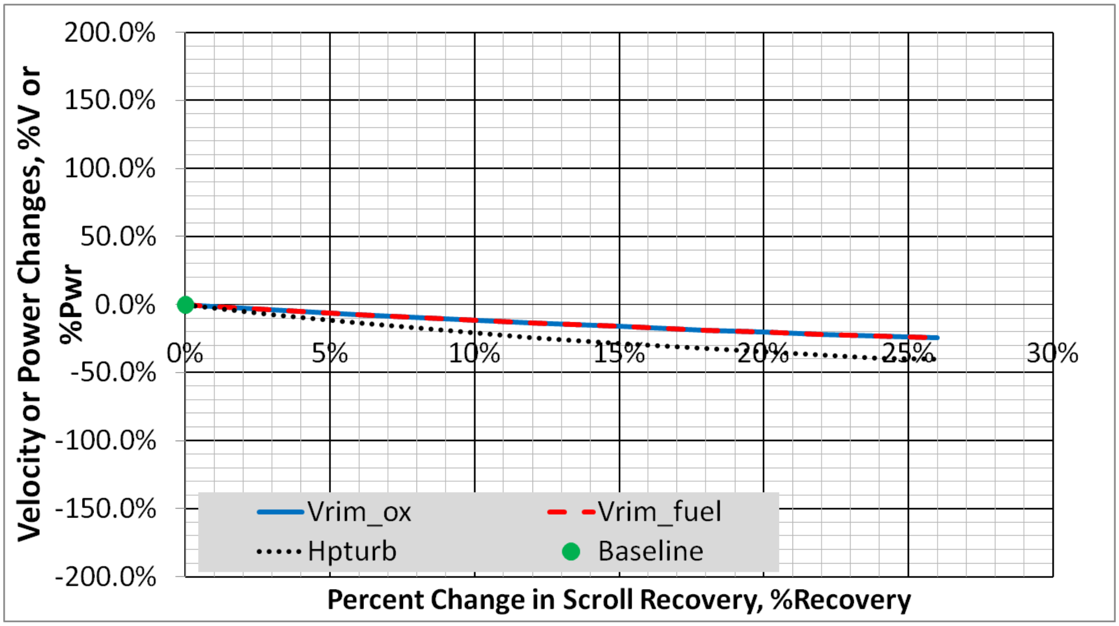


Figure 6.46 Round 1 Scroll Pressure Recovery Influence on Power Metrics

The changes in the combustor metrics are consistent with the changes in the fuel flow rate discussed earlier. The oxidizer to fuel ratio increases and the portion of the fuel that goes directly to the rocket also increases. The geometry decreases due to the decrease in shaft size realized in the hydraulic dams. These trends are shown in Figure 6.47.

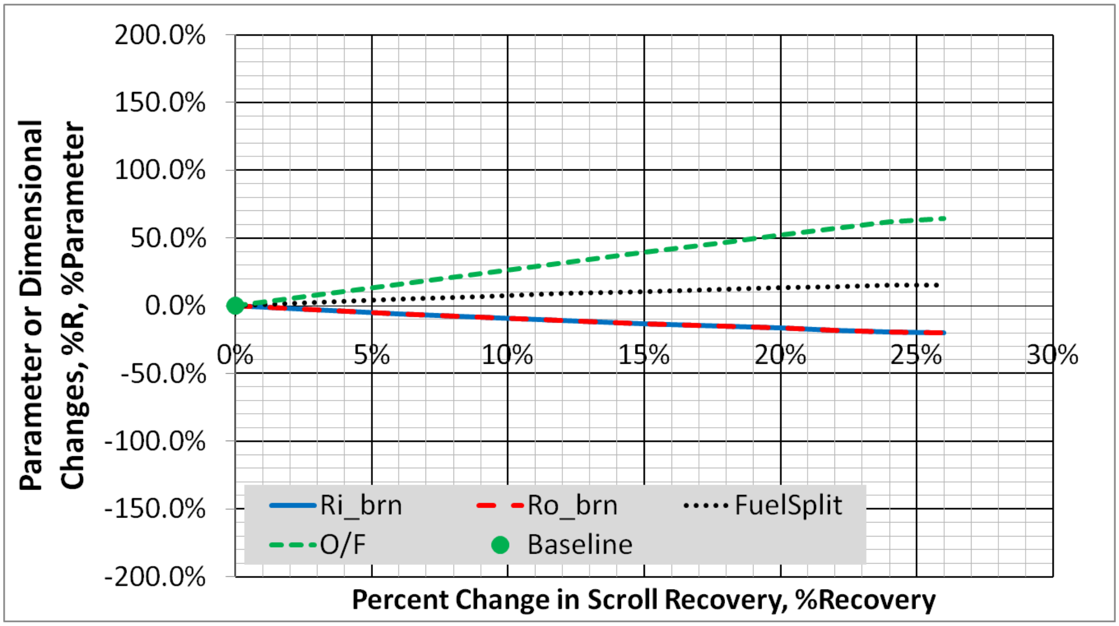


Figure 6.47 Round 1 Scroll Pressure Recovery Influence on Combustor Dimensions

The biggest effect is that the turbine exit pressure decreases by a large amount, even though the pressure ratio remains unaffected, because the pressure in the combustor is reduced. Figure 6.48 also indicates that the efficiency of the turbine decreases slightly due to the decrease in the turbine discharge radius.

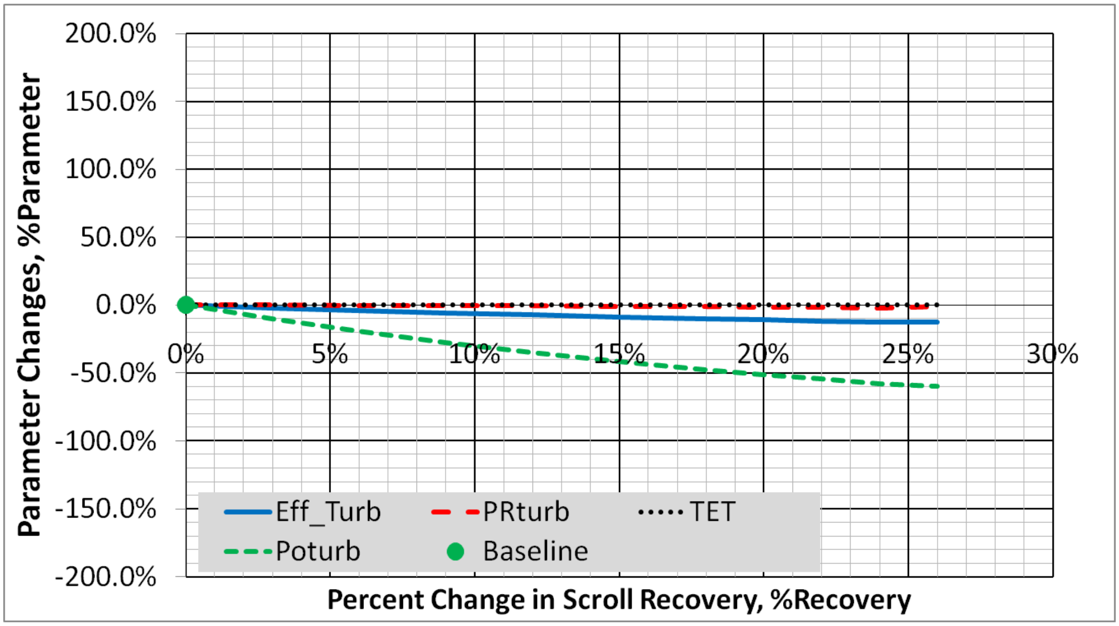


Figure 6.48 Round 1 Scroll Pressure Recovery Influence on Turbine Metrics

The scroll recovery appears to have a significant effect on several of the metrics. However, because the pressure rise occurs partially in the static exhaust system, the pressure coming out of the turbine drops proportionally, which drives the weight of the system. If the turbine exhaust was separate from the main rocket, then it is possible that the effect can be beneficial. Although, the turbine exhaust would likely provide much lower performance than a stage combustion system since it would be at a lower pressure. The scroll recovery is set to the baseline value for future iteration steps, but kept as an alternative in the event that additional performance capability is needed.

6.1.1.9 Hydraulic Dam Outer Margin, ShaftDuctDelta

The hydraulic dam outer margin was not initially believed to be a strong player in the overall optimization of the system because it only influences a small geometric feature. On the main performance metrics, changes in the hydraulic dam outer margin do not have any influence. However, it is clear that it has a significant impact on the overall pump efficiency, as shown in Figure 6.49.

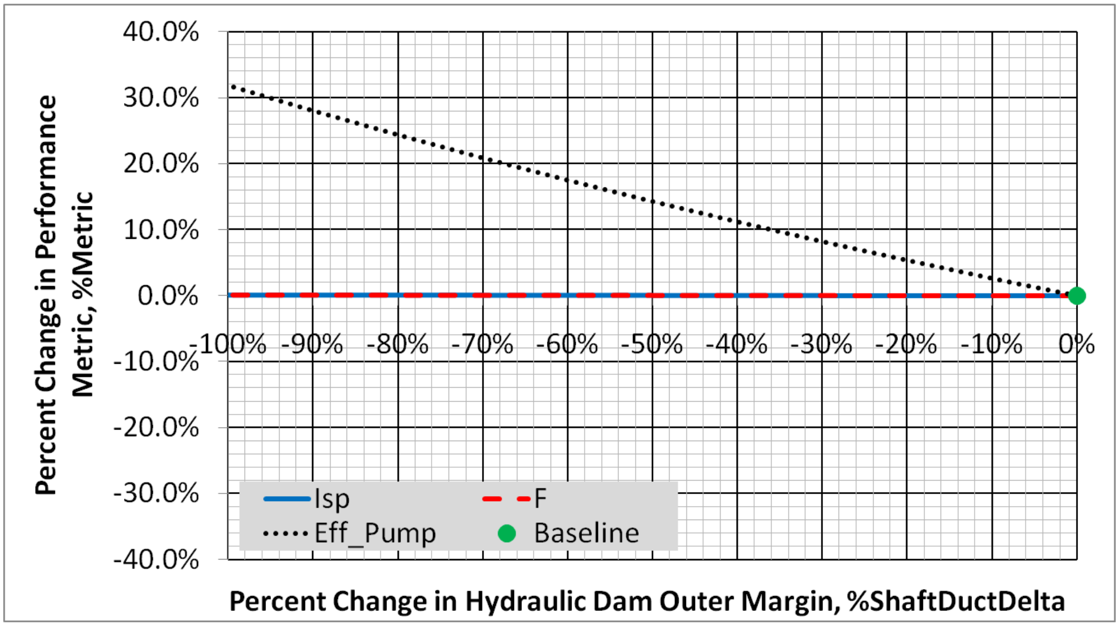


Figure 6.49 Round 1 Hydraulic Dam Outer Margin Influence on Performance Metrics

The mass flow rates are not affected by the changes in the hydraulic margin, as is expected with a constant turbine rotor inlet temperature and a fixed oxidizer flow split. The mass flow rates are insensitive to the hydraulic dam outer margin design parameter. The mass flow rate responses are provided in Appendix A.

The primary geometric parameters shown in Figure 6.50 illustrate the trend that the size of the pump decreases as the margin decreases. The diameter of the pump is directly proportional to the margin, which reduces the weight of the system accordingly.

Additionally, since the margin reduces the power extracted by the turbine, the system weight benefits from the increase in the turbine exit pressure.

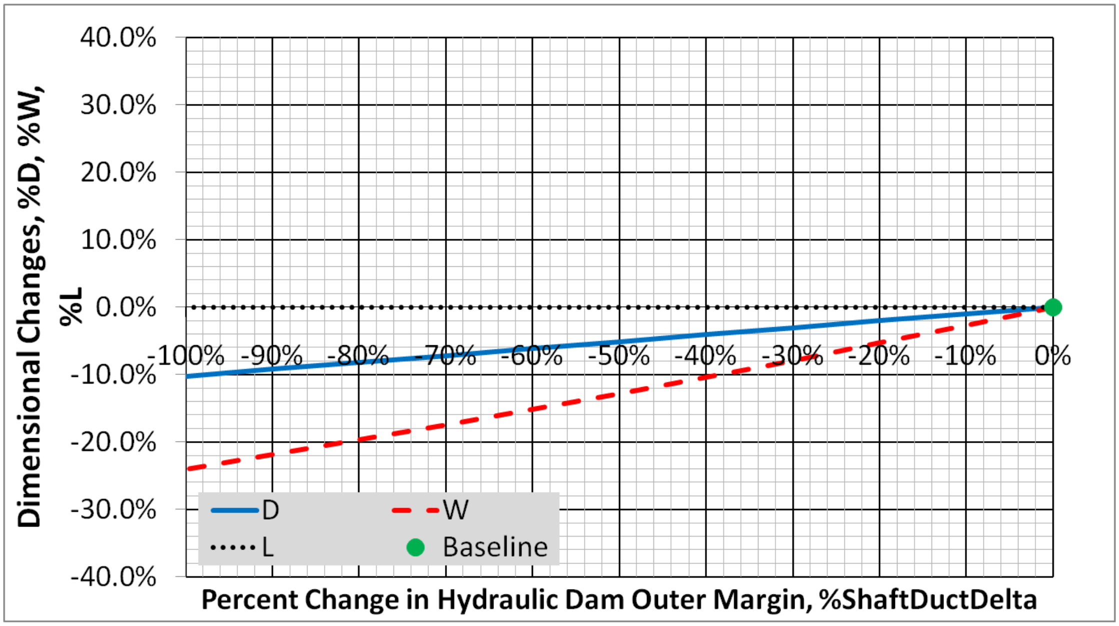


Figure 6.50 Round 1 Hydraulic Dam Outer Margin Influence on Overall Dimensions

Because the hydraulic dam margin is the outer margin, all of the inner dimensions of the hydraulic dams are unaffected by changing the outer margin and can be found in Appendix A. The hydraulic dam outer margin first comes into play with respect to the rotary injectors and the amount of work they consume. Figure 6.51 shows how the power provided by the turbine decreases as the margin decreases.

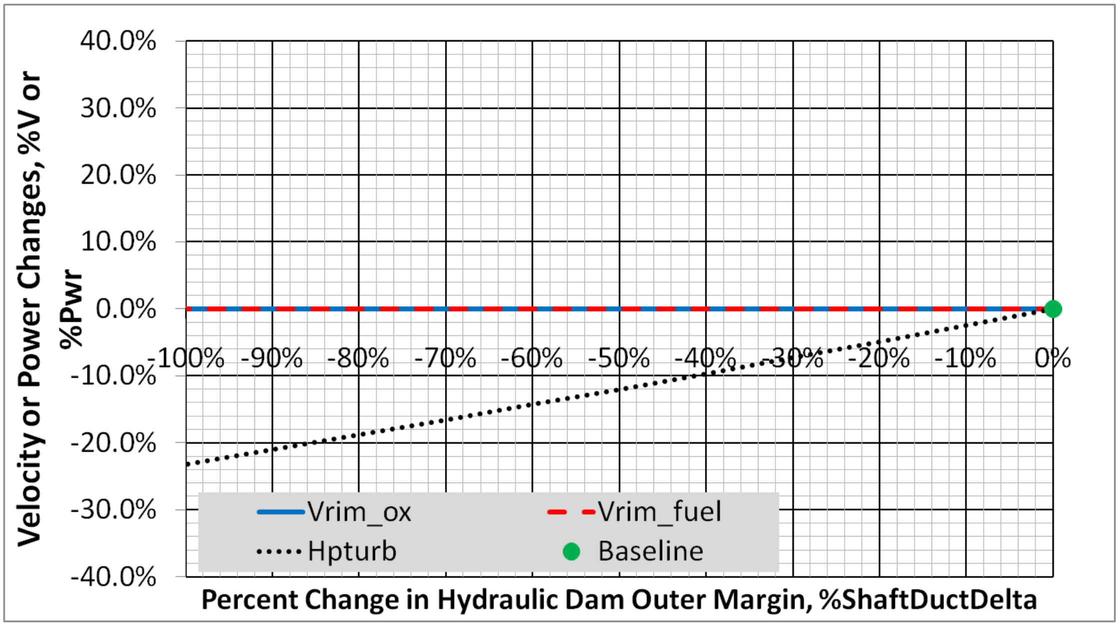


Figure 6.51 Round 1 Hydraulic Dam Outer Margin Influence on Power Metrics

One of the design parameters affecting the combustor geometry is the hydraulic dam outer margin. As the margin decreases, the combustor moves slightly closer to the centerline of the pump. The relationship is shown in Figure 6.52. However, the fuel split and oxidizer to fuel ratio are unaffected.

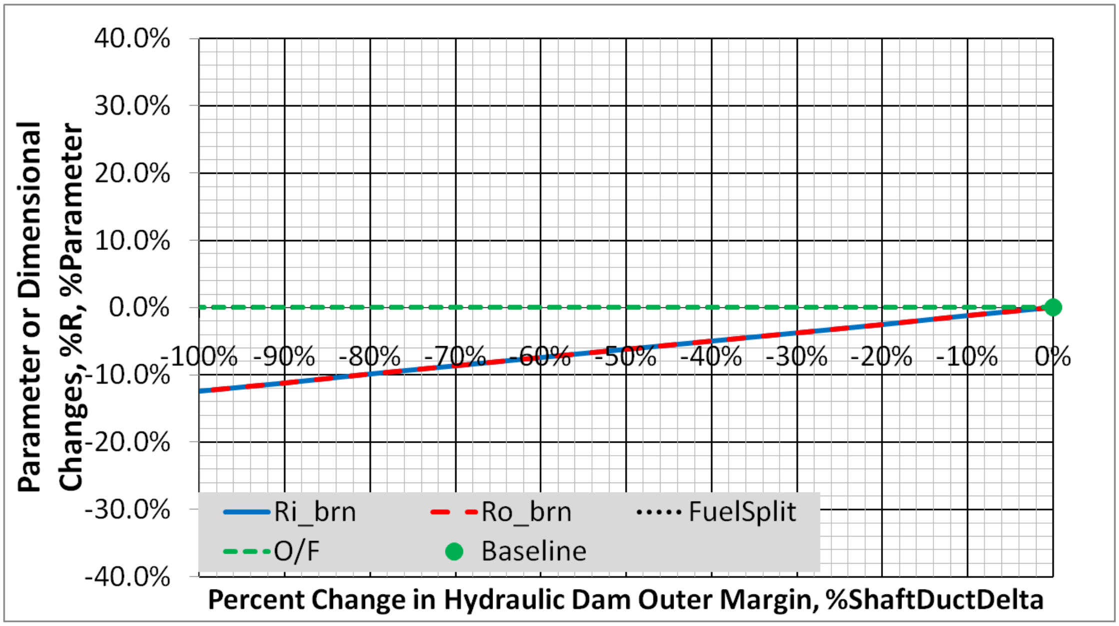


Figure 6.52 Round 1 Hydraulic Dam Outer Margin Influence on Combustor Dimensions

Inspection of the turbine metrics indicates that the shaft power requirement drops, resulting in a decrease in the overall pressure ratio across the turbine, as indicated in Figure 6.53. The corresponding increase in the turbine exit pressure is the cause for the decrease in the system weight. The turbine efficiency increases slightly because of the decrease in the hydraulic dam outer margin. The efficiency increase is due to the drop in turbine pressure ratio. However, the efficiency improvement is tempered by the decrease in the turbine discharge radius, which decreases turbine efficiency.

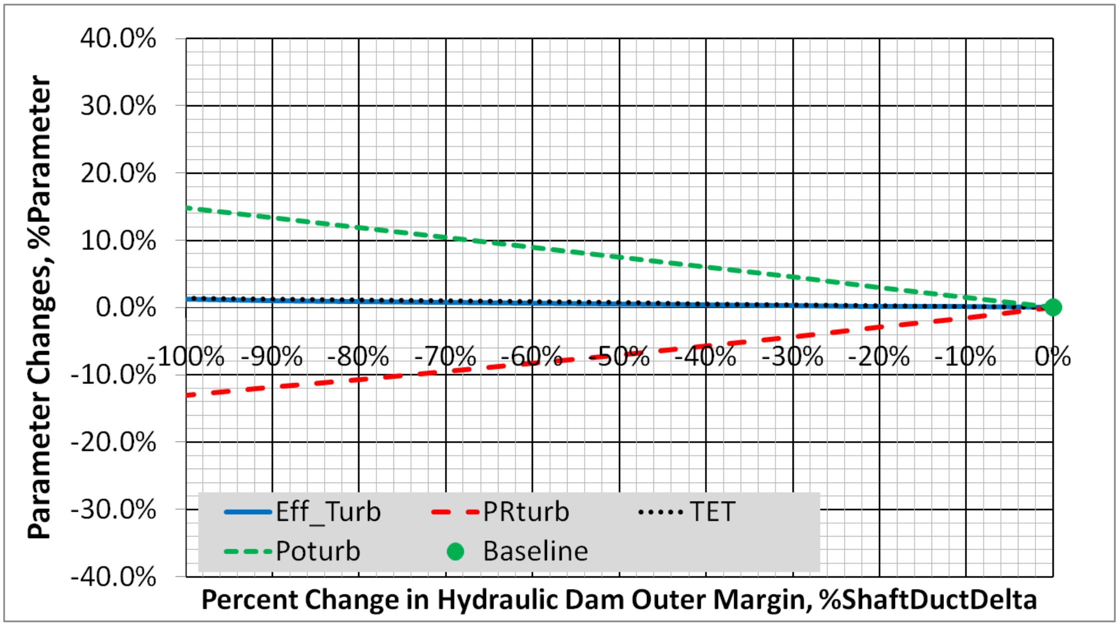


Figure 6.53 Round 1 Hydraulic Dam Outer Margin Influence on Turbine Metrics

The hydraulic dam margin shows to be an interesting parameter that provides several benefits if the margin is reduced. Therefore, for future iterations the hydraulic dam margin is set at the minimum required to manufacture the concept.

6.1.1.10 Hydraulic Dam Inner Margin, %HydMargin

The hydraulic dam inner margin is the margin on the inner portion of the hydraulic dam and is not expected to have anything but the basic impact on the overall geometry of the pump. As can be seen in Figure 6.54, the overall thrust and specific impulse are not affected, but the pump efficiency is inversely related to the margin. As the margin decreases, the size of the pump decreases, allowing the pump to reduce the amount of turbine power needed.

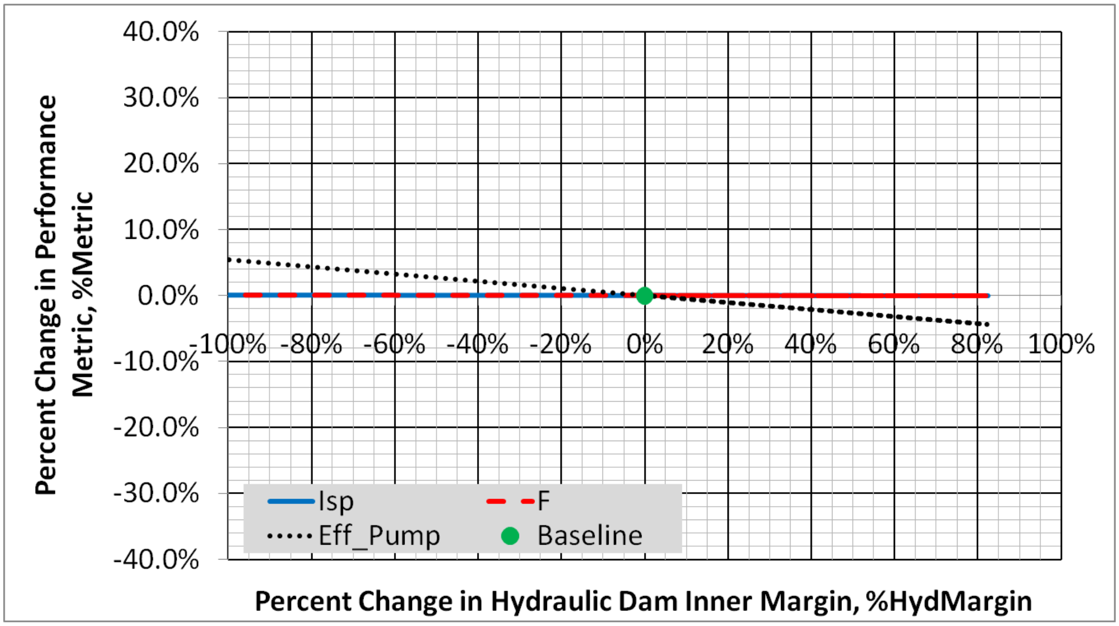


Figure 6.54 Round 1 Hydraulic Dam Inner Margin Influence on Performance Metrics

Since the oxidizer split is not changing and the turbine rotor inlet temperature remains fixed, the mass flow rates remain unchanged and are provided in Appendix A. Conversely, the hydraulic dam inner margin has a direct influence on the overall system weight and the diameter. Figure 6.55 shows how the weight and diameter both decrease as the margin decreases.

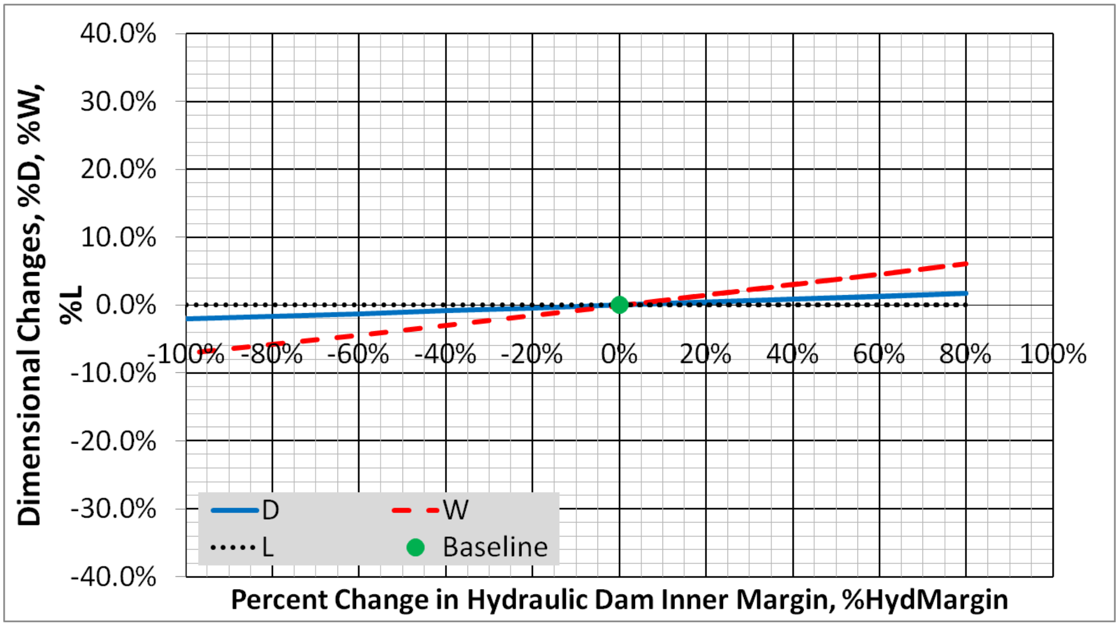


Figure 6.55 Round 1 Hydraulic Dam Inner Margin Influence on Overall Dimensions

The hydraulic dam inner margin starts the stack up for the hydraulic dam geometries, so in Figures 6.56 and 6.57 it can be observed that as the hydraulic dam inner margin decreases, all of the geometric properties of the two hydraulic dams decrease, with the exception of the oxidizer inner radius. The geometry of the two hydraulic dams are linked such that the outer rim radius of the oxidizer inner shaft is the same as the outer rim radius of the fuel inner shaft. Since the MMH has a lower density than the oxidizer, the fuel side hydraulic dam controls the shaft geometry. The result is that the oxidizer geometry inner radius fluctuates in relation to the fuel hydraulic dam instead of the hydraulic dam inner margin.

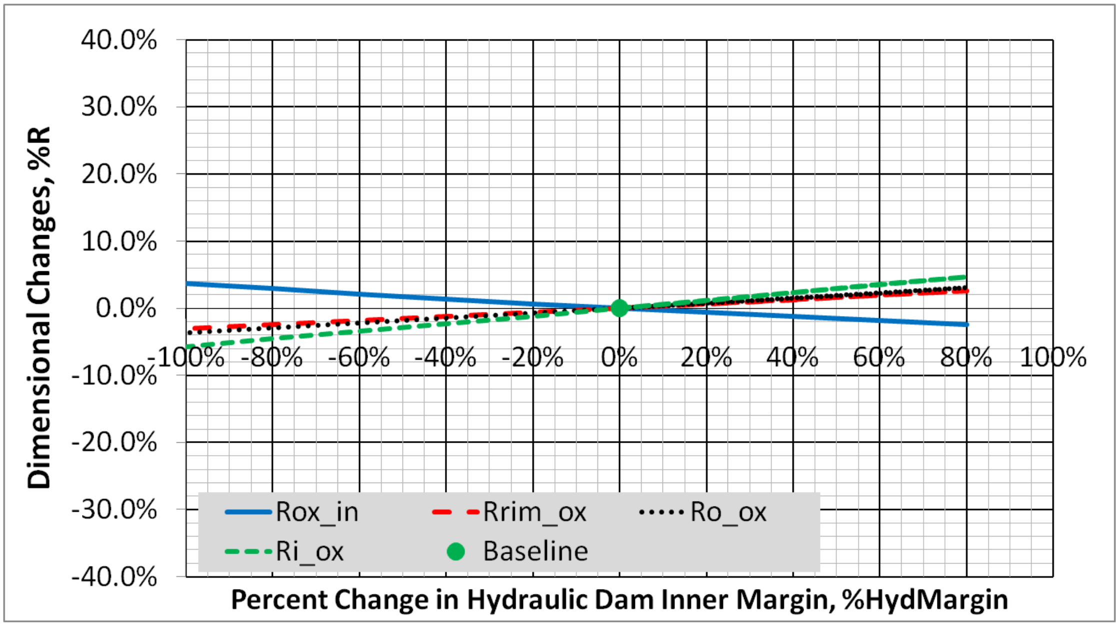


Figure 6.56 Round 1 Hydraulic Dam Inner Margin Influence on Oxidizer System Dimensions

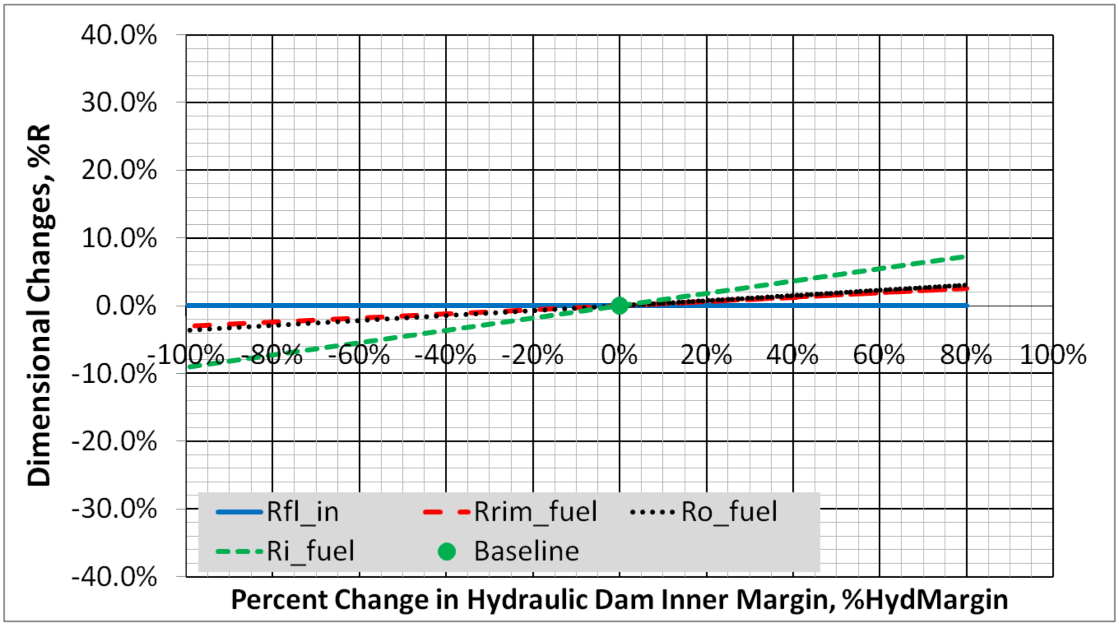


Figure 6.57 Round 1 Hydraulic Dam Inner Margin Influence on Fuel System Dimensions

With the decrease in the overall diameter of the pump, the power produced by the turbine decreases. Figure 6.58 shows how decreases in the hydraulic dam inner margin results in a decrease in the overall power required from the turbine.

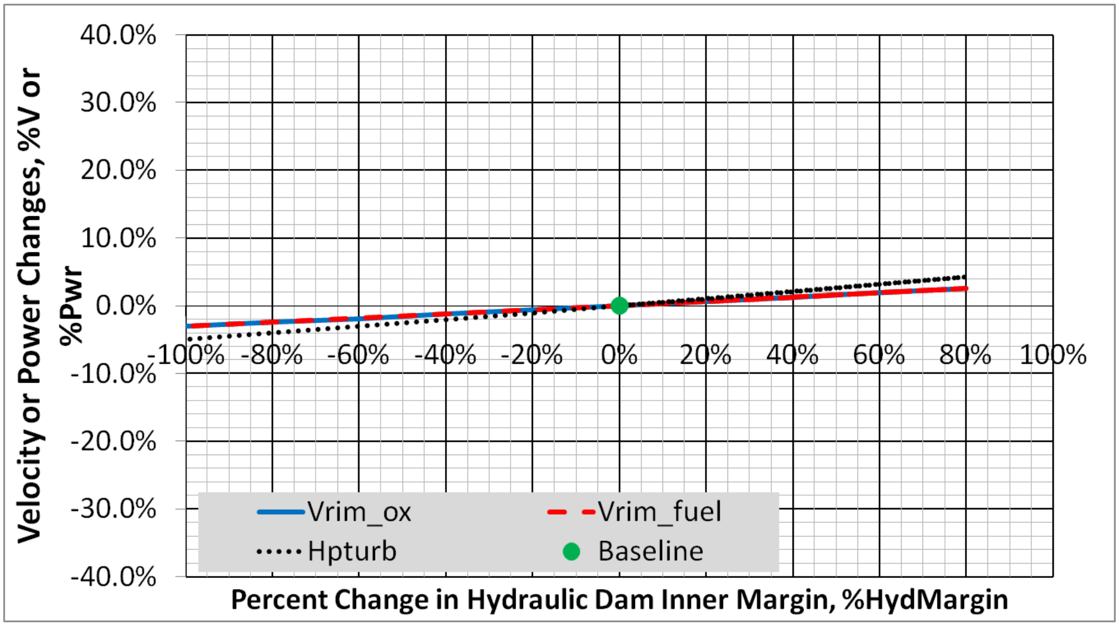


Figure 6.58 Round 1 Hydraulic Dam Inner Margin Influence on Power Metrics

In keeping with the decreased geometry associated with decreasing the hydraulic dam inner margin, the combustor dimensions also decrease, as shown in Figure 6.59. However, the oxidizer to fuel ratio and the fuel split are unaffected.

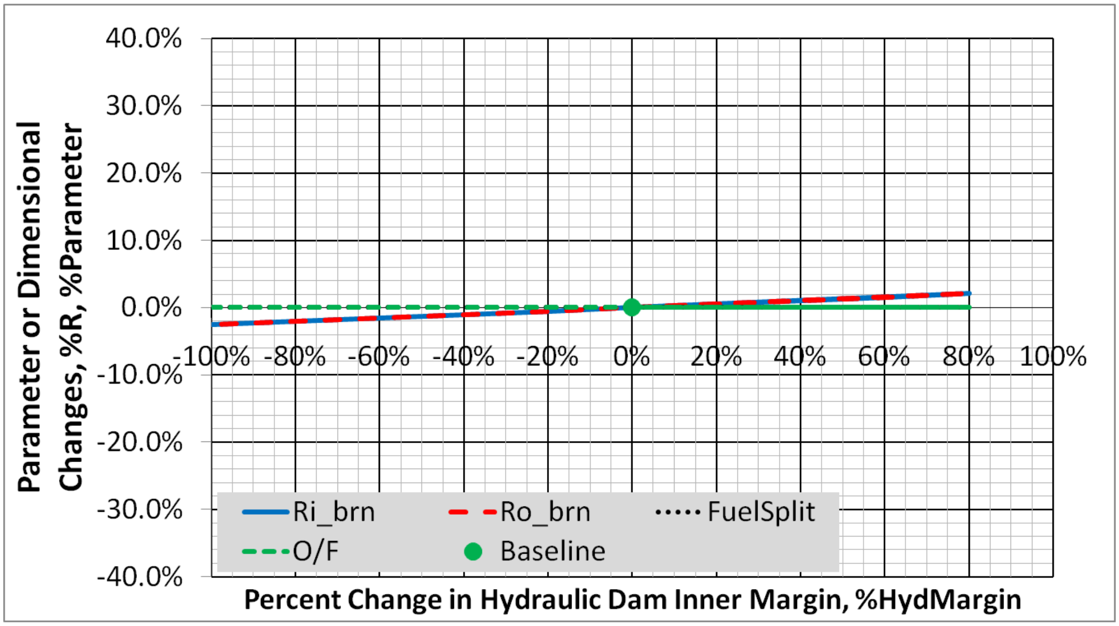


Figure 6.59 Round 1 Hydraulic Dam Inner Margin Influence on Combustor Dimensions

Turbine performance metrics illustrate that the turbine power demand decreases as the margin decreases. Figure 6.60 shows that the turbine pressure ratio also drops as the power demand decreases, which raises the turbine exit pressure, resulting in the improved weight trend observed earlier. The overall turbine efficiency is unaffected by the change in margin.

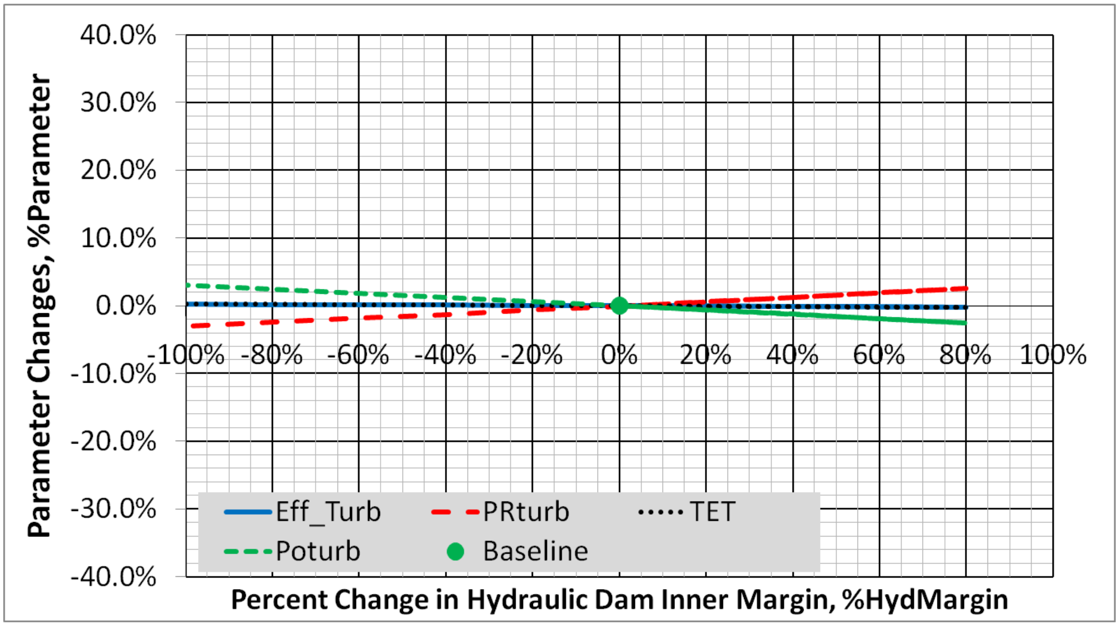


Figure 6.60 Round 1 Hydraulic Dam Inner Margin Influence on Turbine Metrics

The hydraulic dam inner margin reveals positive trends when the margin is decreased. Thus, the hydraulic dam inner margin is eliminated in future iterations to optimize the overall performance of the system. As will be discussed later, the decision to eliminate the hydraulic dam inner margin had an unintended consequence.

6.1.1.11 Rotary Injector Height, %InjdeltaR

The rotary injector height is another purely geometric parameter that was expected to have a purely geometric influence on the overall system. As can be seen in Figure 6.61, the pump efficiency is affected by changes in the rotary injector height, but the thrust and specific impulse showed no sensitivity to the design parameter.

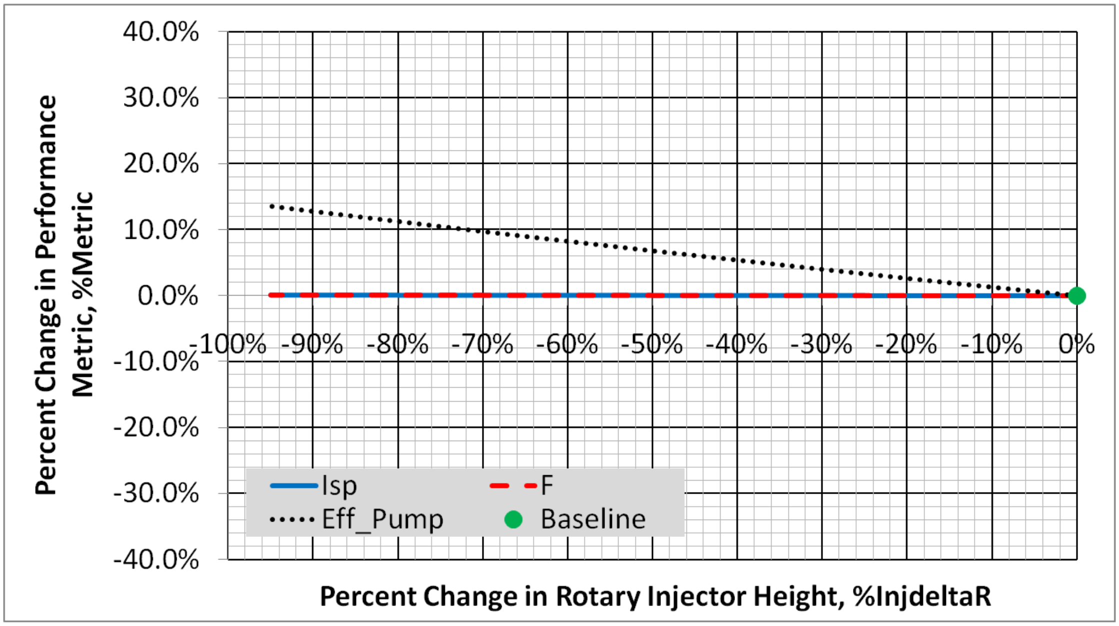


Figure 6.61 Round 1 Rotary Injector Height Influence on Performance Metrics

Similar in nature to the hydraulic dam outer margin, the rotary injector height did not influence the mass flow rates, which can be found in Appendix A. The reason for the insensitivity is the fact that the turbine rotor inlet temperature and the oxidizer flow split are held constant. The change in the injector height did have a noticeable influence on the diameter of the pump and on the total system weight. Figure 6.62 illustrates the decrease in weight of the system corresponding with the decrease in pump diameter driven by the decrease in the injector height. The weight decrease is also related to the increase in the turbine exit pressure resulting from the decrease in work for lower radii injectors.

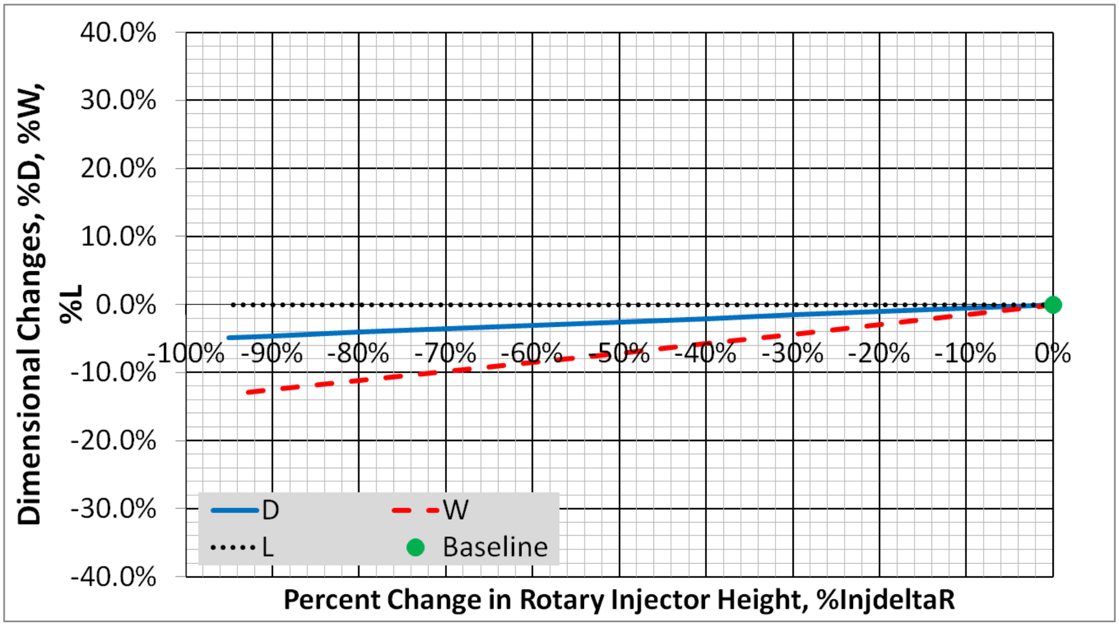


Figure 6.62 Round 1 Rotary Injector Height Influence on Overall Dimensions

Since the rotary injectors are further out in radius than the hydraulic dams, the hydraulic dams show no dependence upon the injector height design parameter, so their responses are provided in Appendix A.

As with the hydraulic dam outer margin, the decrease in rotary injector radii result in a decrease in the power demand of the shaft. Thus, the turbine power output decreases, as the rotary injector height decreases, as shown in Figure 6.63.

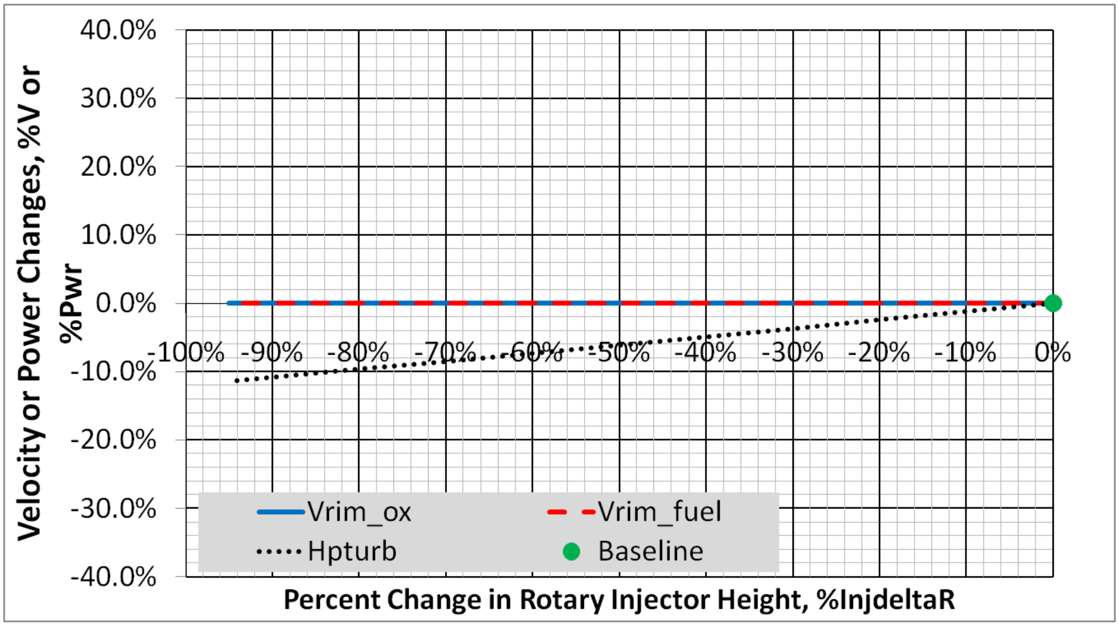


Figure 6.63 Round 1 Rotary Injector Height Influence on Power Metrics

The combustor parameters, Figure 6.64, show that only the geometry of the combustor is influenced by the changes in rotary injector height. As the injector height decreases, the combustor moves closer to the centerline. The fuel split and the oxidizer to fuel ratio are not influenced by the design parameter.

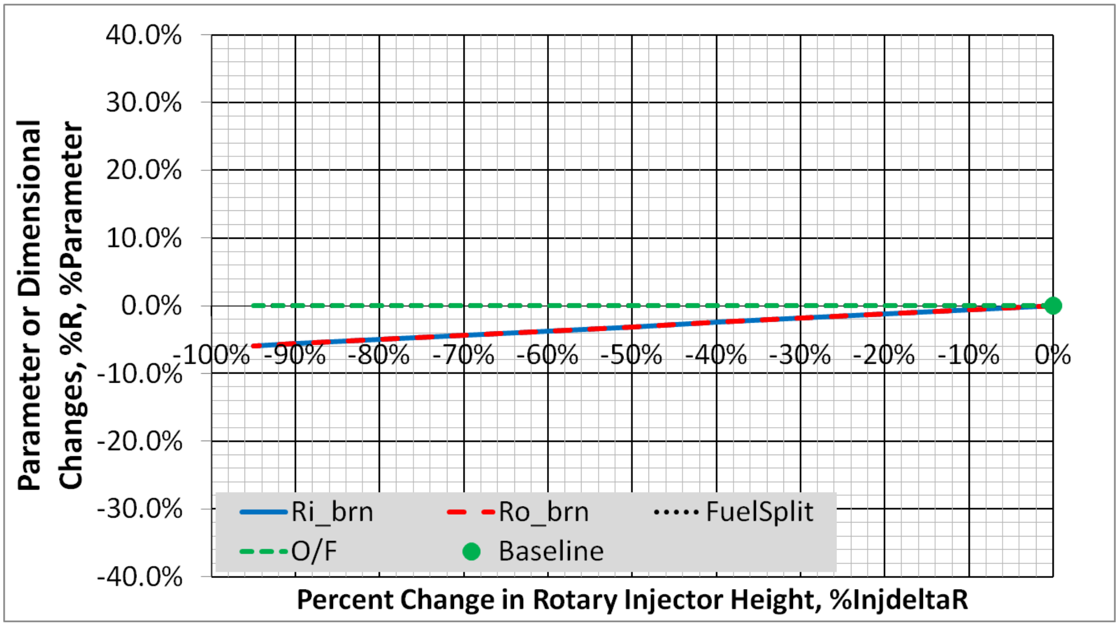


Figure 6.64 Round 1 Rotary Injector Height Influence on Combustor Dimensions

The turbine metrics point to the biggest driver in the weight change for the system. Figure 6.65 shows that the turbine pressure ratio decreases with a decrease in the injector height parameter because the rotary injector power demands decrease as the rotary injector height decreases. The resulting improvement in the turbine exit pressure allows the system weight to decrease.

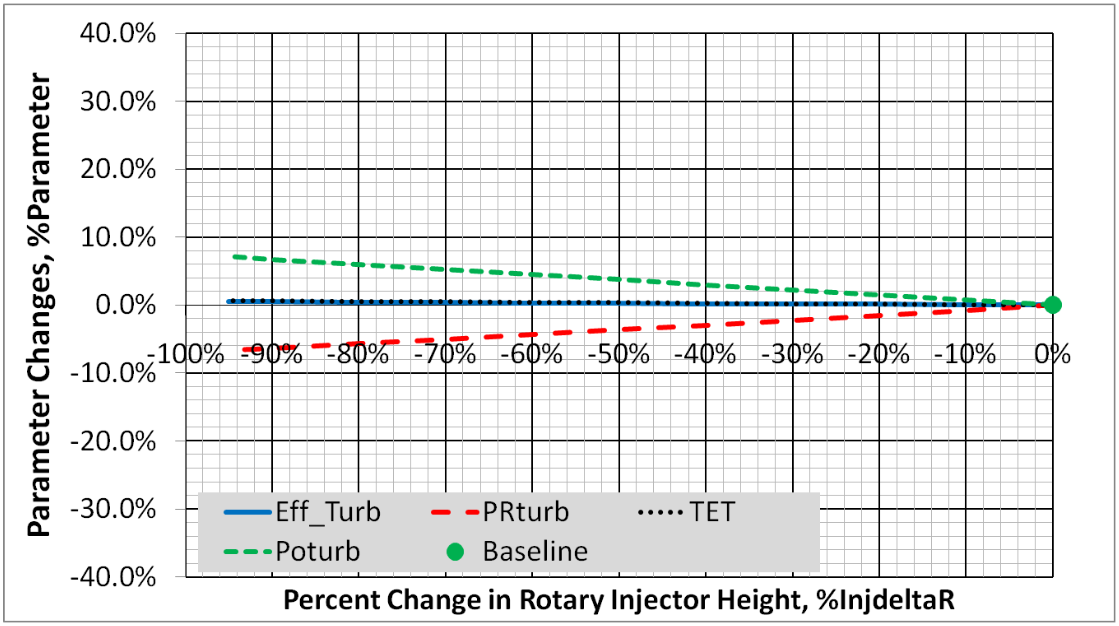


Figure 6.65 Round 1 Rotary Injector Height Influence on Turbine Metrics

The rotary injector height design parameter shows that any excess deltas in the overall radial stack up of the pump result in significant increases in the system weight. Some rotary injector height is generally necessary in order to be able to make the pump. Thus, the rotary injector height was set at the minimum believed to be manufacturable and was eliminated from further consideration.

6.1.1.12 Swirl

The swirl parameter was included to attempt to reduce the amount of work the turbine would have to produce to pump the propellants by giving the fluids an initial velocity with a significant tangential component. The reduction in the amount of work stems from the fluid not having to accelerate as much. However, the inlet static pressure also decreases due to the increase in the velocity. As can be seen in Figure

6.66, the efficiency of the pump does increase, but only slightly for large changes in the inlet swirl. The overall thrust and specific impulse are not affected by the inlet swirl.

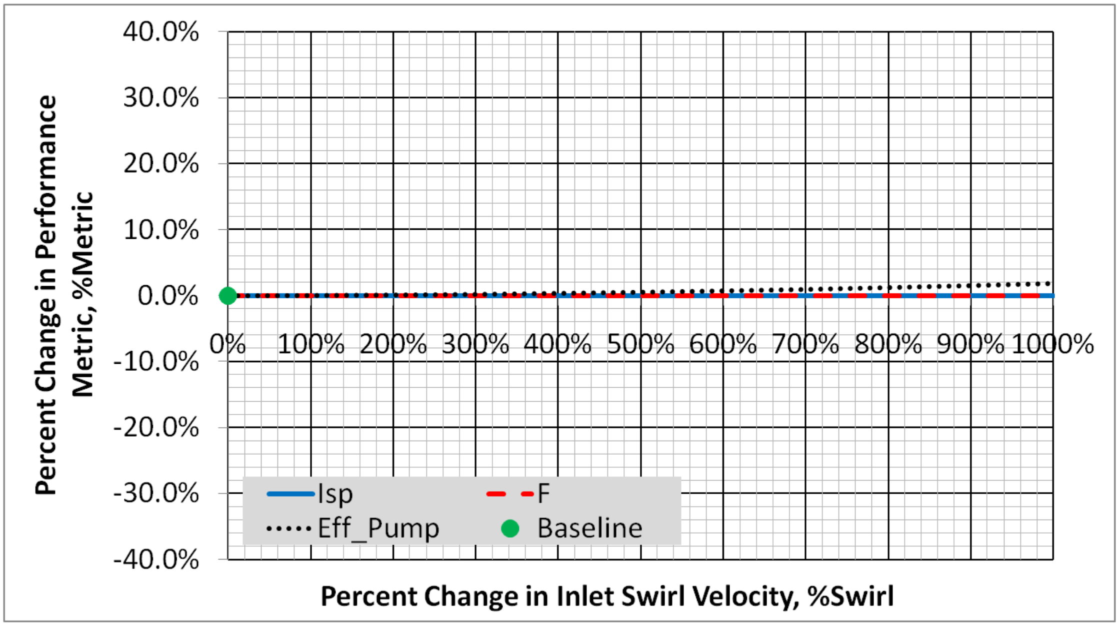


Figure 6.66 Round 1 Inlet Swirl Velocity Influence on Performance Metrics

The inlet swirl did not appear to have any effect on the mass flow rates. With the turbine rotor inlet temperature and the oxidizer split maintained at constant values, there is no logical path for changing the mass flow rates. Appendix A contains the mass flow rate responses.

The inlet swirl did have a minimal impact on the overall weight of the system. From Figure 6.67 it is clear that the decrease in turbine work resulting from increasing the inlet swirl does have a small benefit in the overall system weight. However, the length and diameter of the pump are not affected by the swirl parameter.

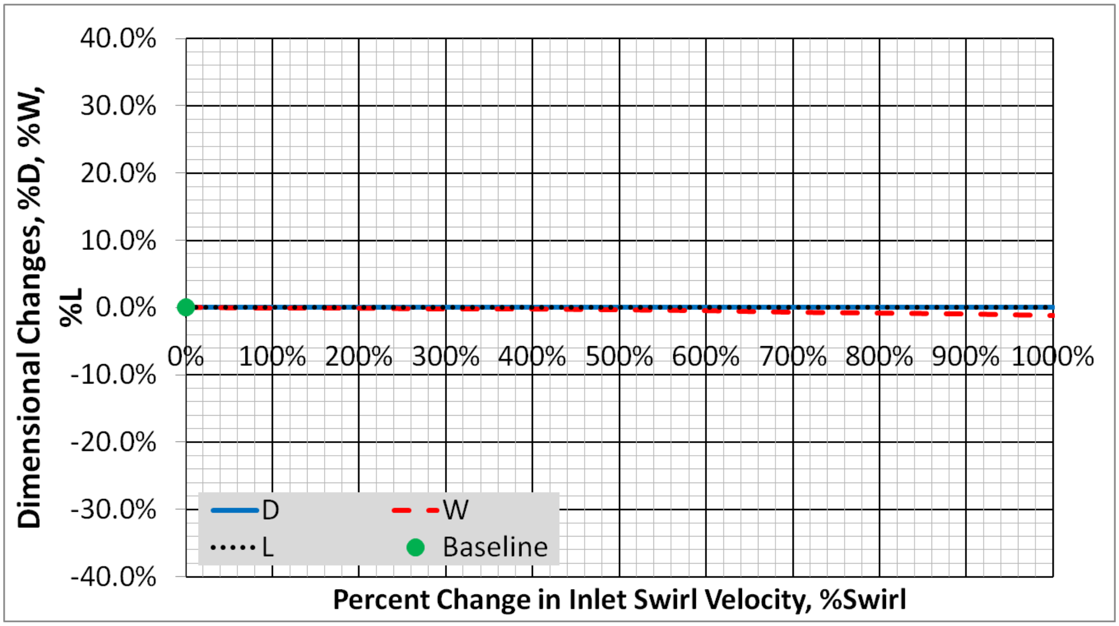


Figure 6.67 Round 1 Inlet Swirl Velocity Influence on Overall Dimensions

It is not unexpected that the geometry did not change noticeably. The impact of the inlet swirl is definitely a small influence on the overall pump design and its responses are included in Appendix A. However, the turbine power draw, shown in Figure 6.68, does decrease. The decrease appears to be insignificant in comparison to the overall power that the turbine has to provide.

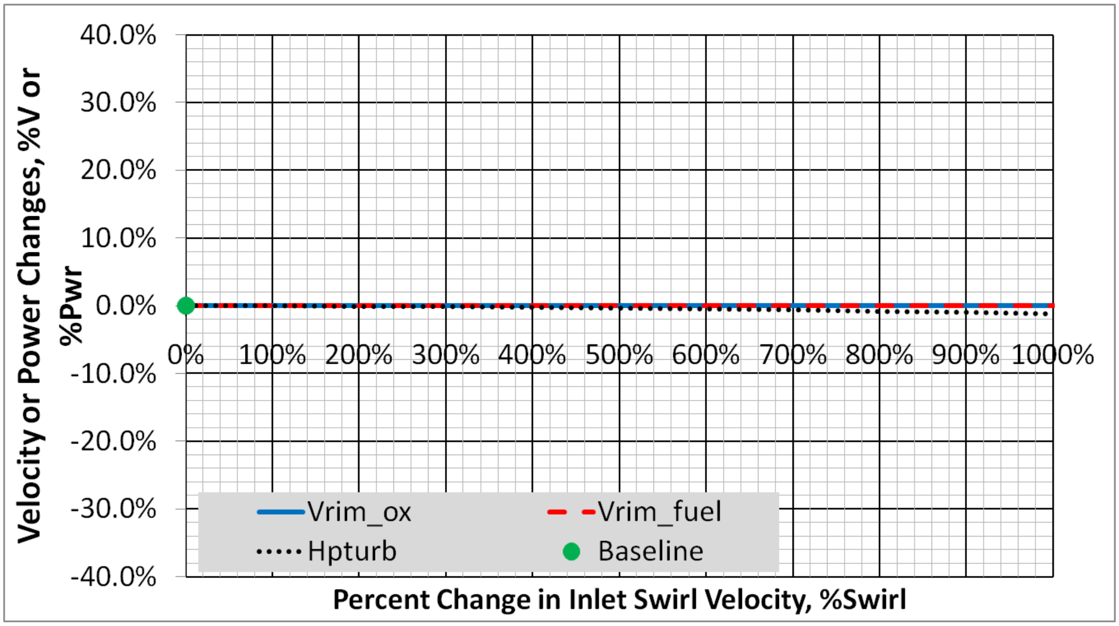


Figure 6.68 Round 1 Inlet Swirl Velocity Influence on Power Metrics

The combustor metrics are completely unaffected by the inlet swirl. The result makes sense, as the pump still has to produce the same pressure and does so by using the same geometry. The fuel split and the oxidizer to fuel ratio are likewise unaffected by the inlet swirl. The combustor metric responses are included in Appendix A.

Conversely, the turbine performance metrics, Figure 6.69, illustrate what is actually going on with changes in the inlet swirl. The swirl reduces the amount of work that has to be produced by the turbine by preswirling the flow in the direction of rotation. Therefore, the turbine does not have to work as hard to produce the same result. Thus, the pressure ratio decreases and the exit pressure increases, allowing the system weight to decrease modestly.

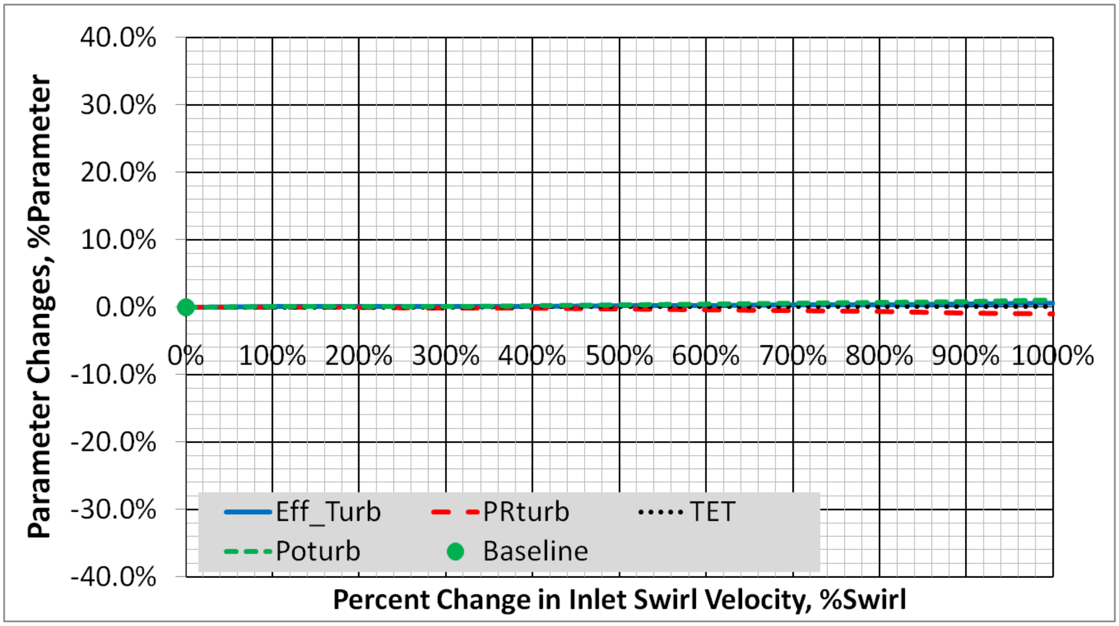


Figure 6.69 Round 1 Inlet Swirl Velocity Influence on Turbine Metrics

The overall influence of the inlet swirl is very small because the amount of power saved with the preswirl is small in comparison to the overall power provided by the turbine. However, there is an improvement associated with preswirling the flows. It was decided to set the preswirl at a high value, but not high enough to prevent actual flow from traveling axially into the pump. As the swirl increases, the film thickness increases on the inside of the shaft, so the swirl velocity is limited to a fraction of the inlet velocity to maintain a reasonable film thickness.

6.1.1.13 Turbine Rotor Inlet Temperature, TRIT

The final parameter in the initial iteration set is the turbine rotor inlet temperature. In gas turbine engines, the turbine rotor inlet temperature plays a significant role in overall performance, so it was anticipated that the turbine rotor inlet temperature in the Combustion Driven Drag Pump would also influence its operation and performance. As shown in Figure 6.70, the temperature does impact the thrust, specific impulse and pump efficiency. As the temperature decreases, the thrust increases, but the specific impulse and the pump efficiency decrease as a result.

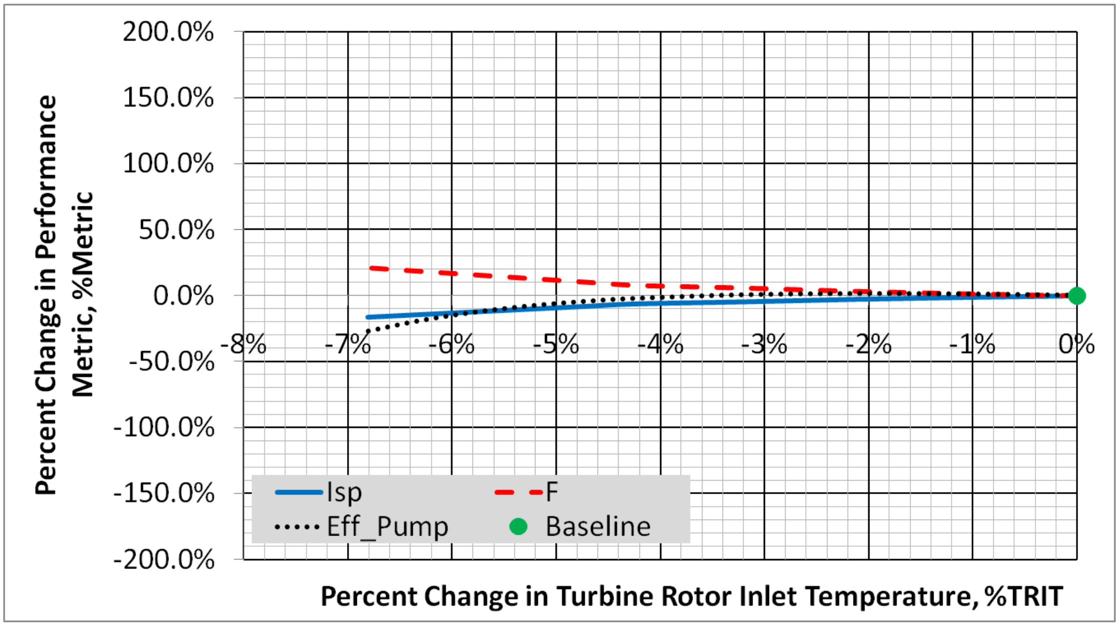


Figure 6.70 Round 1 Turbine Rotor Inlet Temperature Influence on Performance Metrics

The turbine rotor inlet temperature, as shown in Figure 6.71 influences the mass flows. The oxidizer is defined by the oxidizer split parameter, so the fuel going into the combustor has to increase in order to reduce the combustion temperature. The increase results in an overall fuel flow increase and an increase in the flow entering the combustor by a large amount.

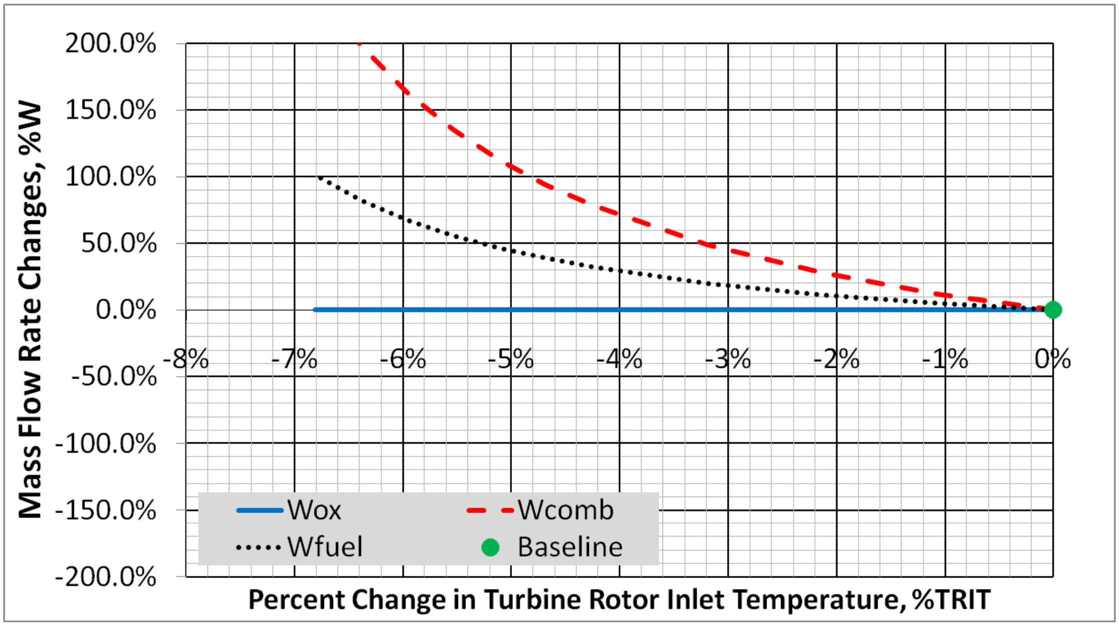


Figure 6.71 Round 1 Turbine Rotor Inlet Temperature Influence on Mass Flow Rates

The overall dimensions, Figure 6.72, show that the weight initially decreases but then increases as the turbine rotor inlet temperature decreases. Also, it shows that the diameter of the system starts to increase as the temperature decreases.

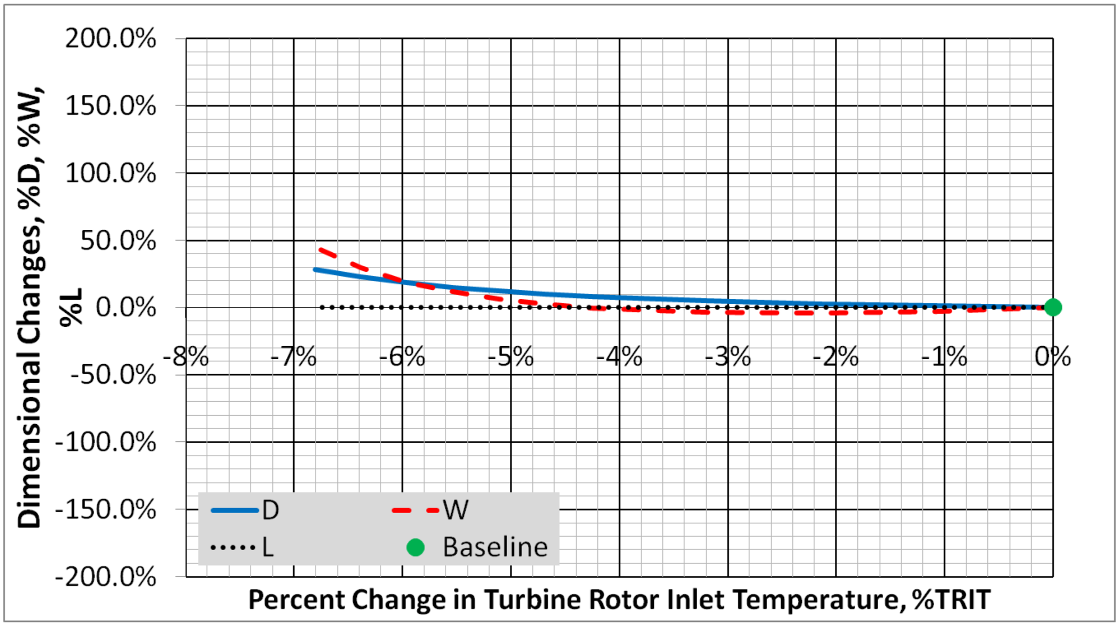


Figure 6.72 Round 1 Turbine Rotor Inlet Temperature Influence on Overall Dimensions

The geometry of the hydraulic dams increase as a function of decreasing turbine rotor inlet temperature. Figure 6.73 and 6.74 illustrate the changing geometry trends. The reason for the increase in geometry is the significant increase in the overall fuel flow rate. Since the fuel is the lower density propellant, increases in its flow rate drive the inner shaft diameter to increase in order to accommodate the flow and maintain the film thickness specified. With increases in the fuel hydraulic dam geometry, the rest of the pump geometry increases.

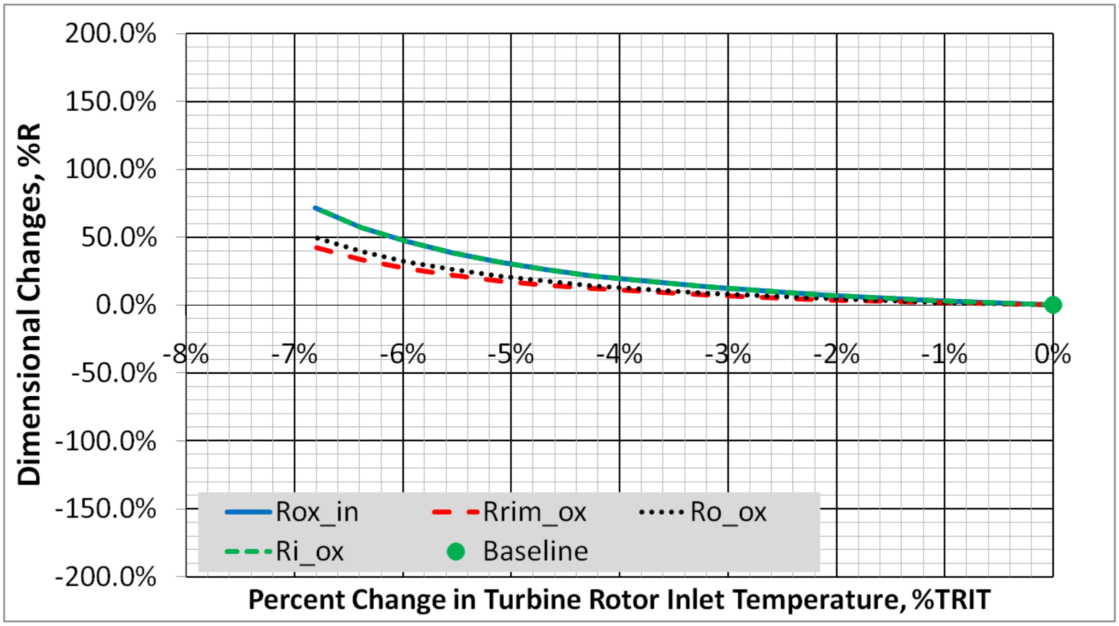


Figure 6.73 Round 1 Turbine Rotor Inlet Temperature Influence on Oxidizer System Dimensions

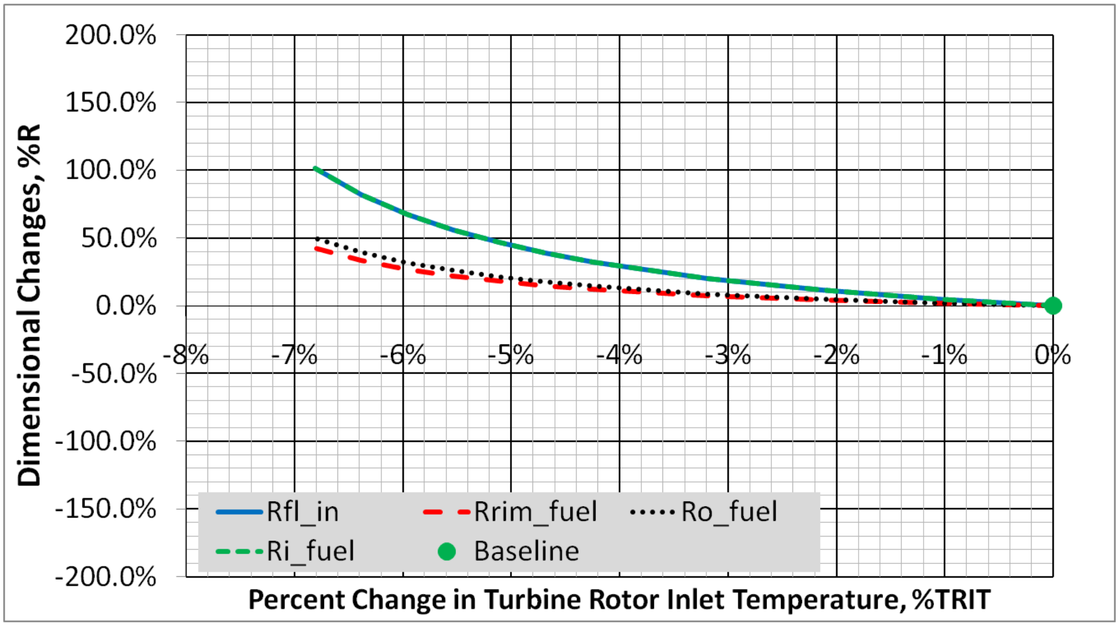


Figure 6.74 Round 1 Turbine Rotor Inlet Temperature Influence on Fuel System Dimensions

The increase in the pump diameter, due to the decreasing turbine rotor inlet temperature, increases the amount of power required to maintain the same shaft speed. At the same time, the amount of propellant increases, due to the increase in the overall fuel flow rate, which also increases the turbine power demand, as shown in Figure 6.75.

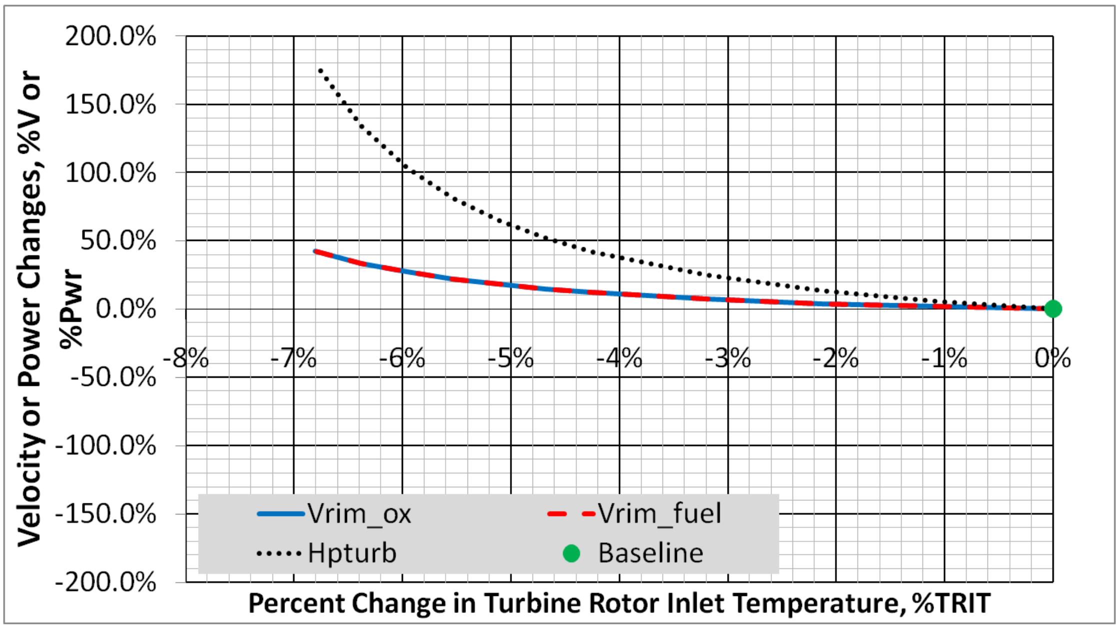


Figure 6.75 Round 1 Turbine Rotor Inlet Temperature Influence on Power Metrics

The turbine rotor inlet temperature affects the geometry of the pump, as discussed earlier, and shown in Figure 6.76. Additionally, the fuel split decreases, meaning that more fuel goes through the pump combustor as the turbine rotor inlet temperature decreases. Along with that is the decrease in the oxidizer to fuel ratio within the burner.

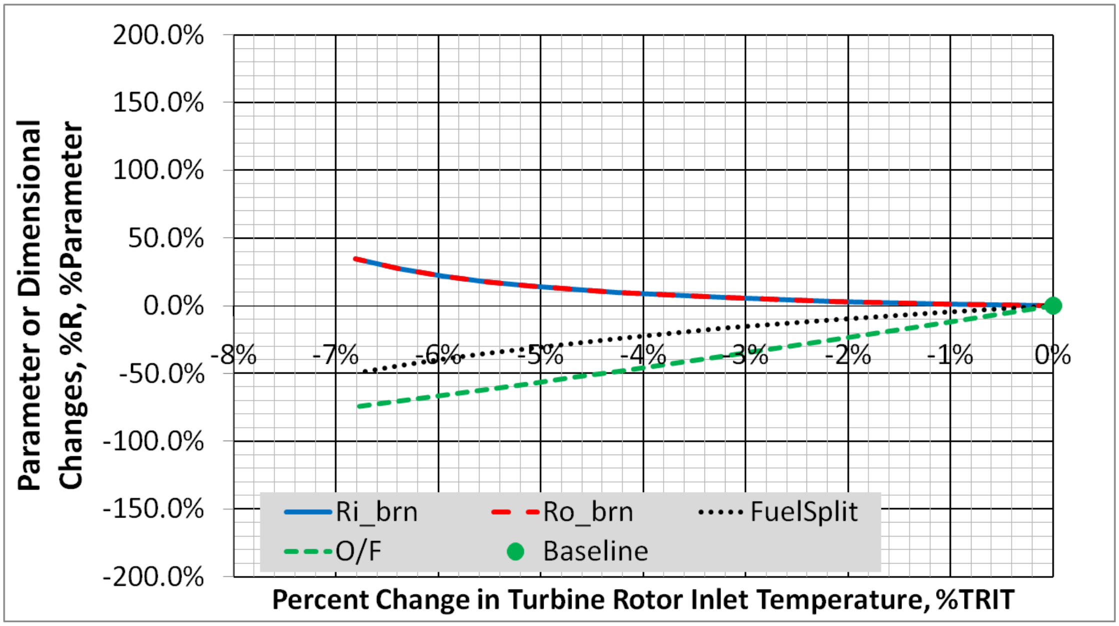


Figure 6.76 Round 1 Turbine Rotor Inlet Temperature Influence on Combustor Dimensions

The turbine performance metrics, shown in Figure 6.77, show that the turbine efficiency increases as the turbine rotor inlet temperature decreases, but at the same time the turbine pressure ratio increases to accommodate the increased demand for turbine power. The pressure ratio and efficiency off set each other such that the turbine exit pressure does not change as much as would be expected by the increase in the power demand. In fact, the exit pressure appears to stabilize at the lowest temperatures run.

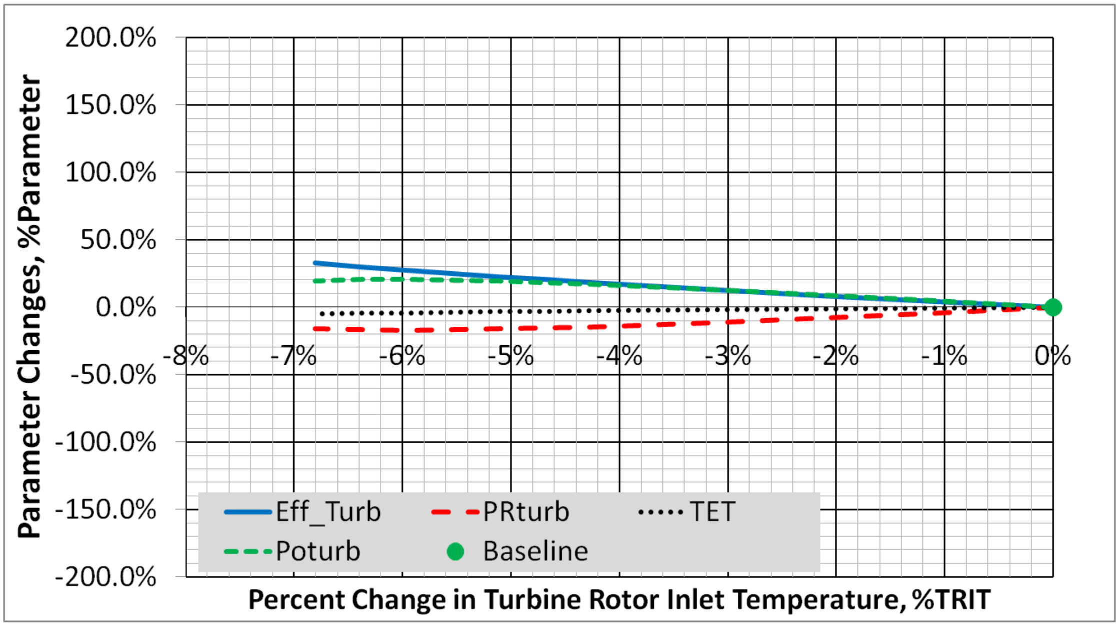


Figure 6.77 Round 1 Turbine Rotor Inlet Temperature Influence on Turbine Metrics

Of all the parameters investigated so far the turbine rotor inlet temperature has the most far reaching impact. The design parameter affects both the size of the pump and the weight of the system. Additionally, the turbine rotor inlet temperature influences the overall performance metrics. The temperature is set at the left edge of the bucket of the weight curve (-4.2%), which is slightly lower than the initial setting and will be investigated further in the next iteration set.

6.1.2 Second Iteration

The first iteration was an all encompassing study to understand the relationships between all of the design parameters and all of the metrics. During the first iteration, it was observed that several of the design parameters could be optimized without further analysis. The optimized parameters could then be removed from consideration in later studies to simplify the analysis and optimization process. Likewise, it was observed that several of the metrics provided identical or redundant information and could be removed from further consideration.

Starting with the design parameters, the first design parameter that was excluded from further study was the combustor pressure drop. The responses for the combustor pressure drop survey indicated that the combustor pressure drop should be minimized. Since the design of the combustor can accommodate a large volume relative to the flow rate it is feasible to build a low pressure drop combustor. It should be noted that even though the combustor pressure drop is set at a constant value, the actual value of combustor pressure drop should be a function of the mass flow rate and the heat release. In other words, the pressure drop for a physical combustor will vary from operating condition to operating condition. The true variation is likely small, lending credibility to the approach of modeling a constant loss for the initial design studies.

The next parameter eliminated from further investigation was the combustor efficiency. The combustor efficiency did provide some interesting results, generally indicating that setting the efficiency as high as possible would be the most reliable. Since the combustor can be designed within a large expanding volume, a high combustor efficiency is a reasonable design intent. Plus, the hypergolic nature of MMH and MON-3 reactions tend to support high combustion efficiency [58], [72].

Thirdly, the parasitic losses were set to a reasonable level with the expectation that the variations in losses associated with changes in loads and shaft speed would be relatively low. Therefore, estimating the losses as a constant value is a reasonable assumption. Furthermore, setting the losses to a low percentage of the overall shaft power is a reasonable approach as the windage losses and seal friction losses are relatively low due to the compact nature of the shaft. The bearings themselves are not likely to have a high loss because the axial loads are opposing in nature, so the only bearing losses are likely to be from non-uniform radial loads, which should also be relatively minor in comparison to the total turbine shaft power.

The fourth parameter eliminated from further consideration was the scroll recovery. In the initial stages of the optimization process, it was assumed that none of the dynamic head developed by the rotating injectors would be recoverable due to the high tangential velocities involved. The recovery factor could provide a net benefit to the system, but it was decided to keep that as a backup in case optimizing the system proved difficult with the remaining parameters.

The hydraulic dam inner and outer margins along with the rotating injector height were all minimized based on the responses that were observed in the first phase of the trade studies. In order to accommodate the minimization of these parameters, the design of the shaft assembly was altered. The change in design will be discussed in more detail later. However, it is relevant to point out that the values the margins were set to are achievable with the design changes.

After eliminating the above design parameters, the design space was reduced from thirteen parameters to six design parameters. The remaining design parameters are the combustor radius ratio, the film thickness, the design shaft speed, the oxidizer flow split, the inlet swirl velocity and the turbine rotor inlet temperature. The reduction is shown in Figure 6.78.

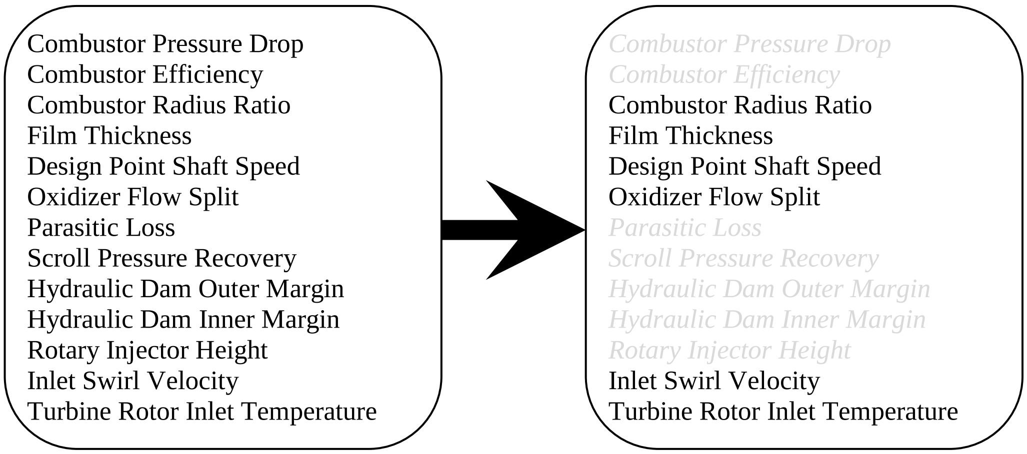


Figure 6.78 First Round Design Parameter Elimination

As with the design parameters, several of the metrics could be eliminated based on duplicate responses with other metrics or on whether or not the information was useful. After the first round in the study, most of the shaft radii parameters could be eliminated in that the overall diameter, the oxidizer inner shaft radius and the oxidizer outer rim radius duplicated the responses. Likewise, the rim velocity parameters for the fuel and the oxidizer both showed the same information, so the oxidizer rim speed was maintained. The fuel rim speed was eliminated. The mass flow rates were also redundant with specific impulse and the oxidizer to fuel ratio. Finally, none of the parameters affected the length of the pump, so it was eliminated. The number of metrics identified for evaluation in the next iteration dropped from the initial twenty-eight to fifteen, as shown below in Figure 6.79.

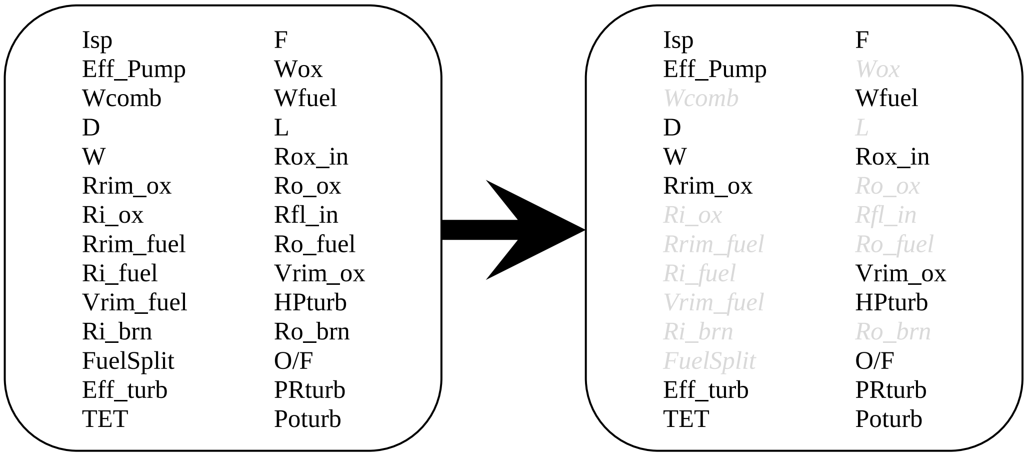


Figure 6.79 First Round Metric Elimination

It should be noted that running CEA at the new design point with all the new values for the design parameters resulted in a failure in CEA to converge to a solution for the thrust and specific impulse values. The failure of CEA to provide thrust and specific impulse at the design point cascaded into the individual cases as well. As a consequence of the failure of CEA to run at the new design point, the thrust and specific impulse responses appear to be flat for the second iteration. Failure of CEA is attributed to small deltas between solver passes that could not be resolved due to the limited number of significant digits in the CEA output.

Finally, in the second iteration, the new design point run at the beginning of the variation is noted by the yellow triangles on each graph. The yellow triangles show how the new design point contrasts with the original value given by the green circle.

6.1.2.1 Combustor Radius Ratio, CRo

The first parameter that was rerun from the design condition was the combustor geometry parameter. As can be seen in Figure 6.80, the pump efficiency increases with increasing combustor radius ratio. However, the weight and the diameter also increase as expected. There does appear to be a local minimum for the weight, such that reducing the combustor radius ratio below that point will not provide any additional benefit in weight.

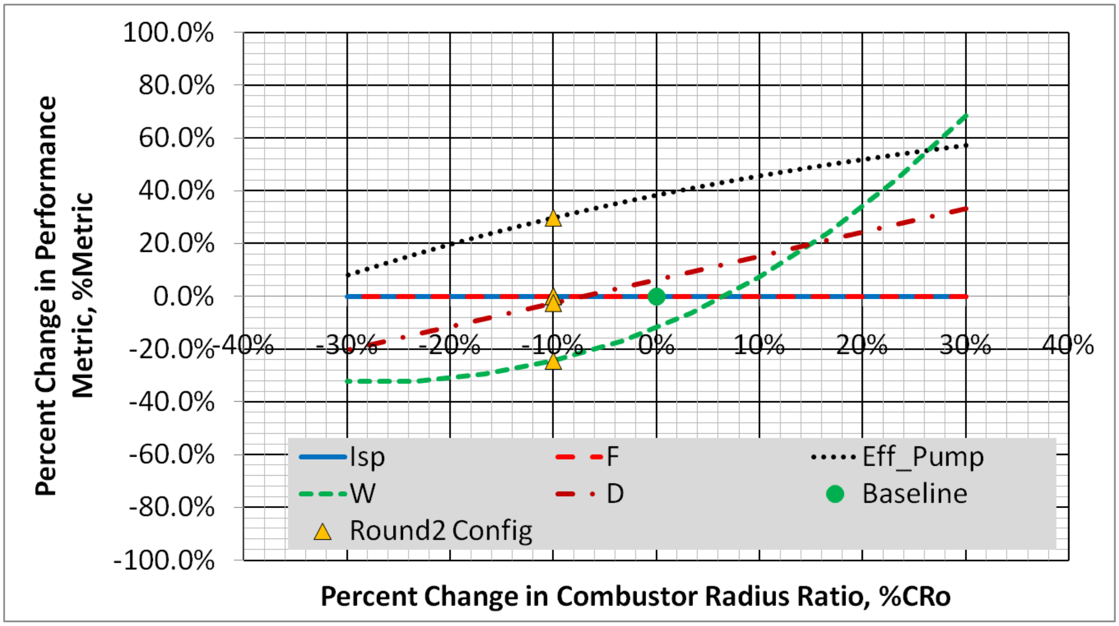


Figure 6.80 Round 2 Combustor Radius Ratio Influence on Overall Metrics

The combustor radius ratio does not show a noticeable influence on the mass flow metrics or the shaft power factors. Likewise, the combustor radius ratio does not influence the shaft geometry metrics. The insensitivity for the shaft geometry, mass flow rates and shaft power are consistent with the observations in the first iteration. The related metric responses are provided in Appendix A for completeness.

For the turbine parameters, the turbine efficiency appears to be strongly linked to the combustor radius ratio, as shown in Figure 6.81. The turbine efficiency improvement is a result of the combustor pushing the turbine out in diameter, which increases the turbine rim speed. Along with the turbine efficiency improvement is the increase in turbine exit pressure as the combustor radius ratio increases.

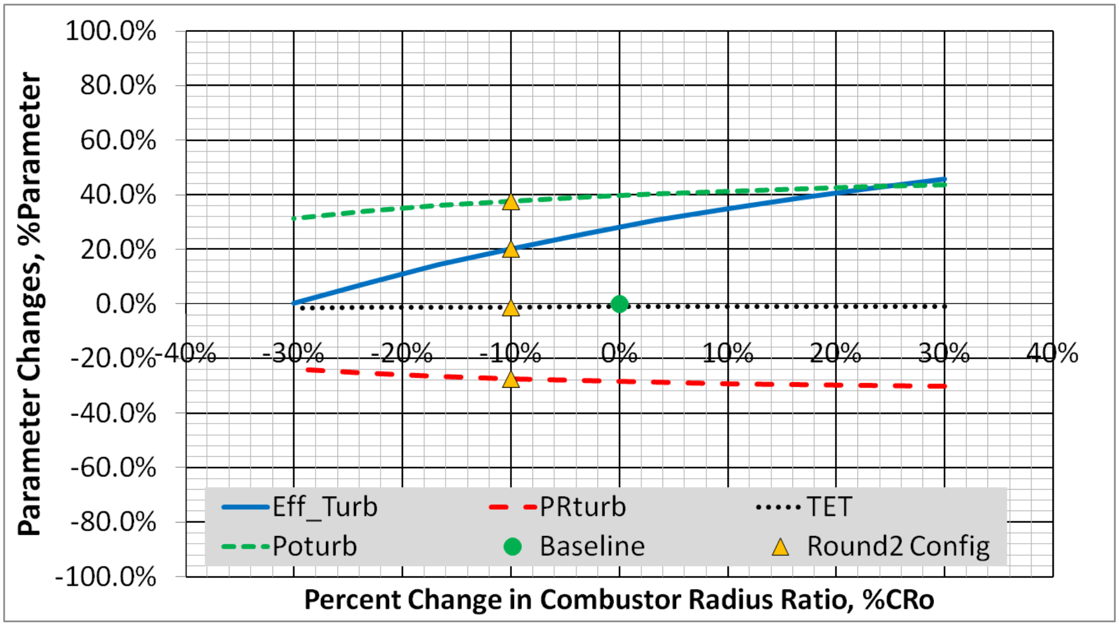


Figure 6.81 Round 2 Combustor Radius Ratio Influence on Turbine Metrics

The observations of the influences with respect to the combustor radius ratio are consistent with the trends observed in the first round, so setting the combustor radius ratio for the next phase and beyond is acceptable. The trade between the weight and the pump efficiency indicates that the radius ratio should be set slightly higher than the weight minimum to provide the minimum weight configuration, as well as, a slight improvement in performance. The resulting point coincides with the value set at the beginning of round two at -10%.

6.1.2.2 Film Thickness, Film

For the film thickness, the trends are similar to those in the first round. The pump efficiency, diameter and weight all improve as the film thickness increases, as illustrated in Figure 6.82. The trend makes sense when considering the fact that as the film thickness increases, the pump looks more and more like a conventional pump.

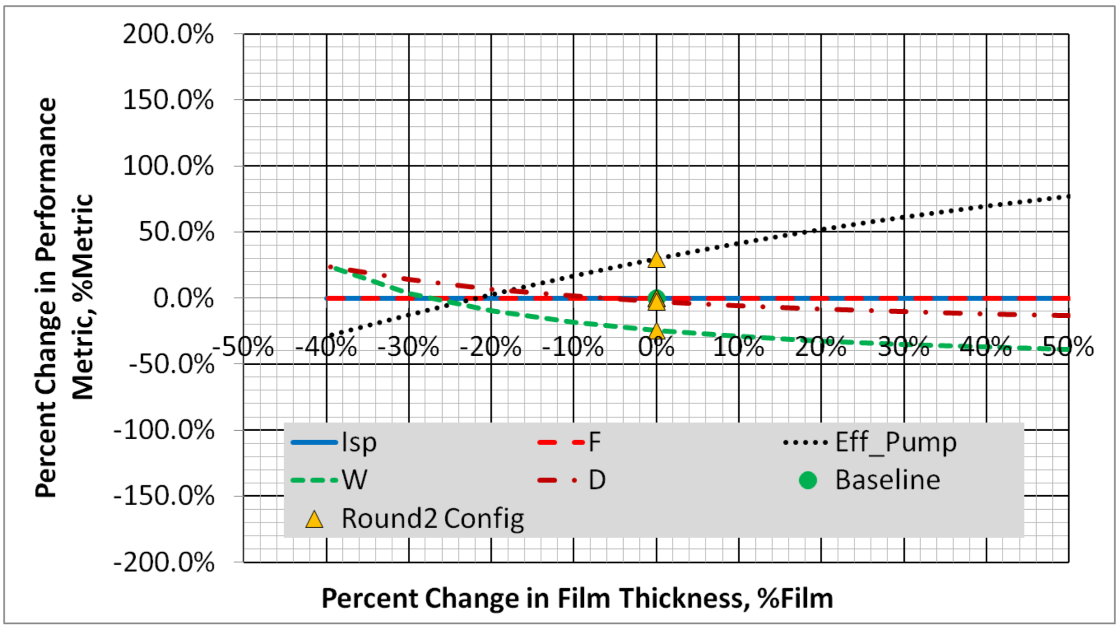


Figure 6.82 Round 2 Film Thickness Influence on Overall Metrics

The film thickness influence on the power factors show that the flow rates are still not influenced by the film thickness, but the turbine power draw decreases with increasing film thickness, just as in the original film thickness variation. The trends are shown in Figure 6.83.

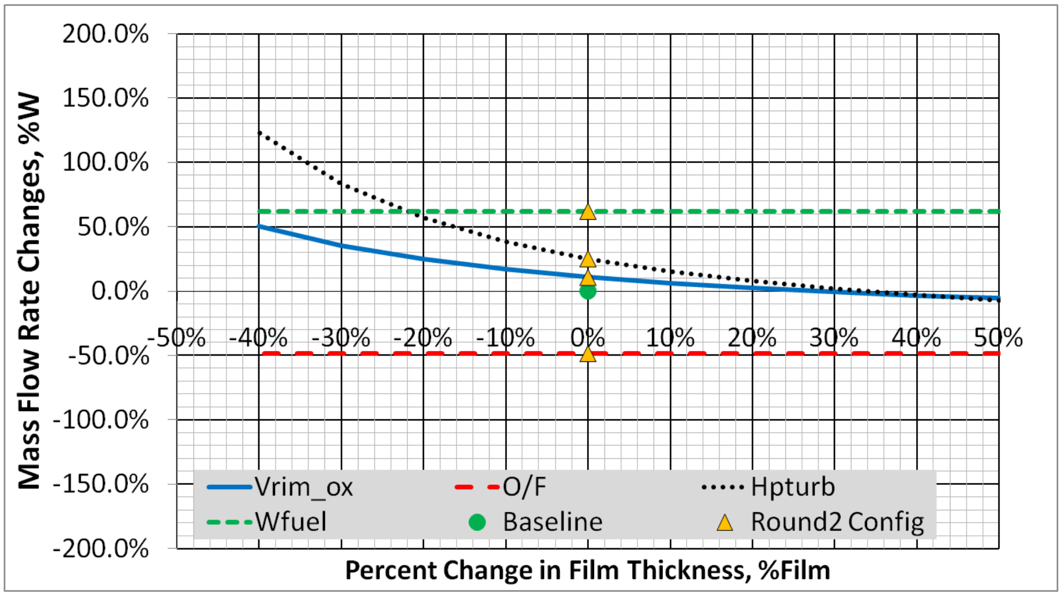


Figure 6.83 Round 2 Film Thickness Influence on Power and Mass Flow Metrics

The shaft radius metrics provide the same sensitivities as in the original study. The radii decrease as the film thickness increases, as shown in Figure 6.84.

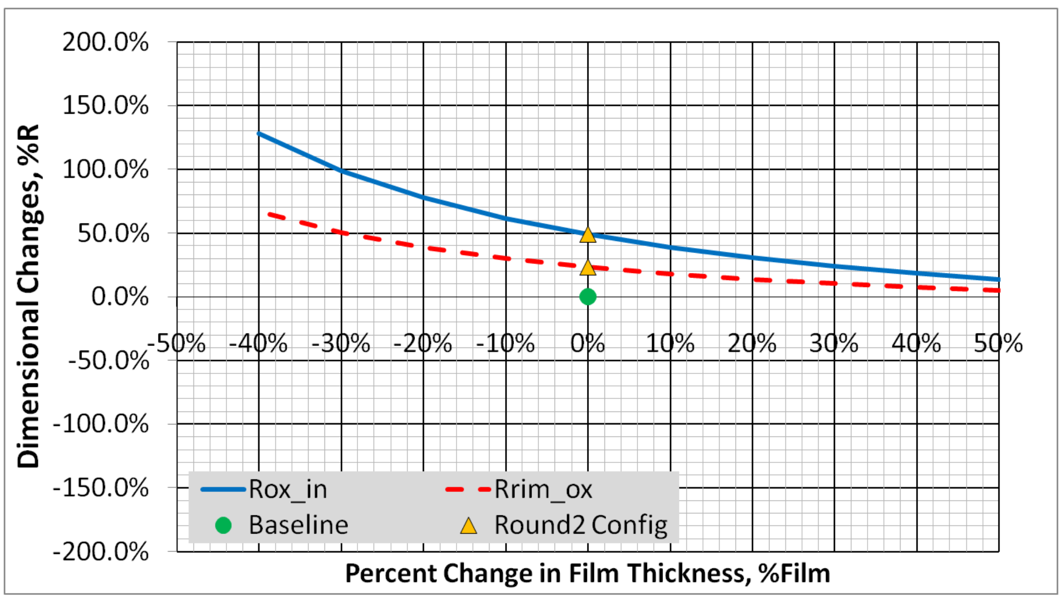


Figure 6.84 Round 2 Film Thickness Influence on Shaft Geometry Metrics

From evaluating the turbine metrics, Figure 6.85, the turbine sensitivities to the film thickness remain the same as observed previously. The turbine pressure ratio decreases as the film thickness increases, due to the decrease in the diameter of the shaft.

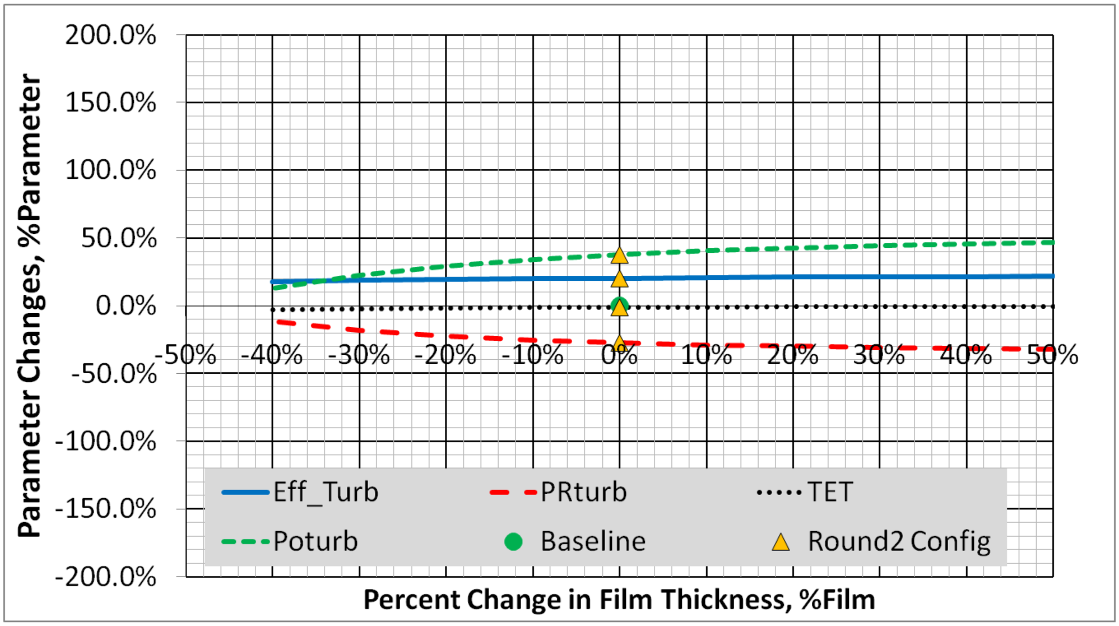


Figure 6.85 Round 2 Film Thickness Influence on Turbine Metrics

The maximum film thickness investigated was the maximum believed to be practical for the design. Any additional increase in the film thickness places an additional risk on the system in that the transition from inlet flow to solid body rotation takes on an increasingly turbulent aspect. However, setting the film thickness at the maximum predetermined limit is still considered acceptable for the remainder of the iterations.

6.1.2.3 Design Point Shaft Speed, N

The design point shaft speed parameter continues to have a strong effect on the pump efficiency, as shown in Figure 6.86. It also has a moderate influence on the diameter of the pump and on the weight of the system. In the initial survey, the shaft speed had a local minimum in weight and does so here, also. The effect is less pronounced than in the initial baseline condition but is still present.

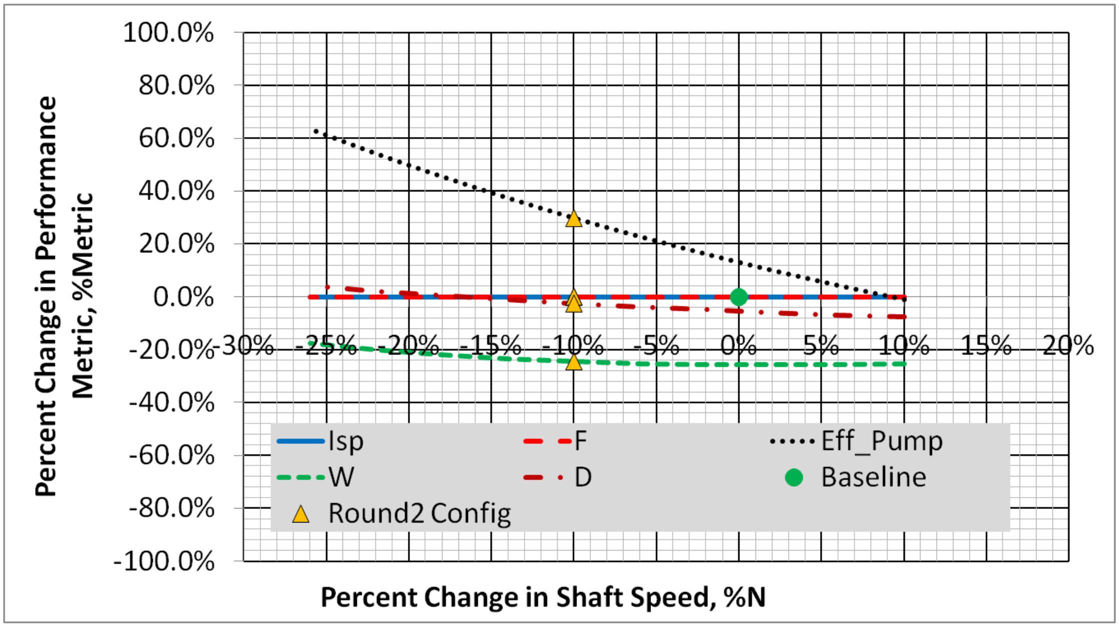


Figure 6.86 Round 2 Design Shaft Speed Influence on Overall Metrics

The mass flow rates were unaffected, while the increasing shaft speed increased the amount of power required to pump the propellants to the same pressure, as depicted in Figure 6.87. Both trends replicate the observations from the first survey.

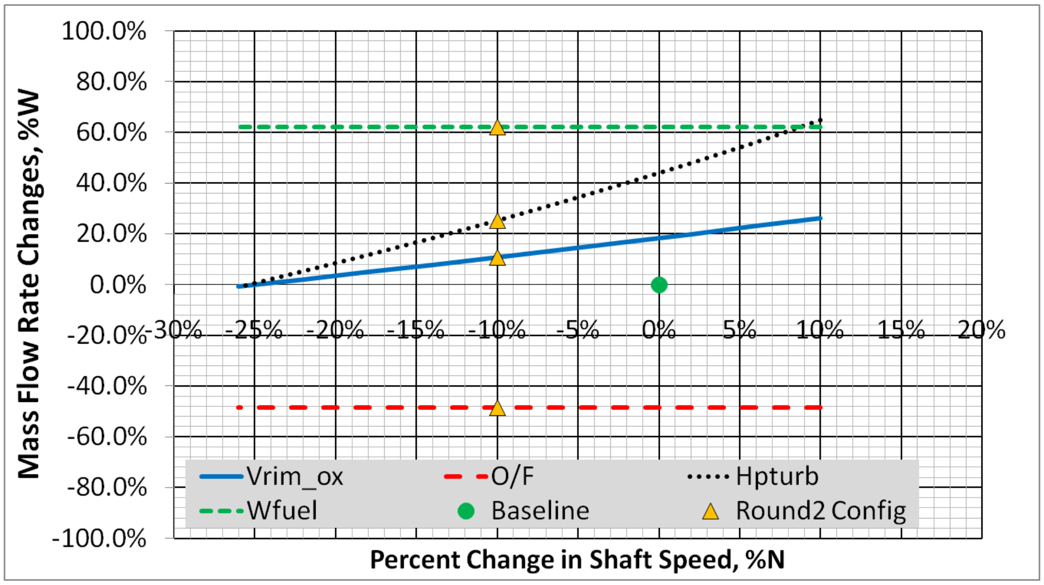


Figure 6.87 Round 2 Design Shaft Speed Influence on Power and Mass Flow Metrics

The overall diameter of the shaft decreases as the design point shaft speed increases, which is consistent with prior observations. Figure 6.88 shows the geometric responses to the design point shaft speed parameter.

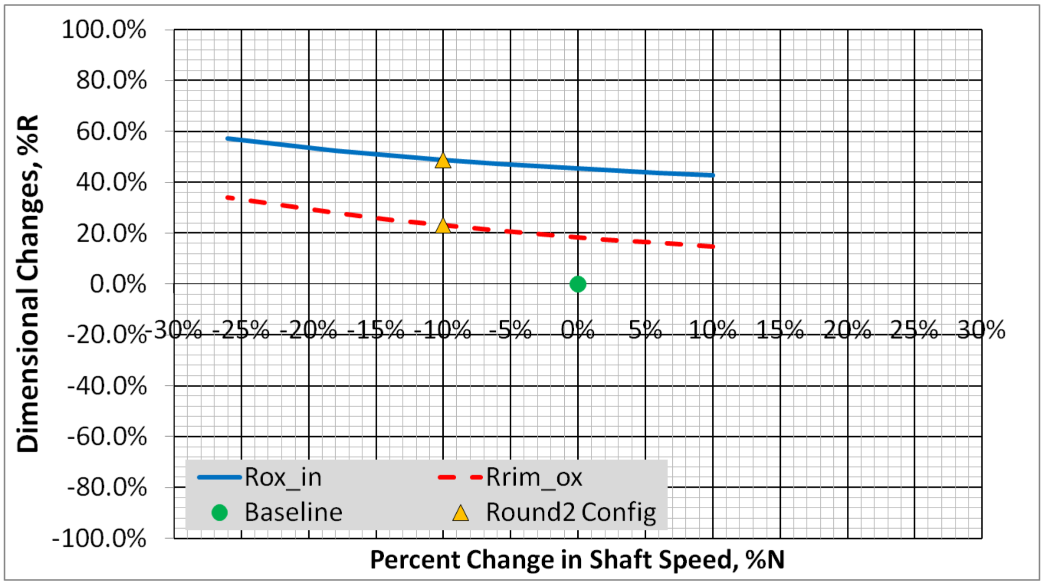


Figure 6.88 Round 2 Design Shaft Speed Influence on Shaft Geometry Metrics

The turbine parameters, illustrated in Figure 6.89, confirm that the overall turbine trends behave as they did initially. Like the previous case, the turbine exit pressure decreases as the shaft speed increases due to the rise in the turbine pressure ratio required to drive the turbine at faster shaft speeds.

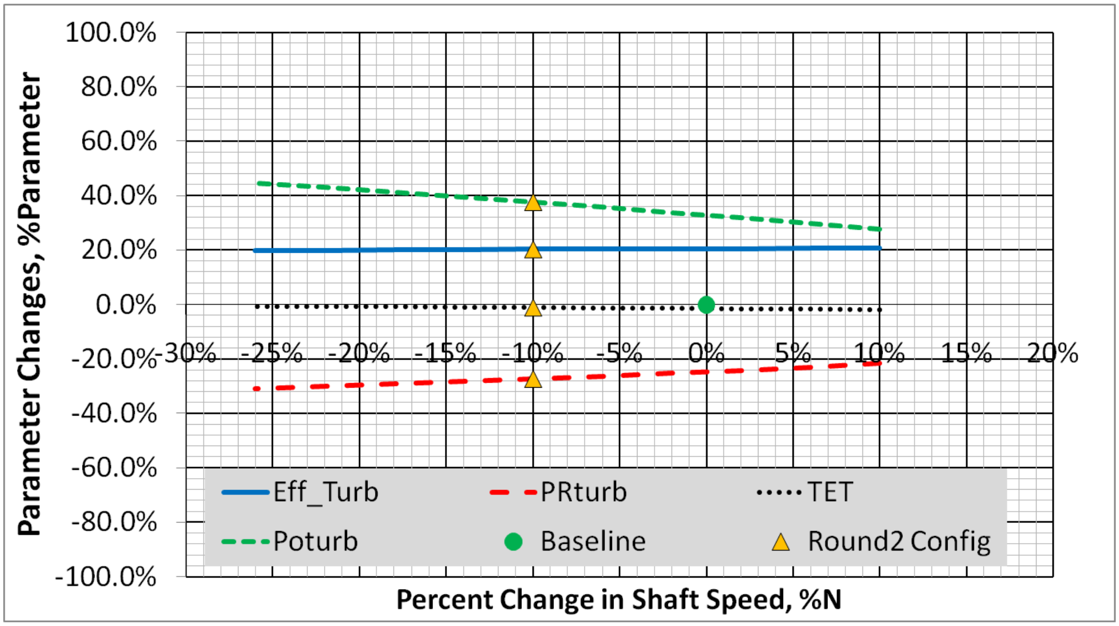


Figure 6.89 Round 2 Design Shaft Speed Influence on Turbine Metrics

The overall optimum design point shaft speed has shifted slightly in response to changing the initial configuration. The combination of design parameters selected for round two increased the initial shaft speed at which the minimum weight occurred. The design shaft speed was increased slightly for the next round of iterations.

6.1.2.4 Oxidizer Flow Split, OxSplit

For the most part, the oxidizer flow split parameter shows consistent changes in the metrics to the first study. The pump efficiency trends down with an increasing oxidizer flow split, as shown in Figure 6.90, which is consistent with the decrease in overall mass flow entering the combustor. However, the weight of the system does not appear to have a local minimum as in the initial study. The shift in the trend is a result of the changes in the design point, which eliminated some of the inefficiencies that were initially incorporated into the baseline configuration.

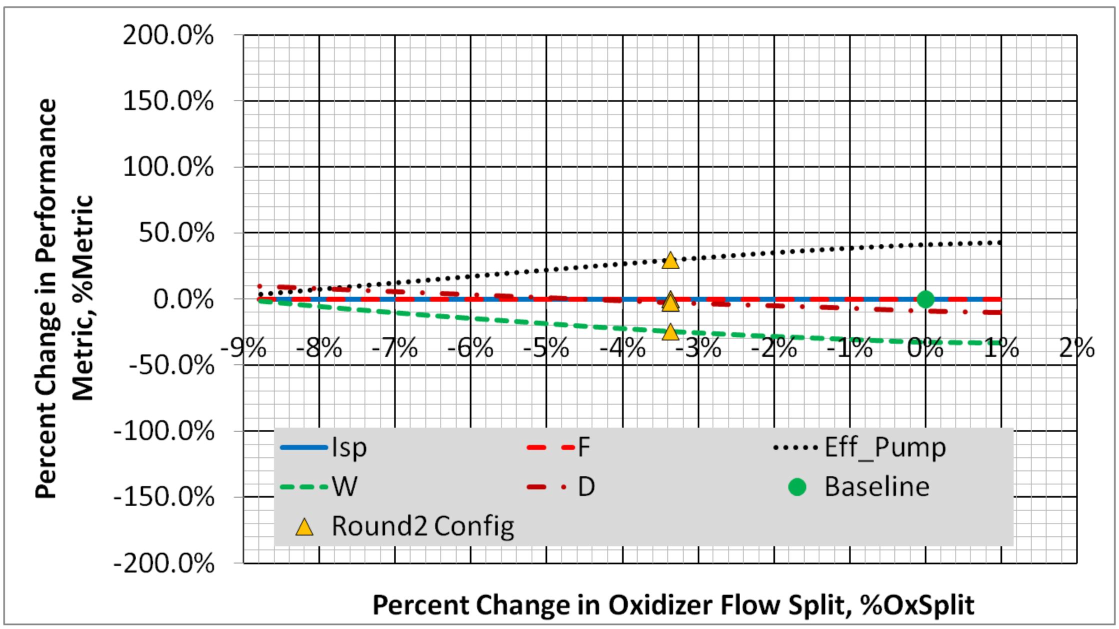


Figure 6.90 Round 2 Oxidizer Flow Split Influence on Overall Metrics

Just as in the original study, the power factors and fuel flow rate go down as the oxidizer split increases. See Figure 6.91 for the responses. The magnitude and general slopes are likewise consistent with the original observations.

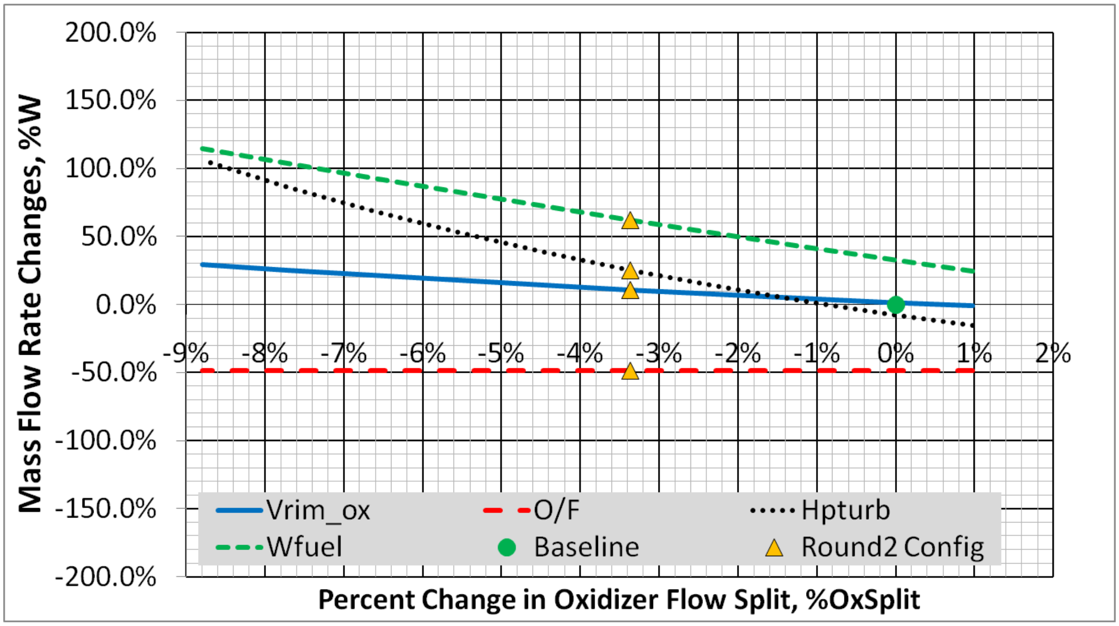


Figure 6.91 Round 2 Oxidizer Flow Split Influence on Power and Mass Flow Metrics

The geometry factors trend in the same direction as in the original study. However, because much of the geometric margin was removed after the initial study, the influence of the oxidizer flow split has increased. Figure 6.92 shows how the geometry of the oxidizer sink trap varies with the oxidizer flow split.

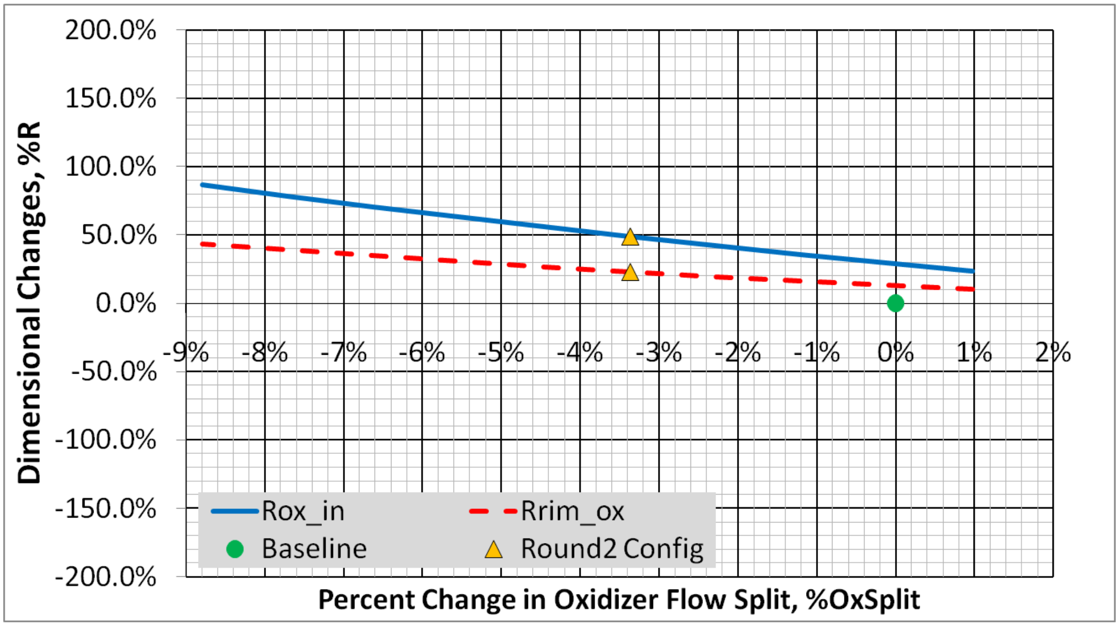


Figure 6.92 Round 2 Oxidizer Flow Split Influence on Shaft Geometry Metrics

As was the case for the changes in the geometry of the shaft, the oxidizer flow split influence on the turbine parameters changed. In this case, the sensitivity of the turbine performance metrics to the oxidizer flow split parameter decreased in comparison to the original survey, as shown in Figure 6.93. The decrease in the turbine performance explains why the system weight does not have a local minimum, since the turbine exit pressure does not change as much as in the original study.

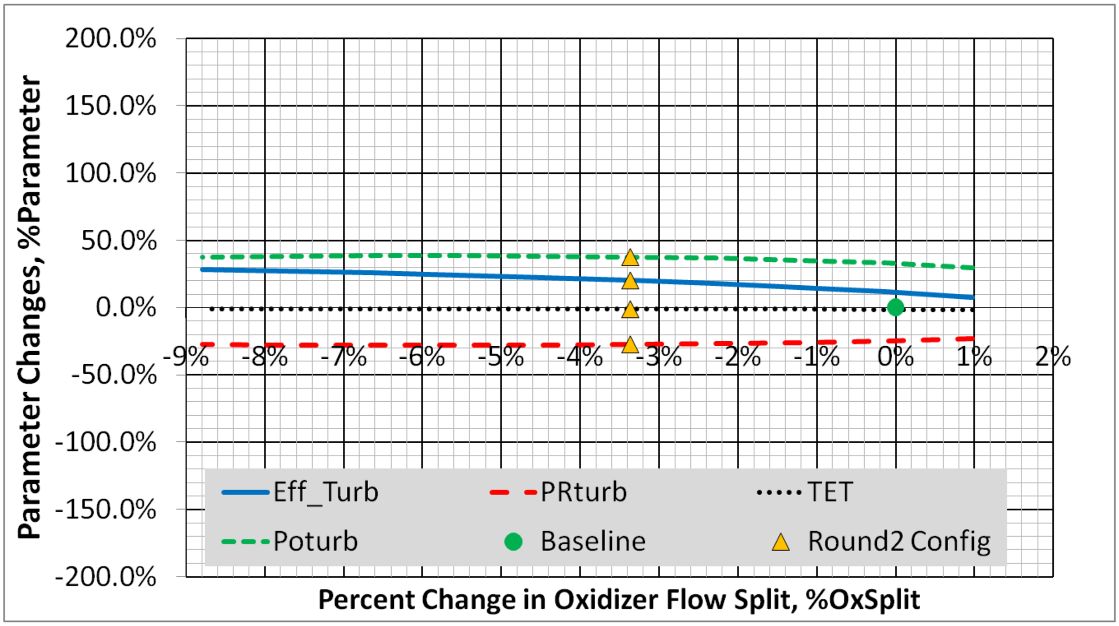


Figure 6.93 Round 2 Oxidizer Flow Split Influence on Turbine Metrics

The oxidizer flow split still has a significant impact on the overall performance metrics. However, the fact that the trends changed implies that the oxidizer flow split can combine with other parameters to have a different effect on the pump trends. Clearly, the oxidizer flow split should be included in future trade study iterations. The oxidizer flow split is set at the maximum value for the next iteration to minimize the weight of the system.

6.1.2.5 Inlet Swirl Velocity, Swirl

Inspection of the inlet swirl velocity design parameter, as it affects the overall performance metrics, reveals that the trends are almost exactly like those observed in the original study. The trends for the overall metrics are shown in Figure 6.94. Again, the trends are not strong functions of changes in inlet swirl velocity.

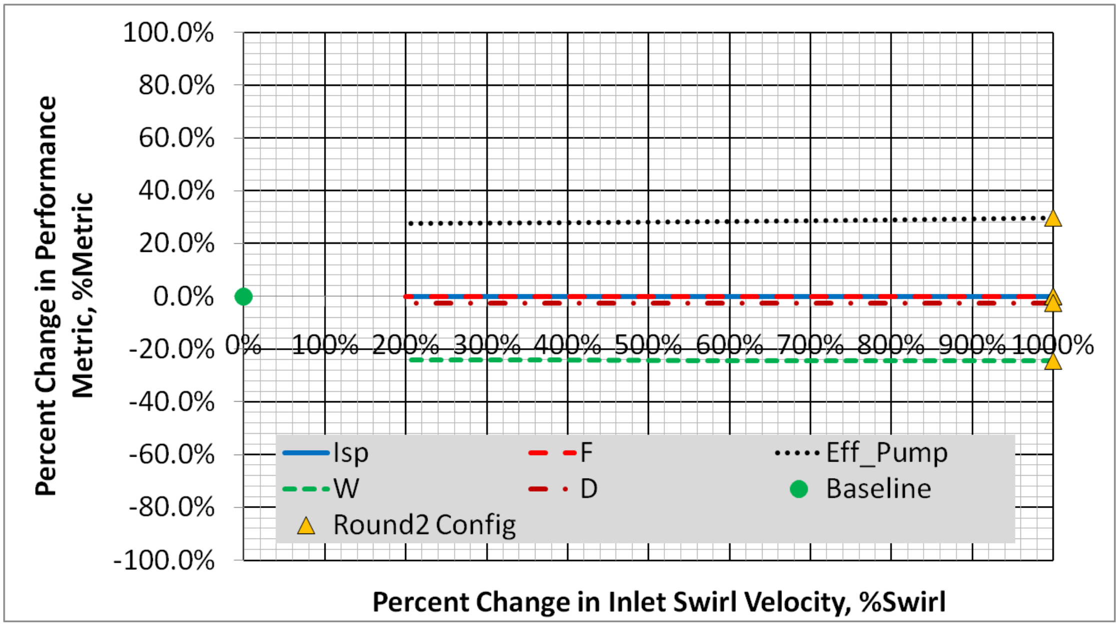


Figure 6.94 Round 2 Inlet Swirl Velocity Influence on Overall Metrics

Additionally, the responses in the metrics associated with power still do not have as large an impact as was initially presumed. The factors do not vary an appreciable amount with respect to the variation in the inlet swirl velocity parameter. Likewise, the swirl parameter does not show any significant influence on the shaft geometry. The trend is consistent with the original observations. In the original investigation, the inlet swirl velocity did have a small effect on the overall turbine parameters. However, the effect is diminished now that many of the margins have been reduced in the geometry of the pump. The responses for power, mass flow, geometry and turbine performance can be found in Appendix A.

The inlet swirl does have an impact on the overall performance and size of the pump. However, the impact is very slight and does not appear to be greatly affected by other influences or the change in the initial design point configuration. The swirl effect was set at a low value to try and make sure that there are not any undesirable effects from adding the swirl. As stated in the original study, the swirl could be increased a fair amount, but there does not appear to be a valid reason to do so.

6.1.2.6 Turbine Rotor Inlet Temperature, TRIT

In comparison to the initial results with respect to the turbine rotor inlet temperature variation, the latest iteration shows that changes in the turbine rotor inlet temperature have a greater impact on the overall metrics than in the first iteration. The changes in weight, diameter and pump efficiency over the same range indicate that the sensitivity has increased, as shown in Figure 6.95.

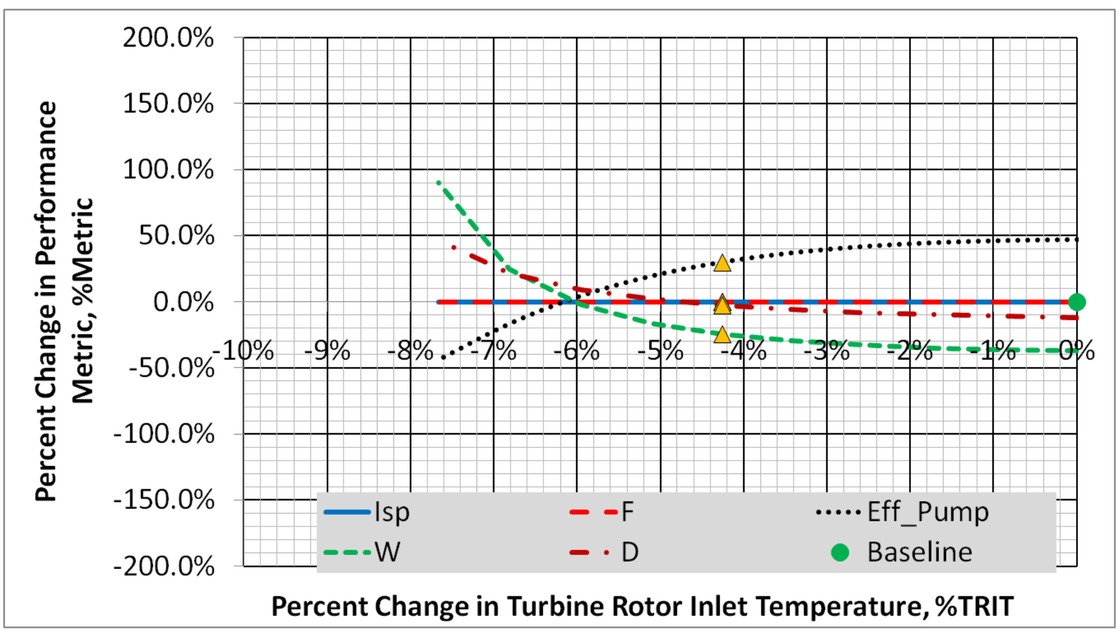


Figure 6.95 Round 2 Turbine Rotor Inlet Temperature Influence on Overall Metrics

The most dramatic changes show up in the power factors. The power demand increases from the original investigation, especially for lower turbine rotor inlet temperatures. Although, the temperature affect on the fuel flow and the oxidizer to fuel ratio does not appear to have changed appreciably from the original study. Figure 6.96 illustrates the responses of the power factors to the turbine rotor inlet temperature changes.

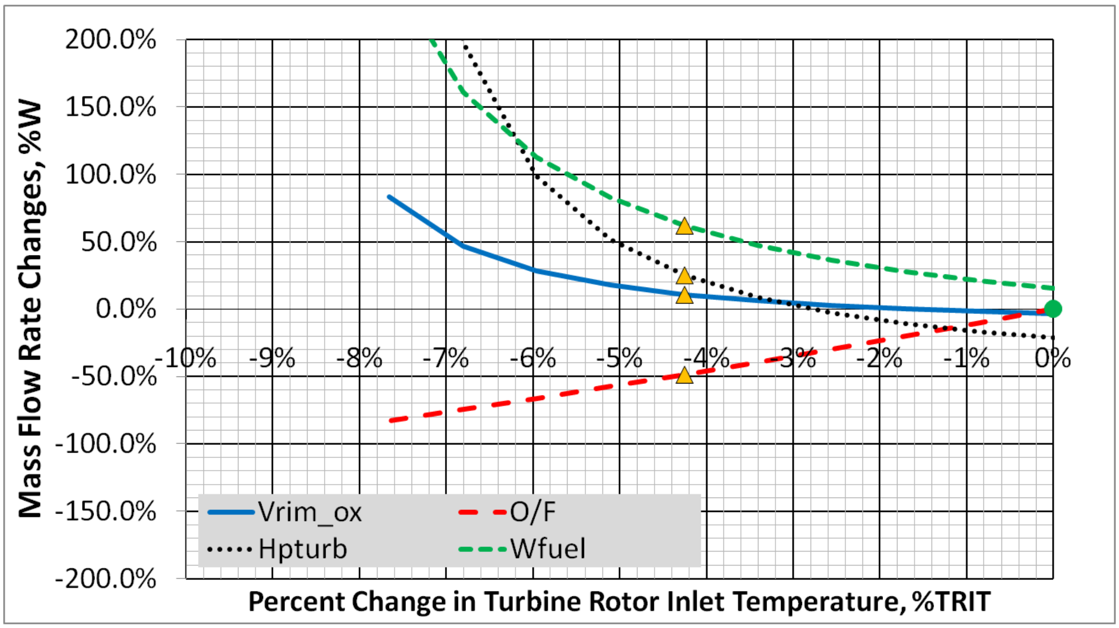


Figure 6.96 Round 2 Turbine Rotor Inlet Temperature Influence on Power and Mass Flow Metrics

In agreement with the increased sensitivity, the shaft geometry metrics, shown in Figure 6.97, also show increased responses to changes in the turbine rotor inlet temperature. The overall change in shaft radius is consistent with the decrease in the margins in the hydraulic dams and rotary injectors.

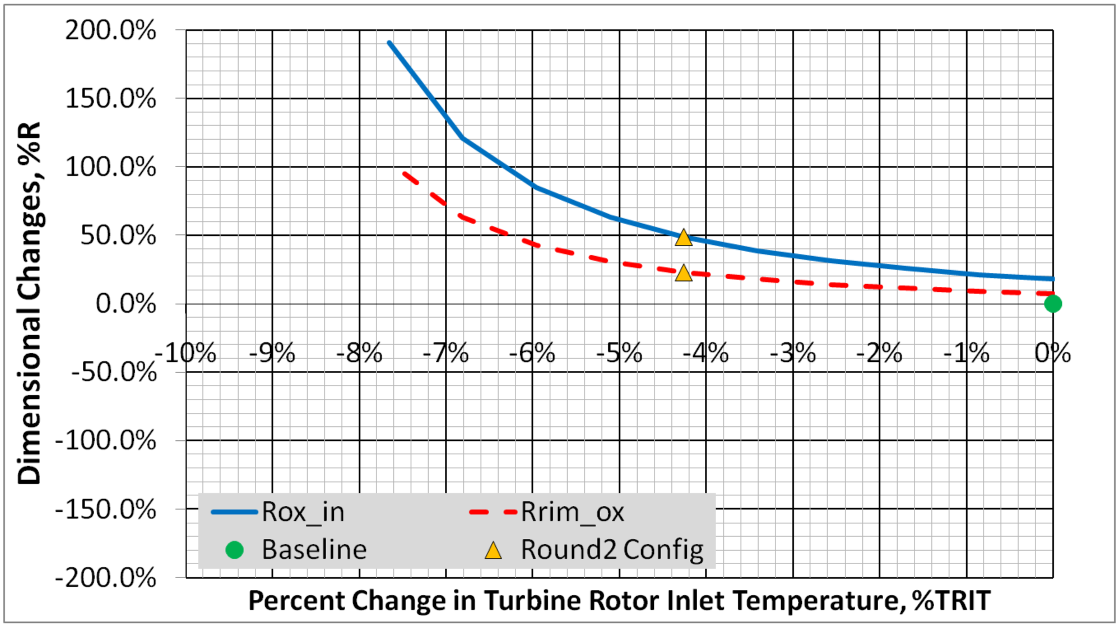


Figure 6.97 Round 2 Turbine Rotor Inlet Temperature Influence on Shaft Geometry Metrics

The most interesting change is associated with the turbine characteristics shown in Figure 6.98. The turbine efficiency trend remains consistent with the original observations. However, the pressure ratio trend did change. In the previous exploration, the pressure ratio trended downward as the turbine rotor inlet temperature decreased, with a local minimum occurring near the bottom of the temperature range. In the current survey, the pressure ratio is flat until the very bottom of the temperature range, where it begins to increase slightly.

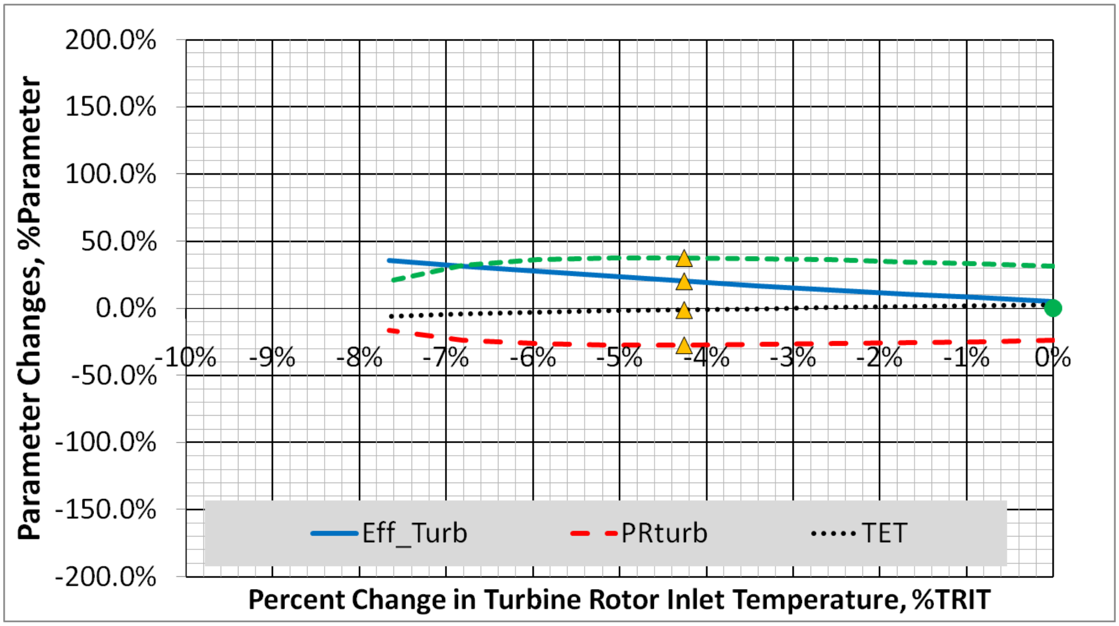


Figure 6.98 Round 2 Turbine Rotor Inlet Temperature Influence on Turbine Metrics

The turbine rotor inlet temperature is a strong driver in the performance of the pump. It will be studied further in the next iterations since it appears to have a varying affect on the system, depending on the values assigned to the other design parameters. For the next design point, the turbine rotor inlet temperature is set slightly higher to improve the weight and size of the system.

6.1.3 Third Iteration

During the second iteration, the six design parameters fell into two distinct categories based on their behavior. The first category consists of those parameters having a major impact on the metrics and may change their influences depending on the values of the other design parameters. The other category consists of those parameters that were static and/or had only minor influences on the design space. The latter category was eliminated from further evaluation, as shown in Figure 6.99. The design parameters were thus reduced from six to three.

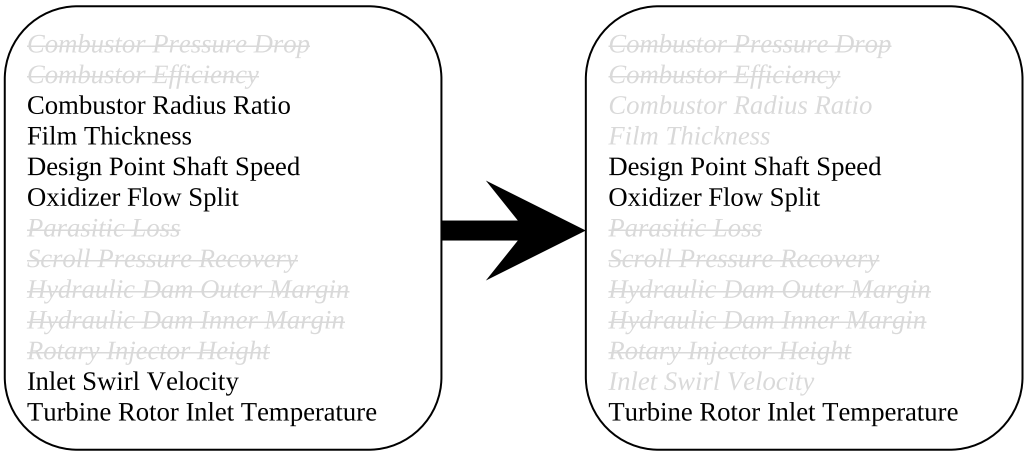


Figure 6.99 Second Round Design Parameter Elimination

In addition to eliminating three more design parameters, several of the metrics were deemed to be redundant or could be encapsulated within the responses of other metrics. The metrics eliminated at this stage of the investigation have been determined to be uninformative. The metrics reduced from fifteen to eight, as shown in Figure 6.100.

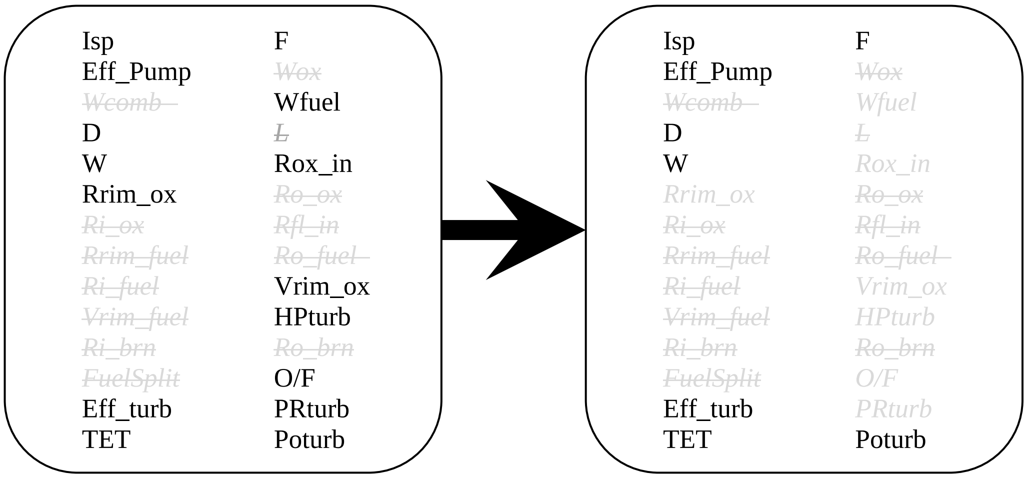


Figure 6.100 Second Round Metric Elimination

The new design point based on the second iteration does not cause problems with the CEA thrust calculations, so the thrust and specific impulse are compared for iteration number three. The eliminated design parameters had the same influences on the metrics between iterations one and two, so the thrust and specific impulse metric responses can be evaluated in round three without any loss in fidelity. Additionally, it should be noted that with the reduced number of metrics all the responses can be shown on one graph, making the evaluation much simpler. The asterisks with the yellow background represent the design point where the third series of iterations begins.

6.1.3.1 Design Point Shaft Speed, N

With the move in the design point, the design shaft speed variation reveals several trends, shown in Figure 6.101. The new design point appears to be very close to the minimum with respect to the system weight. Additionally, the pump diameter is on the lower side with respect to the design point. However, the design point configuration is also on the low side with respect to the pump efficiency. The overall trend does suggest that increasing the design shaft speed may provide some improvement.

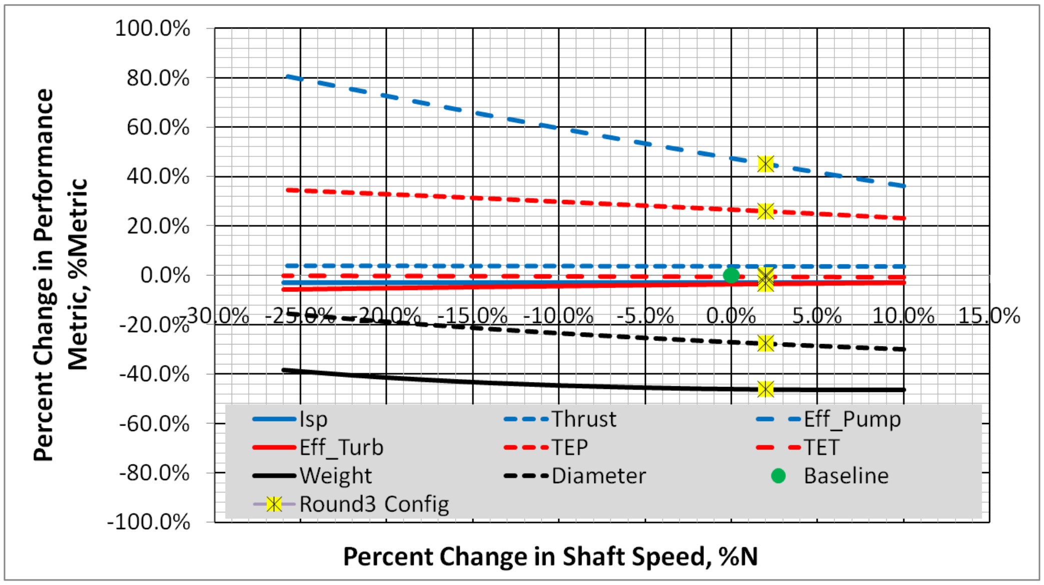


Figure 6.101 Round 3 Design Shaft Speed Influence on Metrics

6.1.3.2 Oxidizer Flow Split, OxSplit

The oxidizer flow split variation from the most recent design point reveals that there is a limit to how far the flow split can be increased. In Figure 6.102, the increase higher than approximately +4% in the oxidizer flow split drives the weight of the system to increase substantially. The weight increase is due almost entirely to the fact that the turbine exit pressure drops because of the increase in the turbine pressure ratio. The turbine pressure ratio increases due to two factors. The first is that the mass flow through the turbine drops as the oxidizer flow split increases, which means that the pressure ratio across the turbine has to increase in order to produce the same total power to drive the shaft. The second effect is that the turbine efficiency drops, which also requires an increase in the pressure ratio in order to maintain the power output. The drop in turbine efficiency is due to the decrease in the turbine exit radius indicated by the steady decrease in the pump diameter. The knee of the weight curve appears to occur at roughly +4%, so it is reasonable that the oxidizer flow split can be increased to about +2% in order to slightly improve the specific impulse.

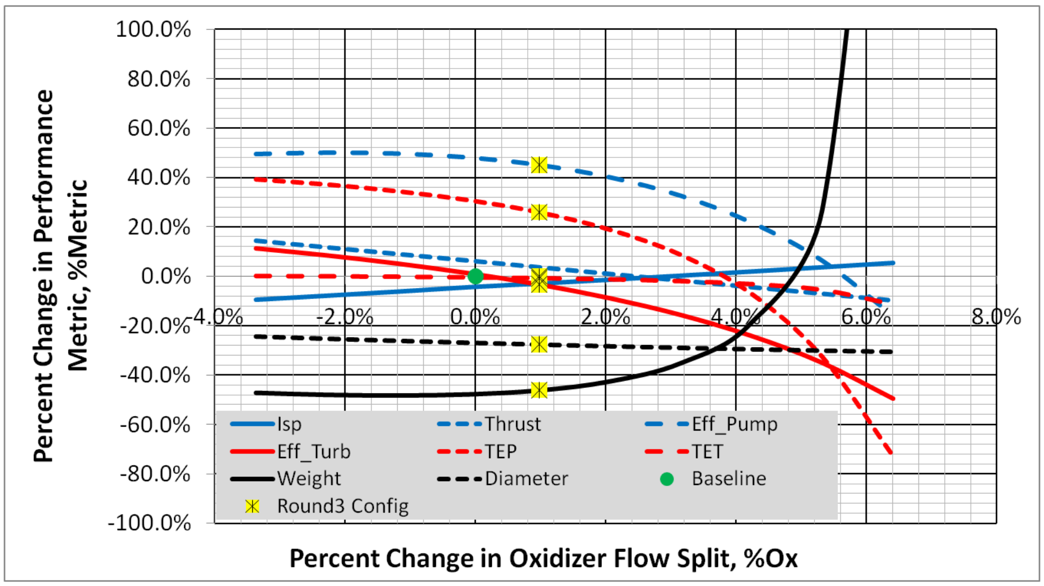


Figure 6.102 Round 3 Oxidizer Flow Split Influence on Metrics

6.1.3.3 Turbine Rotor Inlet Temperature, TRIT

The turbine rotor inlet temperature influences are shown in Figure 6.103. The trends took on yet another slightly different aspect from the previous two studies. As noted before, the turbine influences are contradictory in nature. The system weight and pump efficiency have clear optimums at a temperature slightly lower than the current design point. However, both the specific impulse and the pump diameter increase with increasing temperature. It was decided to shift the turbine rotor inlet temperature slightly lower for the next study, in favor of improving the system weight.

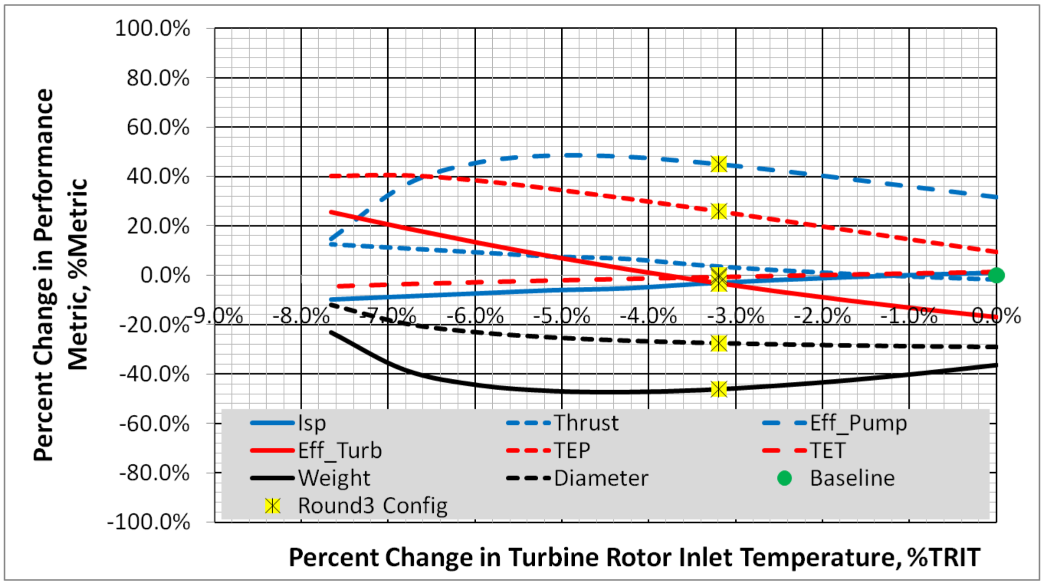


Figure 6.103 Round 3 Turbine Rotor Inlet Temperature Influence on Metrics

6.1.4 Fourth Iteration

It was observed during the third iteration that the metrics in general appeared to be more sensitive to changes in the design parameters than in the earlier iterations. The primary reason for this shift is due to the fact that many of the design parameters that have been optimized were diluting the effect of the primary factors by adding margins and buffers into the system. With the optimization of the less important design parameters, the primary factors now have a greater impact on the system.

The fourth iteration was conducted slightly differently from the first three. In the first three iteration sets, each of the design parameters was individually varied over a range of acceptable values, while the other parameters were held constant at their design point values. In the fourth iteration, the three primary design parameters were all varied simultaneously to investigate their interactions in order to select the best overall configuration. In Figures 6.104 and 6.105, the variations take the form of nested loops where the inner loop changes the oxidizer split from a slightly lower value to the design value to a slightly higher value. The looping is repeated for three different levels of turbine rotor inlet temperature: slightly lower, design point and slightly higher. Finally, the looping repeats for slightly lower shaft speed, design point shaft speed and slightly higher shaft speed. In the figures, lines are used to connect variations in the oxidizer flow split and groupings represent the turbine rotor inlet temperature variations and shaft speed variations. Each graph contains a list of cases and the combination of shaft speed, turbine rotor inlet temperature and oxidizer flow split.

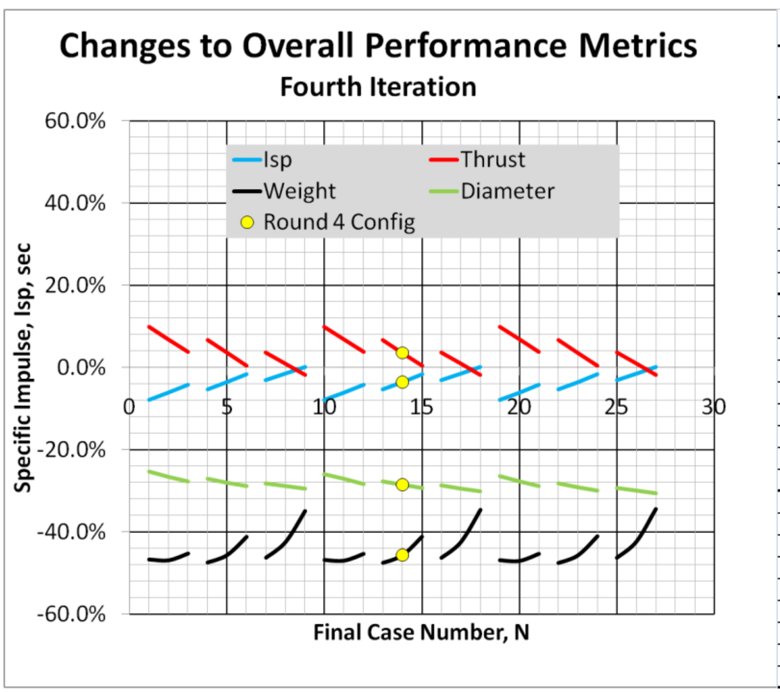


Table of Points

Case	Shaft Speed	TRIT	OxSplit
1	-	-	-
2	-	-	$OxSplit_{des}$
3	-	-	+
4	-	$TRIT_{des}$	-
5	-	$TRIT_{des}$	$OxSplit_{des}$
6	-	$TRIT_{des}$	+
7	-	+	-
8	-	+	$OxSplit_{des}$
9	-	+	+
10	N_{des}	-	-
11	N_{des}	-	$OxSplit_{des}$
12	N_{des}	-	+
13	N_{des}	$TRIT_{des}$	-
14	N_{des}	$TRIT_{des}$	$OxSplit_{des}$
15	N_{des}	$TRIT_{des}$	+
16	N_{des}	+	-
17	N_{des}	+	$OxSplit_{des}$
18	N_{des}	+	+
19	+	-	-
20	+	-	$OxSplit_{des}$
21	+	-	+
22	+	$TRIT_{des}$	-
23	+	$TRIT_{des}$	$OxSplit_{des}$
24	+	$TRIT_{des}$	+
25	+	+	-
26	+	+	$OxSplit_{des}$
27	+	+	+

Figure 6.104 Round 4 Iteration on Overall Metric Responses

The trend to look for is whether any of the combination of the three parameters provides a clear improvement in overall performance, system weight or size. According to Figure 6.104, the specific impulse increases as both the turbine rotor inlet temperature and the oxidizer flow split increase, but appears to remain flat with shaft speed. However, the curves also show that the weight of the system increases as the turbine rotor inlet temperature and the oxidizer flow split increase. The weight trend with oxidizer flow split is strong enough to promote a decrease in the overall oxidizer flow split. Interestingly, the turbine rotor inlet temperature influence on weight is greatly reduced at the lower oxidizer flow rate, so increasing the turbine rotor inlet temperature provides a net gain in specific impulse. For the shaft speed selection, the higher shaft speed does provide a slight improvement in the pump diameter. Therefore, case 25 was selected for the next configuration.

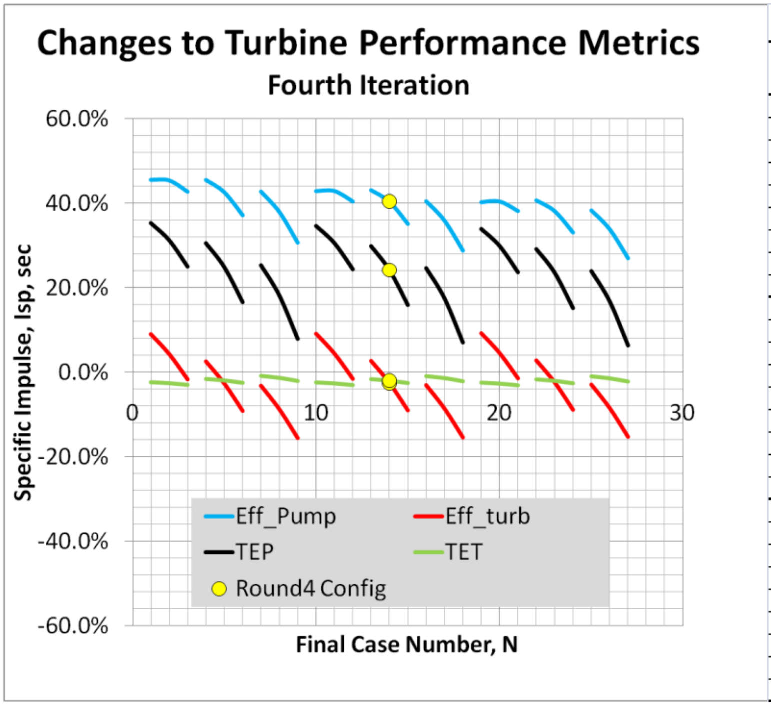


Table of Points

Case	Shaft Speed	TRIT	OxSplit
1	-	-	-
2	-	-	$OxSplit_{des}$
3	-	-	+
4	-	$TRIT_{des}$	-
5	-	$TRIT_{des}$	$OxSplit_{des}$
6	-	$TRIT_{des}$	+
7	-	+	-
8	-	+	$OxSplit_{des}$
9	-	+	+
10	N_{des}	-	-
11	N_{des}	-	$OxSplit_{des}$
12	N_{des}	-	+
13	N_{des}	$TRIT_{des}$	-
14	N_{des}	$TRIT_{des}$	$OxSplit_{des}$
15	N_{des}	$TRIT_{des}$	+
16	N_{des}	+	-
17	N_{des}	+	$OxSplit_{des}$
18	N_{des}	+	+
19	+	-	-
20	+	-	$OxSplit_{des}$
21	+	-	+
22	+	$TRIT_{des}$	-
23	+	$TRIT_{des}$	$OxSplit_{des}$
24	+	$TRIT_{des}$	+
25	+	+	-
26	+	+	$OxSplit_{des}$
27	+	+	+

Figure 6.105 Round 4 Iteration on Pump and Turbine Metric Responses

6.2 Initial Operability

Operability is a concept associated with running the pump simulation at conditions other than at their design point. Using NPSS™ this is referred to as running in off design mode. The difference in the two modes of operation relate to how the simulation solves the characteristic equations provided in Chapter 4. In design point mode, the characteristic equations are solved for geometric values such as radii, passage size, throat areas, etc. based on input performance values such as mass flow rate, desired pressure change, film thickness, etc. In off design mode, the characteristic equations are rearranged such that the simulation uses the geometric values obtained in the design point mode to calculate the performance parameters. The off design mode contains changes to the basic input parameters to represent the same device operating with different feed pressures, mass flow rates and/or inlet temperatures.

The initial operability of the pump was evaluated by adjusting the fuel and oxidizer flow rates independently. As discussed earlier, the flow rates into the pump can be independently varied using pulsing inlet valves. Thus, a wide range of operating flow rates can be evaluated. The runs were made by nesting the loops over the desired ranges of fuel flow rates and oxidizer flow rates.

The operability is defined by three parameters from the output of the simulation. The first and most important is the inner radius of the propellants within the hydraulic dams with respect to the inner shaft inner radius. When the fluid level is smaller than the inner radius of the inner shaft, then the hydraulic dam fails to work properly. The second is the turbine rotor inlet temperature. If the temperature increases beyond the capability of the material, then the operating condition is unlikely to be feasible. Finally, the shaft speed itself is a limit, although it is something of a soft limit, since the shaft can likely be designed to overcome some simple variations in shaft speed.

After the cases were run, it was immediately clear that the pump would not operate at any condition other than the design point. At every point other than the design point, one or both of the hydraulic dams flooded. The term flooded is used to describe what happens when the inner fluid radius of a hydraulic dam is smaller than the inner radius of the inner shaft. Based on that one observation, it is clear that the design has to be adjusted in order to make a functioning pump.

6.3 Design Evolution

Adjusting the design approach consisted of reviewing what needed to be adjusted in order to arrive at a concept that would provide adequate design performance, size and weight, while providing a wide range of operability. The approach taken was to increase the hydraulic dam inner margin since that value most directly contributes to the amount of excess distance the fluids in the hydraulic dam have before they flood the dams.

However, it was also recognized that adding a reasonable margin to the pump design would drive up the shaft diameter and system weight. Therefore, it was decided that an additional design parameter needed to be incorporated into the pump. The additional design parameter is back swirl in the rotary injectors. Back swirl is sometimes added to conventional pumps to produce a more efficient design, but at a reduced pressure ratio [3]. The approach makes sense for the same reasons plus one other. If enough back swirl is added to the design, the collection scrolls may provide some recovery of the dynamic head as the tangential velocity may drop to where the propellant flows can be successfully diffused [68].

6.3.1 Hydraulic Dam Inner Margin, %HydMargin

As mentioned above, the desire to have an operable pump leads to the need to increase the hydraulic dam inner margin. Using the results from the operability evaluation, the amount of margin needed was estimated, based on the maximum amount of flooding observed. Thus, the intent was to increase the margin to accommodate the worst case flooding already witnessed. However, it should be noted that the value is just an estimate and will likely not translate into pump operability at every operating point.

6.3.2 Rotary Injector Back Swirl, %Back

When the hydraulic dam inner margin is added to the design, a new design configuration is created for round five. The configuration is identical in every way to the round four configuration, except for a modest increase in the diameter. The margin increase is relatively small, but does have an effect.

Similar to what was done on the other systematic variations; the design point is run with variations in only the back swirl parameter to evaluate the type of influence back swirl has on the major metrics. As can be seen in Figure 6.106, the most notable change is in the performance of the pump. Increasing the back swirl reduces the power required by the turbine, which increases the turbine exit pressure. The pump efficiency increases five times its base value and the weight decreases by almost 20% for a fivefold increase in the back swirl angle.

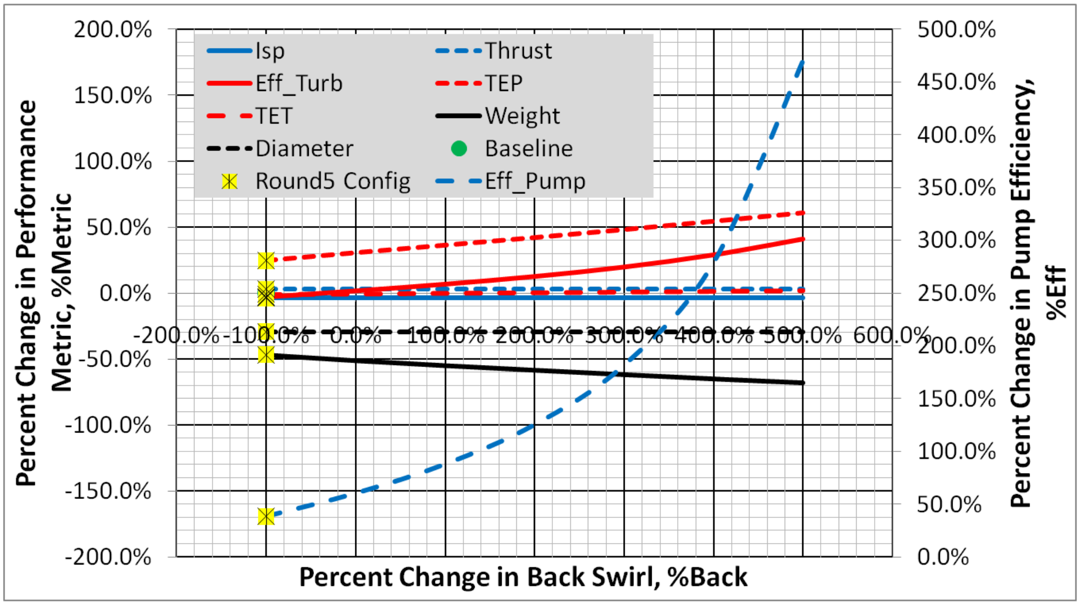


Figure 6.106 Round 5 Rotary Injector Back Swirl Influence on Metrics

The trends suggest that the maximum back swirl that can be achieved is ideal. Thus, the design was reviewed and the maximum practical back swirl angle was used based on manufacturing limitations, such as channel length and angle into the outer shaft.

6.4 Second Pass

With the definition of a new parameter, a portion of the initial study has to be rerun to determine how the new parameter affects the metric responses. Thus, a sixth design point was defined based on the design parameters set at the same value as the fifth configuration, plus setting the back swirl parameter to the maximum possible.

6.4.1 Sixth Iteration

It was decided, that it was unnecessary to redo the entire study, but rather only investigate the major design parameters, plus one other. The other design parameter is the scroll recovery factor. Recalling that the scroll recovery design parameter was set to not recover any of the dynamic head achieved by the rotary injectors due to the high tangential velocity, it is clear that the assumption should be revisited. With back swirl, the tangential velocities may be low enough for the collection scrolls to diffuse the main propellant flows.

6.4.1.1 Design Point Shaft Speed, N

The investigation of the design shaft speed influence is shown in Figure 6.107. In comparing the responses of the metrics to the earlier responses of the metrics, it is clear that weight, diameter and pump efficiency behave differently. Previously, the pump efficiency was influenced by increasing the shaft speed, but now the influence is much stronger due to the overall increase in pump efficiency with back swirl. As the shaft speed increases, the improvement due to back swirl is completely undermined reducing the pump efficiency. The other metrics of diameter and weight show that decreasing the design shaft speed would result in a sharp increase in the weight and diameter, while an increase in shaft speed would reduce both. As a result, the design shaft speed will be increased slightly for the next round.

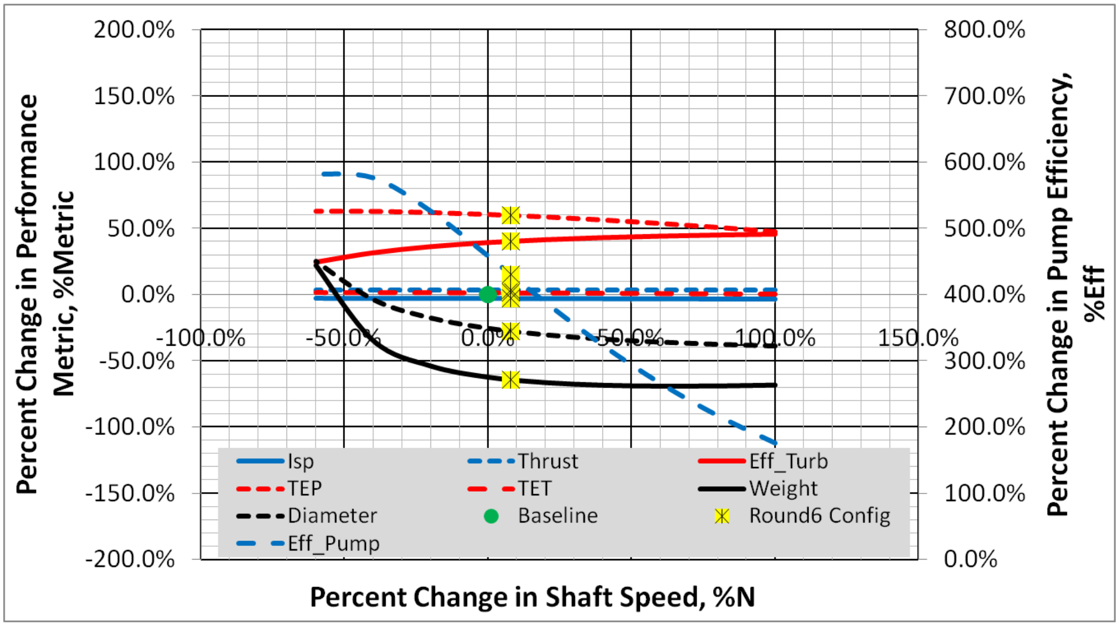


Figure 6.107 Round 6 Design Shaft Speed Influence on Metrics

6.4.1.2 Oxidizer Flow Split, OxSplit

A review of the oxidizer flow split affect on the key metrics reveals that the oxidizer flow split also changed behavior as shown in Figure 6.108. Previously, increasing the oxidizer flow split resulted in sharp increases in weight and sharp decreases in the turbine exit pressure resulting in pump efficiency losses. However, with the addition of the back swirl, the turbine power requirements have dropped so far that the overall detriment of decreasing the mass flow into the combustor is no longer as important as in the previous studies. Thus, the pump efficiency improves with increasing oxidizer split because the total pumped mass flow drops. The decrease in total mass flow also allows the shaft diameter to decrease providing even more benefit as the smaller shaft diameter lowers the overall shaft power further. The oxidizer flow split was subsequently left unaffected for the next round as there is not a clear optimum.

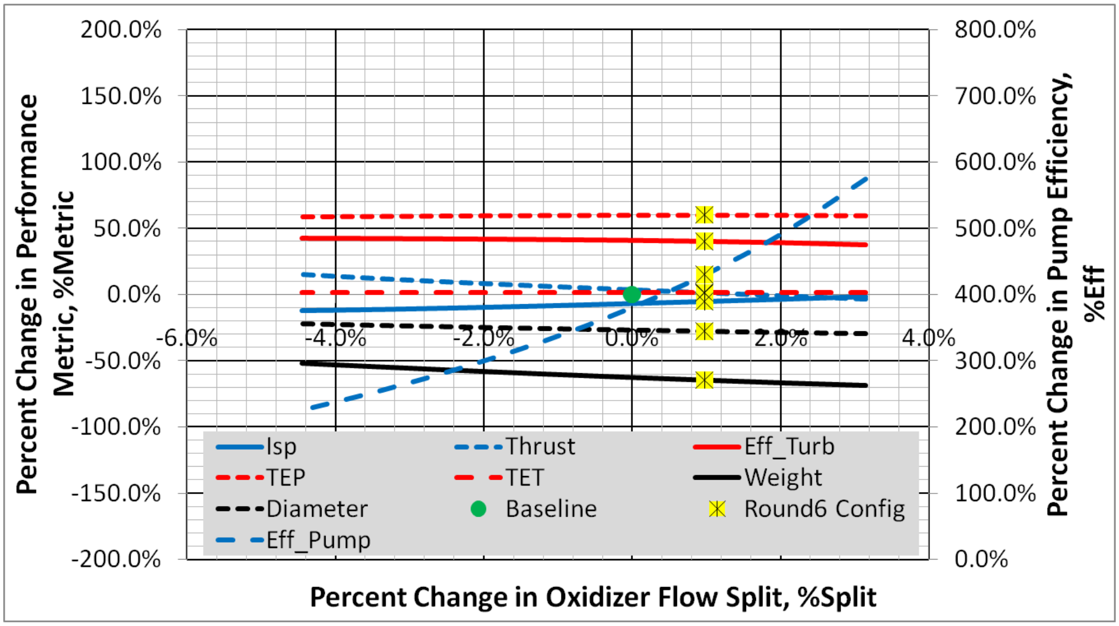


Figure 6.108 Round 6 Oxidizer Flow Split Influence on Metrics

6.4.1.3 Scroll Pressure Recovery, Recovery

In the earlier review of the scroll pressure recovery, it was observed that the weight of the system increased rapidly as the recovery increased. The trend was because as the recovery increased the turbine exit pressure decreased, which increased the size of the rocket chamber and nozzle. Figure 6.109 shows that the same trend is not present in the configuration with back swirl. The overall trend indicates that the decrease in the turbine pressure ratio from the initial design is enough to offset the decrease in the exit pressure. Thus, the increase in the weight is modest in comparison to the earlier studies. Even though the exit velocities decreased as a result of adding back swirl, it was felt that the recovery characteristics for the scrolls should still be maintained at a conservative value, only recovering 20% of the dynamic head.

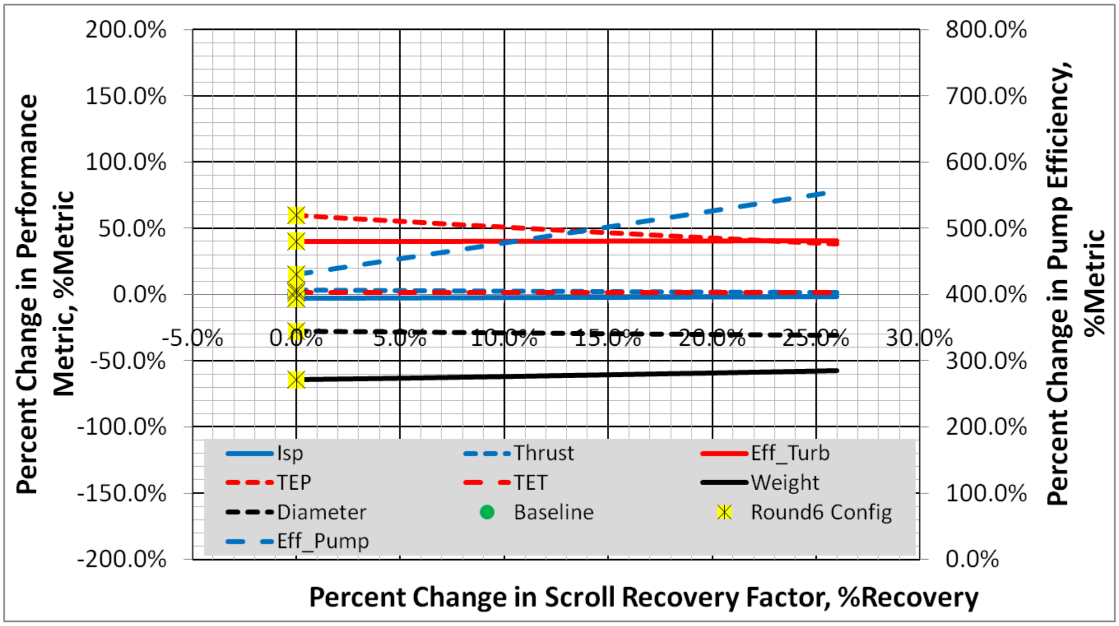


Figure 6.109 Round 6 Scroll Recovery Influence on Metrics

6.4.1.4 Turbine Rotor Inlet Temperature, TRIT

Recalling that the turbine rotor inlet temperature appeared to have the largest impact on the main metrics will illustrate how the sensitivity of the pump has changed with the addition of back swirl. Previously, the turbine rotor inlet temperature showed trends in weight and pump efficiency that revealed local optimums. In the current responses, shown in Figure 6.110, the pump efficiency and system weight appear to keep improving as the temperature increases. Likewise, the diameter of the pump decreases with increasing temperature. The reason for the overall change in behavior is credited to the improvement in pump efficiency allowing the turbine power and pressure ratio to drop. The turbine rotor inlet temperature was increased slightly for the next round.

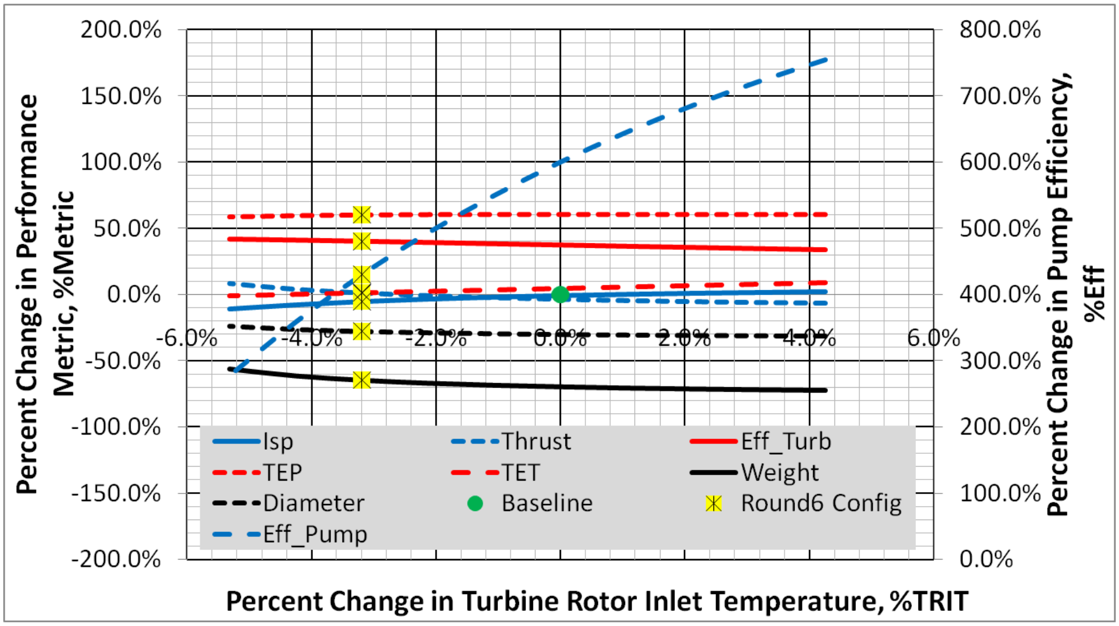


Figure 6.110 Round 6 Turbine Rotor Inlet Temperature Influence on Metrics

6.4.2 Seventh Iteration

The seventh iteration in the process established the responses of the metrics to the three main design parameters after the inclusion and setting of the scroll recovery value. At the conclusion of the sixth iteration, the design shaft speed, oxidizer flow split and the turbine rotor inlet temperature were not changed significantly, in spite of the fact that the response indicated that changing them by larger amounts would be beneficial. The reason is that the recovery parameter may influence how the three main parameters affect the metrics, so it was decided to establish a new design point with recovery being the only major change. From the new design point, the normal variations and investigations reveal the appropriate responses.

6.4.2.1 Design Point Shaft Speed, N

With the inclusion of scroll recovery, the metric variations with shaft speed end up being much less severe in nature, as shown in Figure 6.111. The rapid increases in diameter and weight with decreasing shaft speed largely disappeared. Moreover, the slope decreased for changes in the pump efficiency metric. Thus, it appears that the best location for the design shaft speed is higher than the original configuration. The shaft speed for the next iteration was increased by almost 50% to take advantage of the broad flat in the system weight metric response.

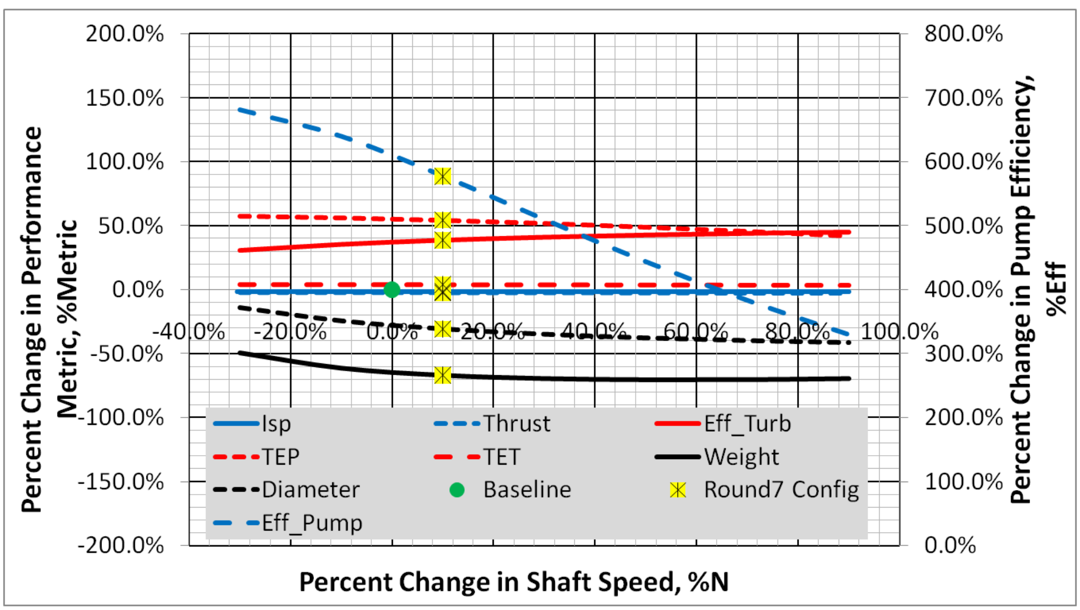


Figure 6.111 Round 7 Design Shaft Speed Influence on Metrics

6.4.2.2 Oxidizer Flow Split, OxSplit

For the oxidizer flow split, the trends remain the same as in the previous run with the exception of the pump efficiency. The general slope of the pump efficiency change is in line with the earlier run, but the overall efficiency level is lower, as can be seen in Figure 6.112. Since the metric responses are fairly flat, it was decided to leave the oxidizer flow split near the current value for the next iteration.

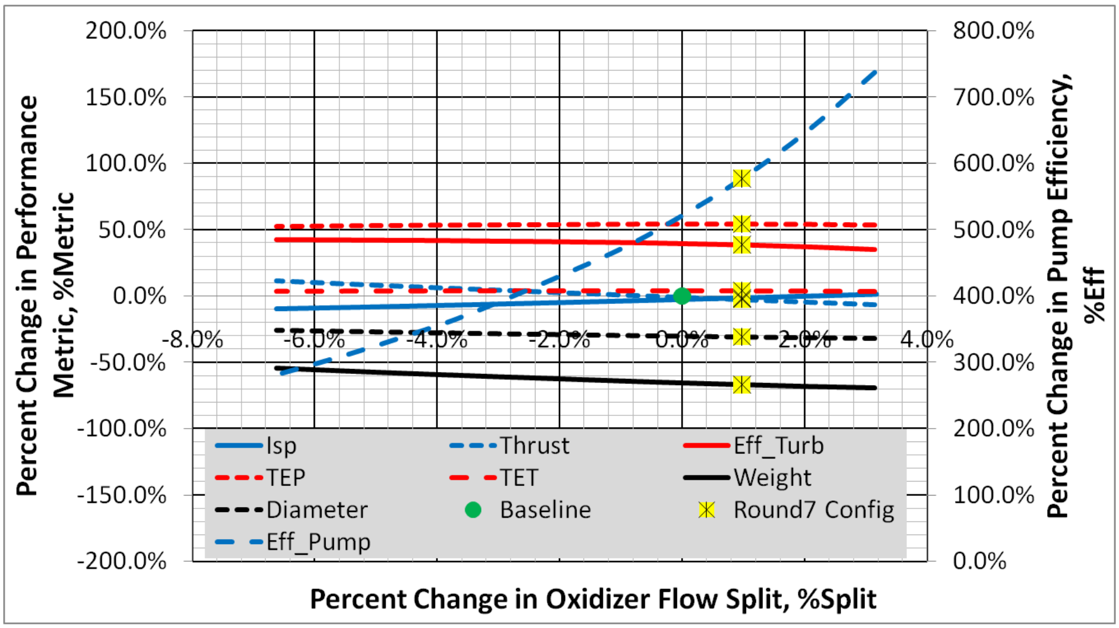


Figure 6.112 Round 7 Oxidizer Flow Split Influence on Metrics

6.4.2.3 Turbine Rotor Inlet Temperature, TRIT

As with the design shaft speed and the oxidizer flow split, the turbine rotor inlet temperature appears to have changed how it affects the metrics. Inspection of Figure 6.113 reveals that the metrics do not respond as strongly to changes in the turbine rotor inlet temperature as in the last iteration. However, there is still a clear advantage in specific impulse, weight and pump efficiency that can be gained by increasing the turbine rotor inlet temperature, so the temperature was increased a modest amount for the next iteration.

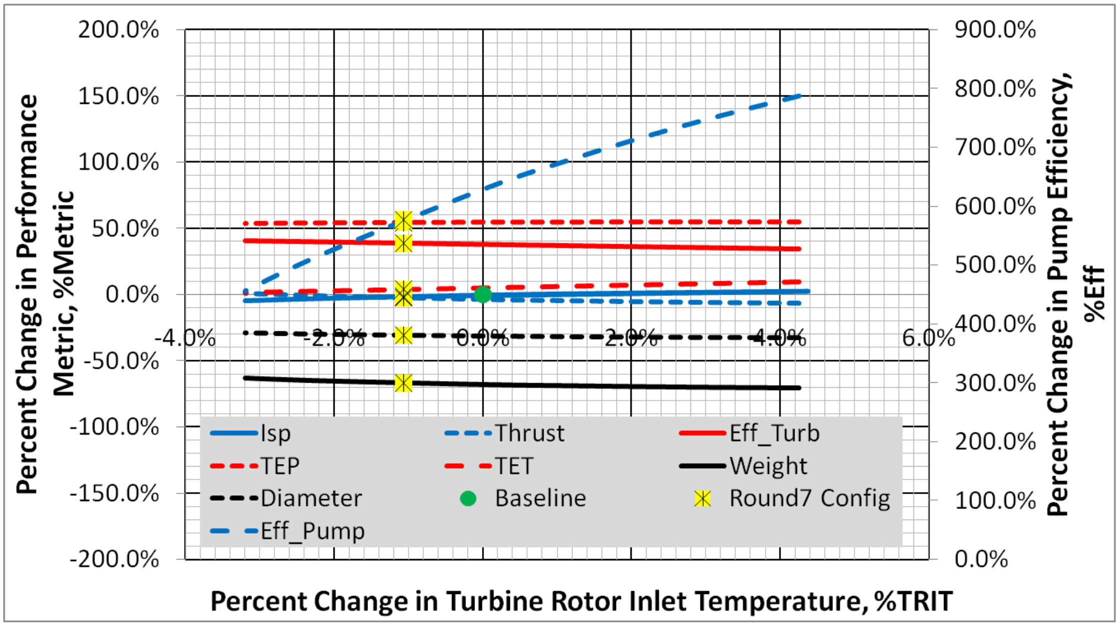


Figure 6.113 Round 7 Turbine Rotor Inlet Temperature Influence on Metrics

6.4.3 Eighth Iteration

The eighth iteration verifies that the iterations are zeroing in on the optimum design for the pump. During the process, it is noted that the design parameters do have different effects on the metrics than in the first attempt. Generally, the trends are much less sensitive to variations in the design parameters, which is generally good for the robustness of the concept.

6.4.3.1 Design Point Shaft Speed, N

After increasing the shaft speed, it is evident that the shaft speed selected is nearly optimum for the new configuration in that the minimum of the weight curve is now at the new design point. Figure 6.114 also confirms that there is not a great deal of sensitivity in the design to modest variations in shaft speed in either direction. The final shaft speed is kept at the design point value.

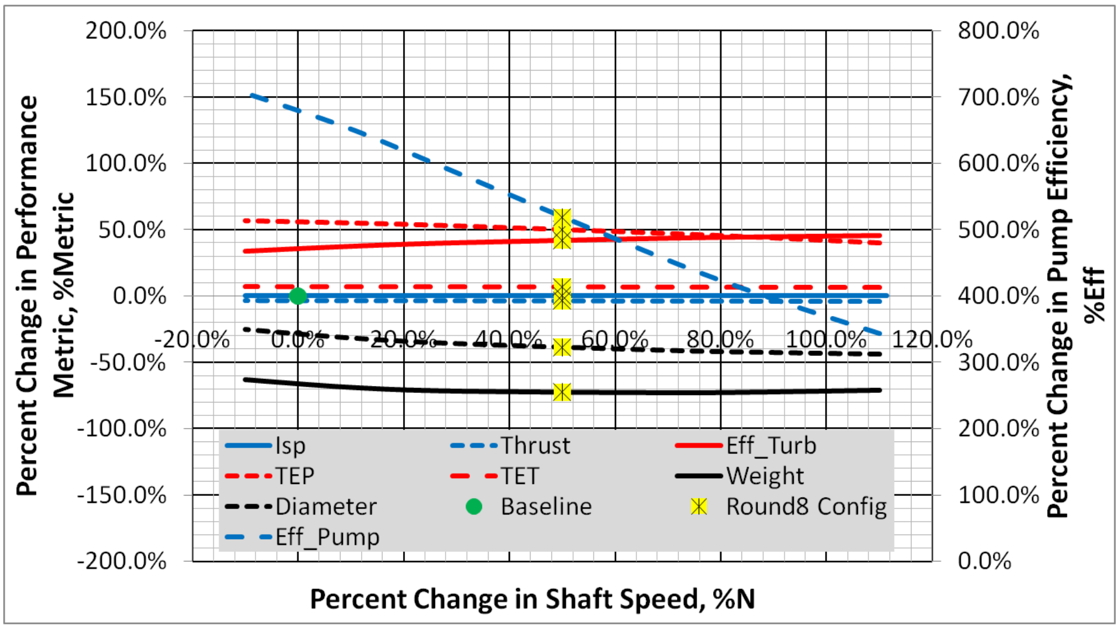


Figure 6.114 Round 8 Design Shaft Speed Influence on Metrics

6.4.3.2 Oxidizer Flow Split, OxSplit

Similar to the design shaft speed are the trends, shown in Figure 6.115, for the metric responses to changes in the oxidizer flow split. Higher values tend to show a slight improvement in specific impulse, system weight, pump efficiency and pump diameter. However, the effect is not large so the oxidizer flow split parameter was only adjusted upward a small amount. It is interesting to note that the oxidizer flow split seems to be oscillating around the point that it will be set for the final configuration.

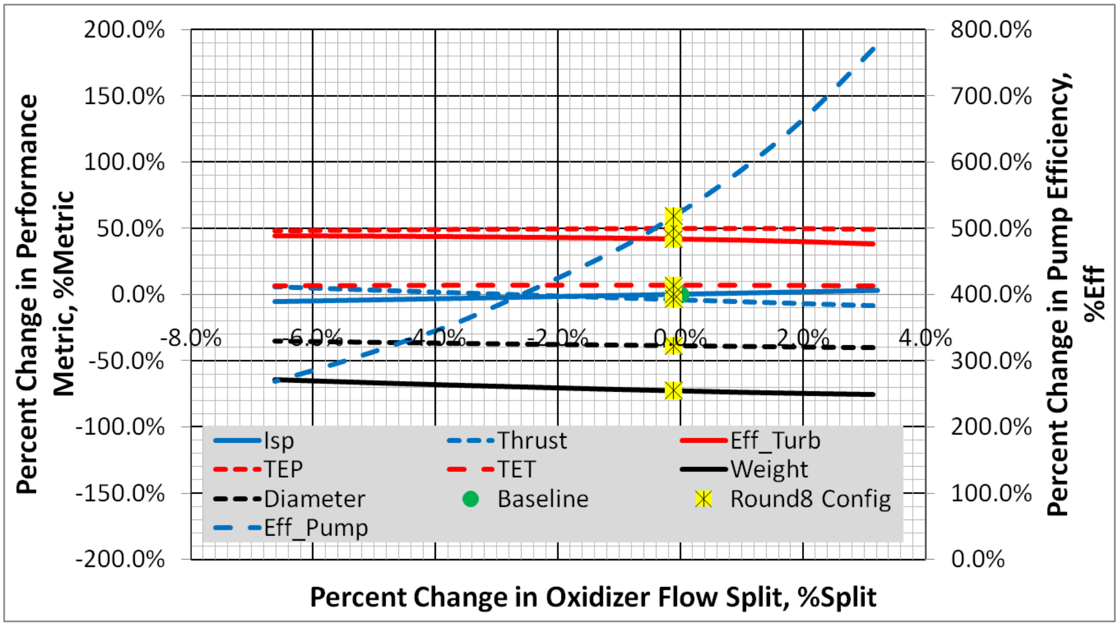


Figure 6.115 Round 8 Oxidizer Flow Split Influence on Metrics

6.4.3.3 Turbine Rotor Inlet Temperature, TRIT

The metrics in Figure 6.116 show the same trends and magnitude shifts for changes in turbine rotor inlet temperature as they did in the last iteration. Overall, the pump becomes more attractive as the turbine rotor inlet temperature increases. However, in order to try and ensure that there is an operable range, the temperature was set lower than the current design point, to prevent the combustor from getting into an over temperature condition.

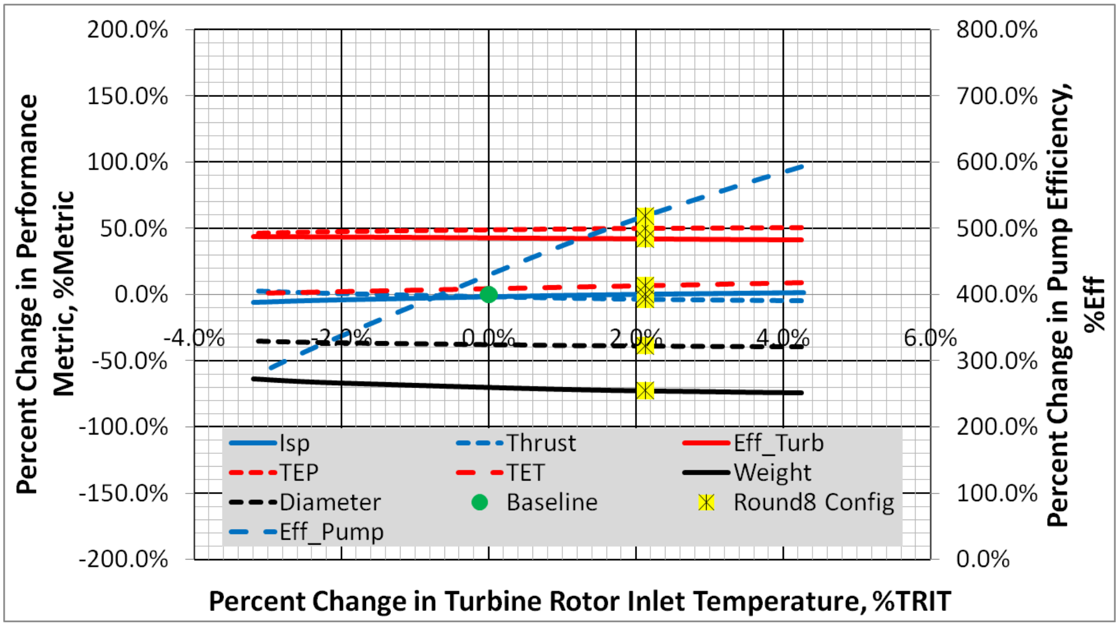


Figure 6.116 Round 8 Turbine Rotor Inlet Temperature Influence on Metrics

6.5 Operability

Operability of the pump depends on running the final configuration through a range of mass flow rates and oxidizer to fuel ratios. As stated earlier, the evaluation of whether the pump is operable at a particular condition depends on whether or not one of the hydraulic dams floods, the turbine rotor inlet temperature exceeds its limit or whether the shaft speed exceeds its limit. The turbine rotor inlet temperature limit is based on the material properties of the turbine and combustor. The shaft speed limit is based on the maximum rim speed not exceeding the self-sustaining stresses of a disk.

The first check is to determine the conditions where the oxidizer hydraulic dam floods. Figure 6.117 shows the map of the hydraulic dam operating conditions. The hydraulic dam operates properly for all cases above the limit plane. As can be seen, the operating range is acceptable for all operating conditions run except the high oxidizer to fuel ratios and low mass flow rates.

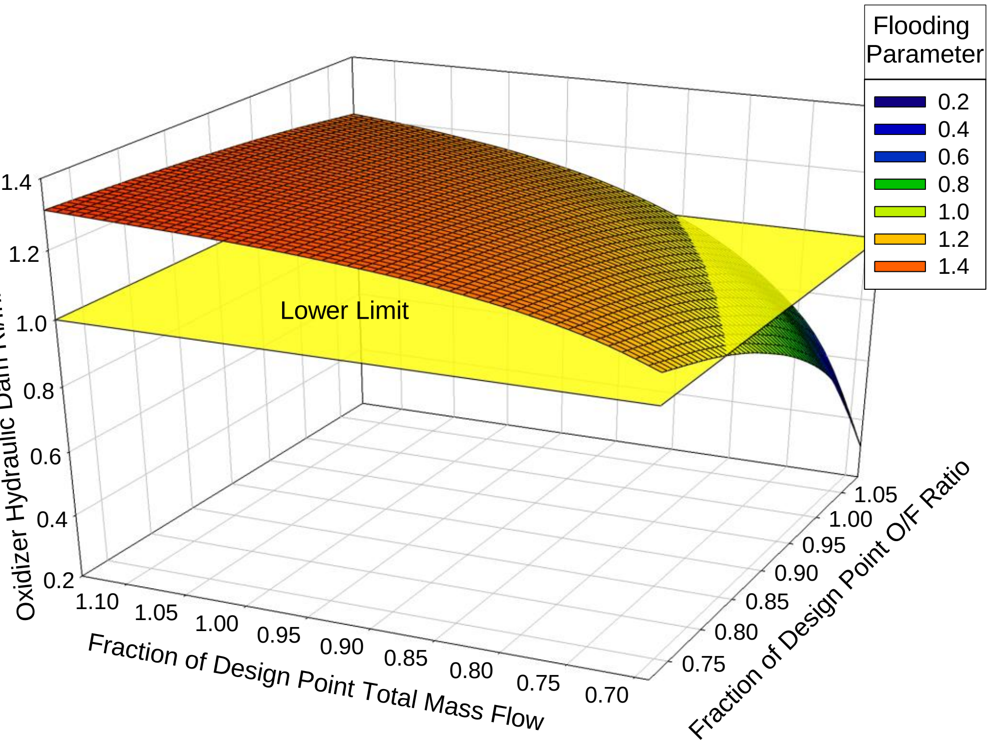


Figure 6.117 Oxidizer Hydraulic Dam Operability Limit

Next is the check of the fuel hydraulic dam. Figure 6.118 describes the relationship of the fuel hydraulic dam fluid inner radius in relation to the inner radius of the inner shaft. As can be seen, the portion of the curve that lies under the lower limit is much larger than observed for the oxidizer hydraulic dam. The reason that the fuel seems to be more restrictive is that MMH has a lower density than MON-3, so changes in the pressure require larger changes in the geometry of the hydraulic dam. Thus, the fuel appears to limit the operation of the pump to about 85% of the design mass flow at the lower end. However, it does appear that the fuel hydraulic dam does not limit the upper end. The potential is that the pump can be optimized for the fuel limitations by designing the pump at the minimum expected mass flow, or possibly using a different tank pressure for the fuel and oxidizer at the system level.

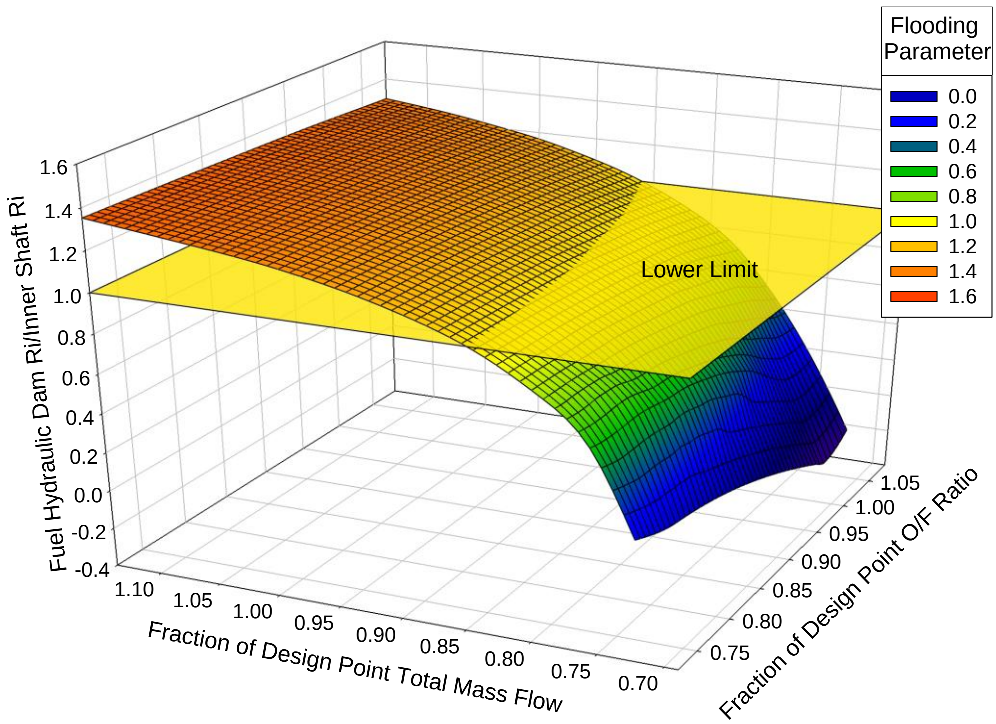


Figure 6.118 Fuel Hydraulic Dam Operability Limit

For the temperature limit shown in Figure 6.119, it is observed that the material capability is well in excess of the temperature that the pump combustor is predicted to get to. From a robust performance perspective, the trend supports the design approach. The take away from the curve indicates that one of three potential options are available. The first is that the structure could be thinned in order to save additional weight, or the second is to increase the turbine rotor inlet temperature to improve the system performance. The third option is to simply use the design as is and maintain a large margin. For a robust configuration, the third option makes the most sense.

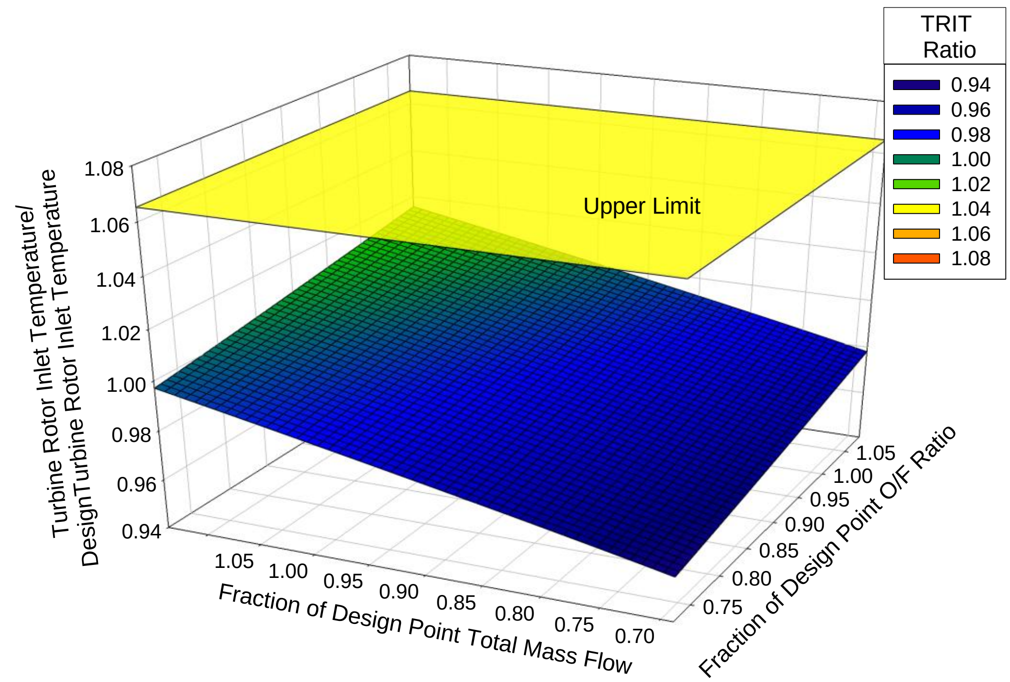


Figure 6.119 Turbine Rotor Inlet Temperature Operability Limit

Finally, the operability of the pump with respect to the shaft speed is evaluated. It is observed in Figure 6.120 that the shaft speed varies by more than 30% from the baseline to its upper and lower extremes. The magnitude of the difference between an idle point and a full power point may be excessive. With a wide range of operating shaft speeds, it may not be possible to maintain shaft operation without crossing one or more of the modes of the shaft. Crossing, or dwelling, at a shaft mode can be detrimental to the pump or even destructive depending on which mode and the magnitude of the amplitude. On top of that, is the fact that the shaft speed is limited at the upper end by the maximum shaft speed. Therefore, the maximum shaft speed was established by the speed below which a spinning disk will not rupture for the shaft material. However, it should be noted that the Combustion Driven Drag Pump shaft is not a conventional shaft, so the limit is approximate in nature.

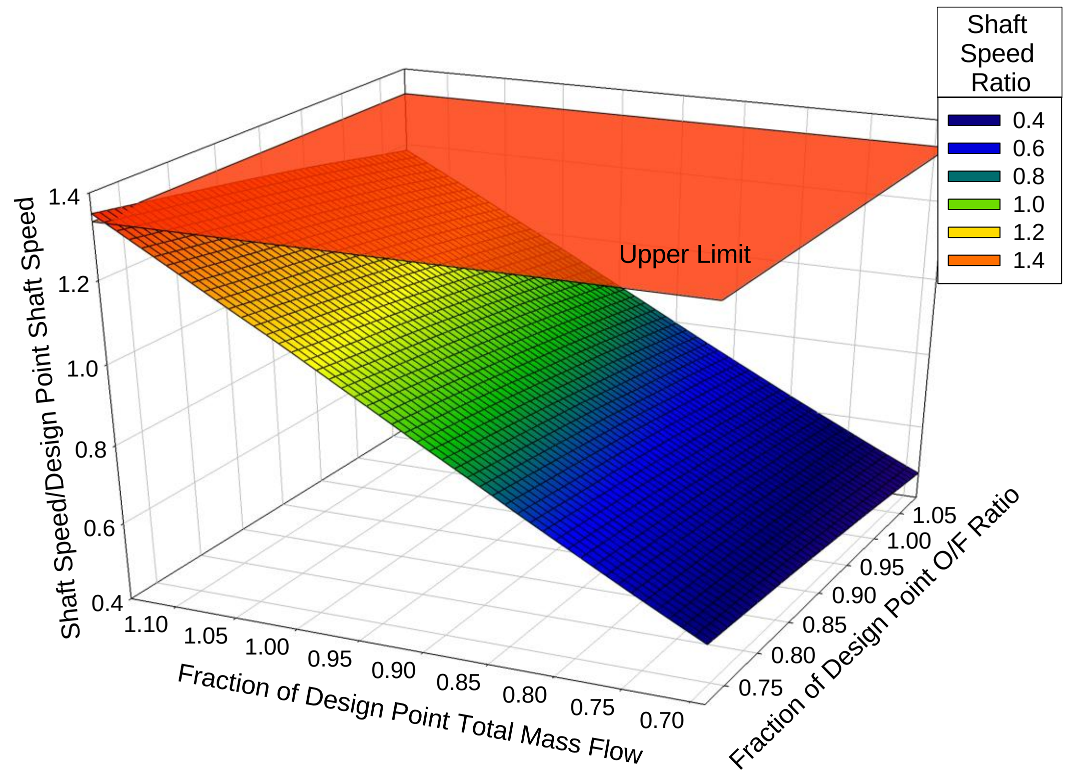


Figure 6.120 Shaft Speed Operability Limit

Based on the results of the study, the pump does appear to have some limitations in how it operates. The shaft speed provides a small region at the upper mass flow rate and lower mixture ratio that may be risky from a structural perspective. Meanwhile, the lower mass flow rates are limited by flooding of the fuel hydraulic dam. The oxidizer hydraulic dam also shows some limitations, but they are completely encapsulated by the restrictions encountered for the fuel flow hydraulic dam. The overall throttle range of the pump appears to be smaller than desirable, but it is still throttleable.

CHAPTER 7

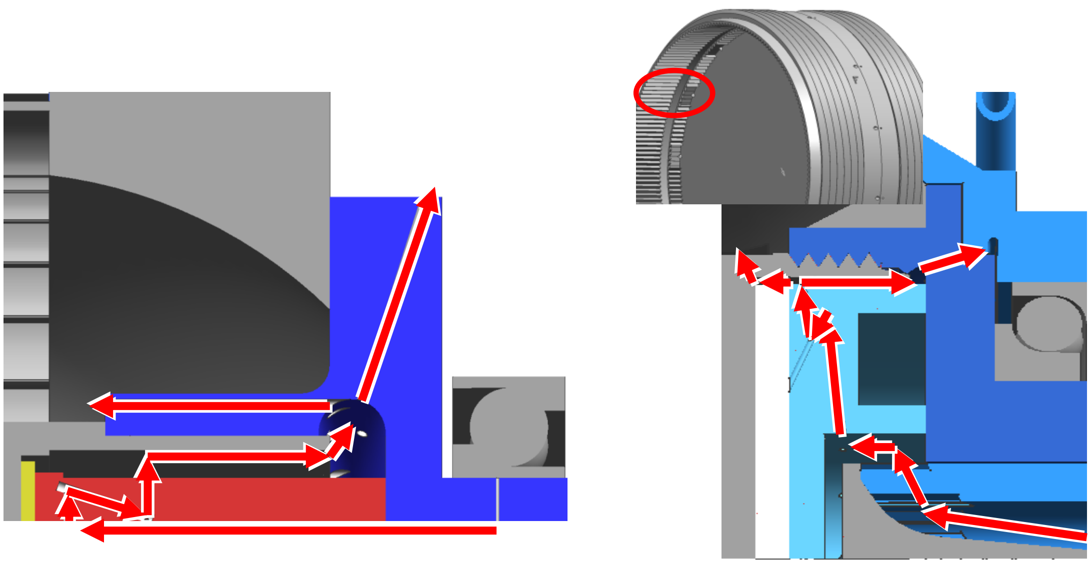
FINAL DESIGN

7.1 Justification/Rationale

The final configuration is different from the baseline configuration in several areas. Going into the study, the approach was to keep the design as simple as possible to try to meet the diverse needs of the industry while still producing an innovative and technically sound device. The approach is best summarized by Einstein's Razor which is often phrased as, "Things should be made as simple as possible, but not any simpler" [84]. In more applicable terms, the Combustion Driven Drag Pump should be as simple as possible, but complex enough to do the job. Even though Einstein's Razor is often used to describe an explanation or theory, it does have a simple truth to it that relates to making sure things are not overly complicated, but rather complicated enough to get the job done.

Along those lines, the initial vision of the Combustion Driven Drag Pump was created to be as simple as possible, but that proved to be inadequate for the job. As a result, the design of the pump had to be modified to give it utility. As the principle of keeping it simple was used from the beginning, there are several additional options available for further improving the design of the pump. The simulation work and the trade studies led to the incorporation of three of the options to improve the overall design and performance of the concept.

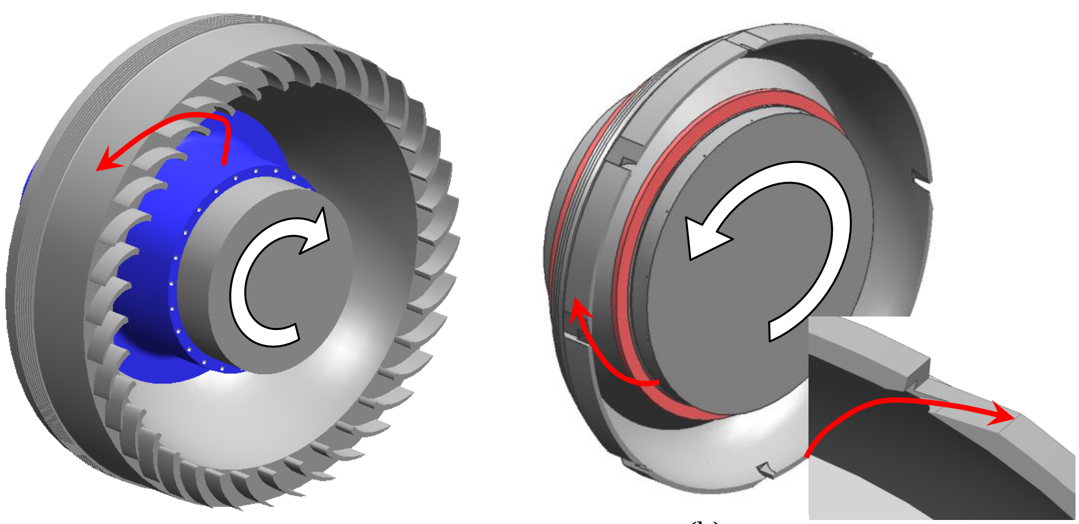
The first feature was the removal of as much of the radial margin as possible to reduce the diameter of the pump. Removing margin where possible led to the incorporation of the flow splitter into the common shaft. Previously, the splitter was in the outer shaft. With the common shaft performing the function of dividing the flow between the pump combustor and the rocket, it was possible to reduce some of the radial stack up distance in the concept. Furthermore, the discovery that the hydraulic dam margin needed to be increased in order for the pump to operate at other conditions placed added importance on reducing the other margins in the design. Figure 7.1 illustrates the change in the basic flow path.



(a) (b)

Figure 7.1 Splitter Improvement (a) Original Design – Splitter in Outer Shaft and (b) Final Design – Splitter in Common Shaft

The second significant change was a result of trying to develop the simulation. Establishing the turbine performance parameters that would define a turbine in design point and then calculate off design performance illustrated the difficulties in the baseline turbine approach. Even before the development of the simulation, it was considered a strong possibility that a radial outflow turbine, as defined in the baseline, may not provide the correct characteristics to match up with the pumping elements. Therefore, it was not a significant surprise that the turbine simulation showed how inappropriate a conventionally bladed turbine was. The two alternatives that were immediately available without causing a major redesign were a partial admission turbine and a Hero turbine also called a reaction turbine. A partial admission turbine was not a good fit with the combustor and uniform radial outflow desired to maintain low stresses on the bearings, so a reaction turbine was used. Upon incorporation of a reaction turbine, the simulation revealed stable operation of the concept. Figure 7.2 shows the change from a bladed turbine to a reaction turbine.



(a) (b)

Figure 7.2 Turbine Change (a) Original Design - Conventional Turbine and (b) Final Design – Reaction Turbine

The final change was incorporated to accommodate the fact that the first investigation into the operability of the pump revealed a significant design flaw. The flaw was that at any operating condition other than the design point, the pump would not have enough margin in the hydraulic dams to ensure that the propellants would remain in solid body rotation. The simulation does not have enough fidelity to predict the full impact of losing solid body rotation inside the inner shafts, but it is certain that the result would be some loss in pressure rise capability. Therefore, the margin for the hydraulic dams needed to be increased to ensure operability.

Increasing the hydraulic dam margin, however, significantly increased the diameter of the pump. Thus, it was decided that adding back swirl to the exit of the rotary injectors for the main flows would reduce the power draw from the turbine and allow the shaft to increase in speed. Simultaneously, adding back swirl to the rotary injectors improved the performance of the collection scrolls. Prior to adding the back swirl, the performance estimates assumed that the dynamic head of the main flows would be completely lost because of the high tangential velocities. Using back swirl decreased the tangential velocities of the main flows and thus reduced the losses in the collection scrolls. With higher performing scrolls, the pump efficiency increased such that the pump size could be decreased and still maintain the same pressure rise. Figure 7.3 shows the change associated with the incorporation of back swirl.

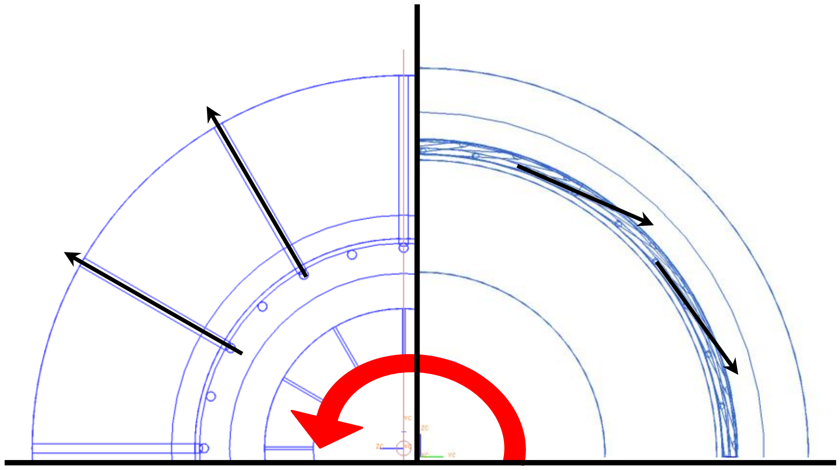


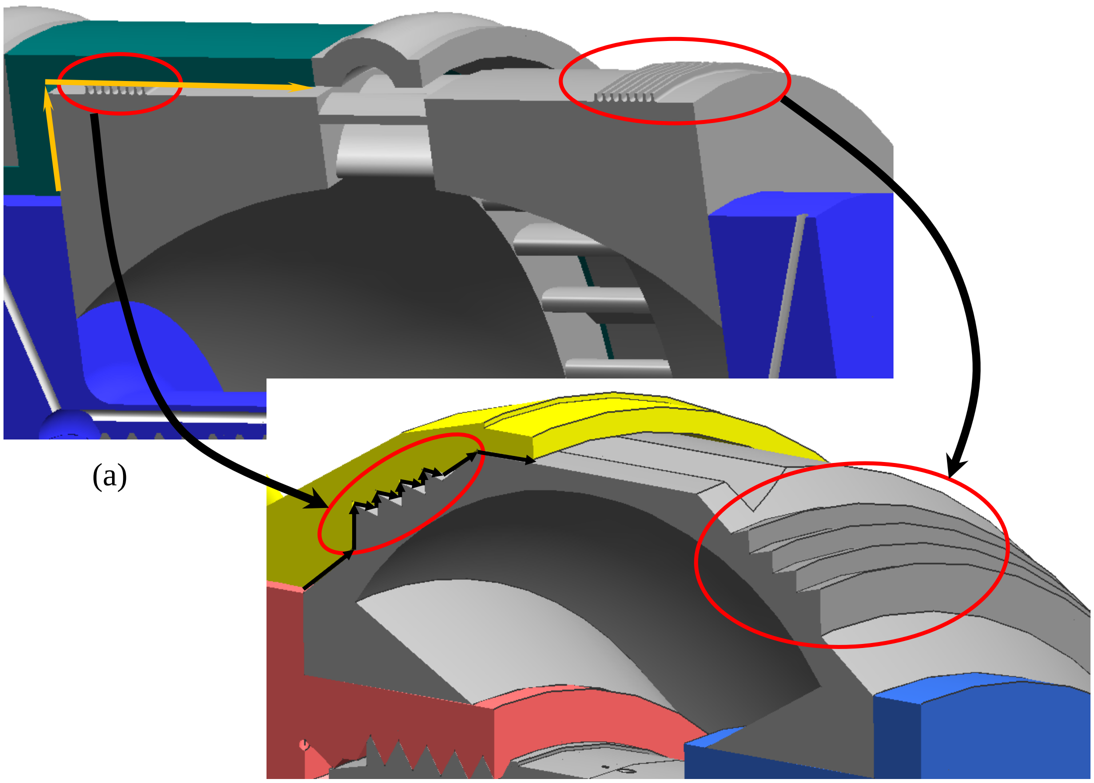
Figure 7.3 Rotary Injector (a) Original Design – Radial Injector and (b) Final Design – Back Swirl Injector

7.2 Comparison to Baseline

In comparing the final concept to the initial baseline, several differences are immediately obvious. The first is the final concept is much more rounded along the axial length of the pump. The largest driver of this change is the fact that the trade study indicated that small rotary injector radii were desirable from a weight and overall performance perspective. Bringing in the radii of the rotary injectors decreased the work of the shaft and reduced the diameter of the pump.

Another change that contributed to the rounding of the outer shell was the change from a conventional bladed turbine to a Hero turbine. The exhaust of the Hero turbine is isolated to a very narrow width, which allowed a decrease in the length of the maximum diameter section. With both changes, the exterior of the pump could be tailored to reduce the combustor wall thickness and improve the weight of the system.

Because of the geometry change, the seals between the turbine exhaust and the main flow discharge areas could be placed on an inclined surface, which would allow a more tortuous path through the labyrinth seals, as shown in Figure 7.4.



(a)

(b)

Figure 7.4 Labyrinth Seals (a) Original Design – Axial Labyrinth Seals and (b) Final Design – Tortuous Path Labyrinth Seals

It should be observed that the turbine exhaust is oriented in the opposite direction from the discharge ports for the main propellant flows, as shown in Figure 7.5. Because the turbine type was changed, the actual direction of the mass discharge from the turbine changed, requiring the adjustment to the overall discharge approach. In some ways, the change may be beneficial from a mechanical interface, in that it spreads out the mechanical arrangement of their connections to the rocket injector.

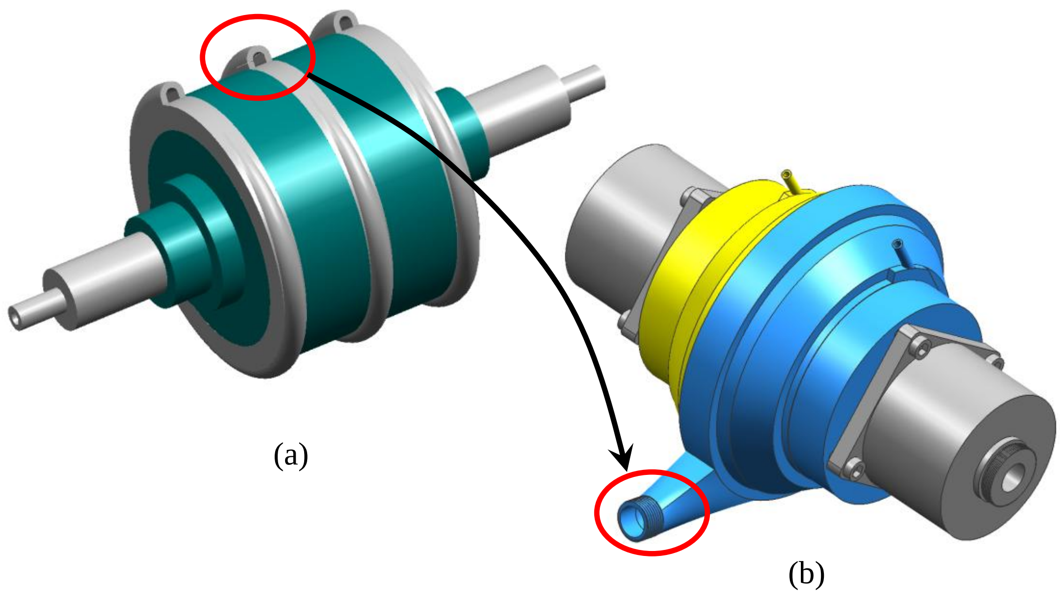
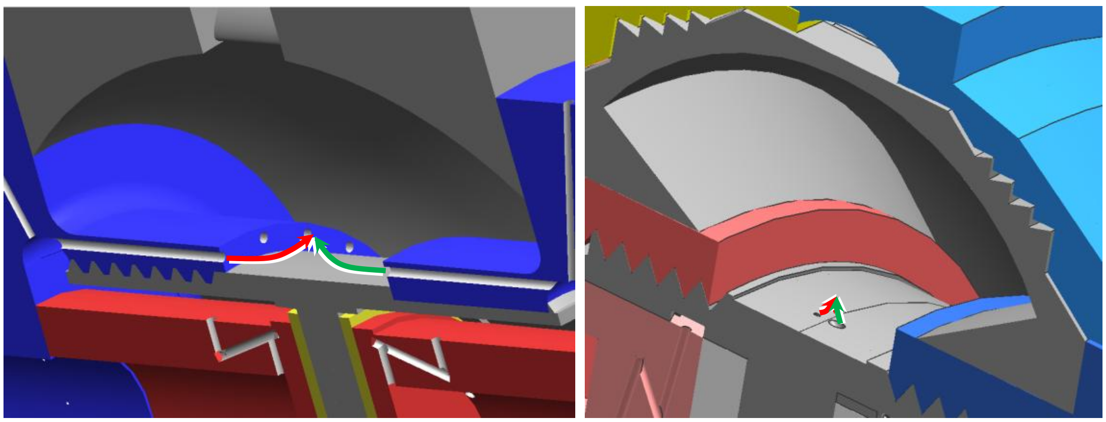


Figure 7.5 Changes in Discharge Locations (a) Original Design – Uniform Discharge Locations and (b) Final Design – Opposite Discharge Locations

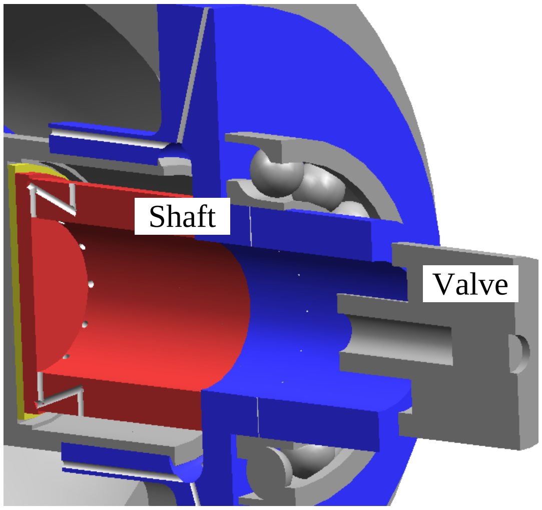
Thirdly, moving the splitters from the outer shafts to the common shaft helped with the overall size of the pump. Putting the flow splitters into the common shaft accomplished two things. The first was to reduce the diameter stack up, which reduced the shaft power as the rotary injectors could be moved inward without loss of capability. The second improvement was the matching of the injectors for the combustor, as shown in Figure 7.6. In the initial concept, the injectors were part of the outer shafts, which were threaded onto the common shaft. The baseline approach left a sizable uncertainty for alignment of the fuel and oxidizer injectors inside the combustor. While researching the properties of hypergolic combustion, two references indicated that the impingement of the fuel and oxidizer was important to ensure combustion [58], [72]. Apparently, the reaction is sometimes vigorous enough to blow apart the injector streams, so placing the combustor injectors on the same shaft allows for tighter control over the injector tolerances.



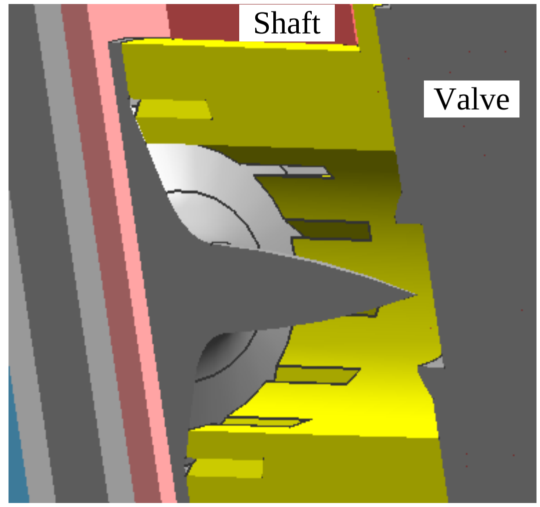
(a) (b)

Figure 7.6 Common Shaft Injectors (a) Original Design – Outer Shaft Injectors (b) Final Design – Common Shaft Injectors

Finally, the inlet of the pump was defined with more detail. It was intended from the very beginning to define an inlet flow nozzle as depicted in the final configuration. However, enough of the details were in flux that representing it at the beginning was not productive. Therefore, the addition of the flow inlet in the final configuration is not as much of a change as it is a definition of the original intent. The difference is illustrated in Figure 7.7.



(a)



(b)

Figure 7.7 Inlet Definition (a) Original Design – Inlet Undefined (b) Final Design – Inlet Defined

The comparison of the final configuration to the baseline is shown in Figure 7.8 in an over/under cross-sectional display. The bottom shows the baseline configuration and the top shows the final configuration. The difference in the size is readily apparent from the comparison and illustrates the strength of the optimization process developed for this investigation.

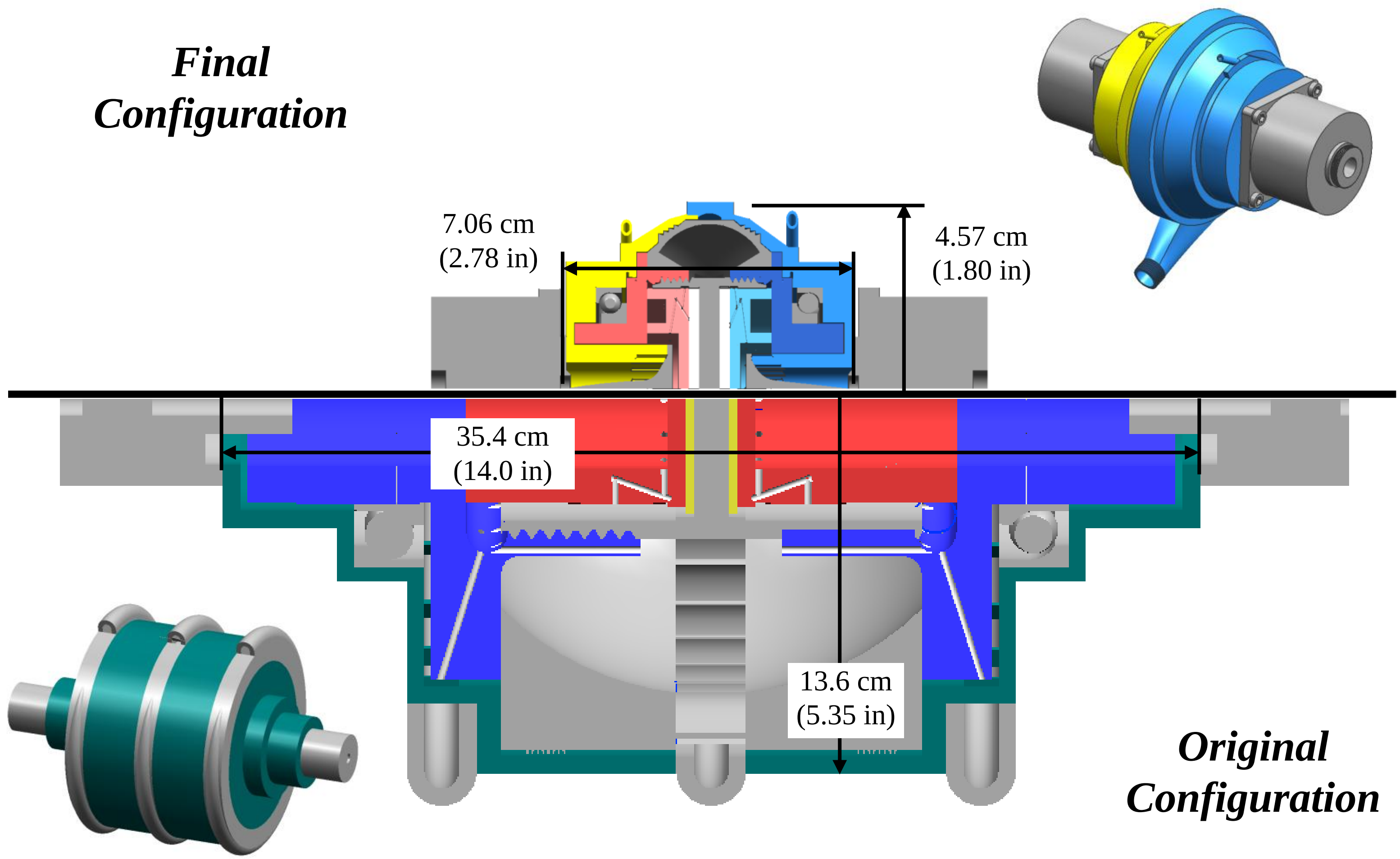


Figure 7.8 Comparison of Original and Final Configurations

CHAPTER 8

LESSONS LEARNED

8.1 Propellant Properties

During the investigation, a couple of interesting details were uncovered, which should be mentioned and documented for later reference. The first revolves around the scarcity and conflicting nature of the propellant properties. Finding publicly available properties on MMH and MON-3 proved to be more challenging than originally anticipated. The problem stems from the sensitive and toxic nature of both substances. Both propellants are commonly thought of as being toxic with the EPA governing various exposure limits and the quantity that can be kept at different types of work sites [77], [81]. The toxic nature and the limited type of use for the two propellants has made it difficult for people to investigate their properties.

From a purely technical perspective, investigating MMH properties, especially at elevated temperatures posses a unique challenge in that MMH tends to exothermally break down at high temperatures. The explosive risk alone makes it hard to obtain adequate measurements of temperature, pressure, density and specific heat [72]. These difficulties encouraged empirical modeling and extrapolation of sparse data. However, Schmidt published a very definitive text on hydrazine and its various derivatives, which MMH is one of the most common [72]. Most of the data used in the simulation was taken from the text by Schmidt. However, it should be noted that even in Schmidt's text conflicts and errors were identified.

For the MON-3, many of the same restrictions and observations were made. The difference is that MON-3 does not have a definitive text to reference its properties. Fortunately, the discrepancies that were identified were not as large as those identified for MMH. However, the data is limited in nature because MON-3 tends to breakdown at elevated temperatures [82]. The breakdown is not exothermic, like in the case of MMH, but it does disrupt the definition of the complete properties of MON-3.

For both propellants, the full definition of their properties was developed to the extent possible without conducting detailed experiments on the two fluids directly. Full development of the pump would benefit from a propellant characterization effort, where the propellants are directly evaluated at the conditions expected to be produced by the pump. It is certain that pumps have been made and tested for both MMH and MON-3, so it is more of an issue to make sure that the performance predictions are accurate than to ensure that it can be done.

8.2 Scope

The original scope of the project was overly ambitious with the desired outcome a Preliminary Design Review (PDR) of the Combustion Driven Drag Pump. In hindsight, the effort to get to a complete PDR level for a brand new concept is realistically a task several times larger than one person can complete in a reasonable time period. However, the effort is definitely further along than what would be expected at a Concept Design Review (CoDR), which is usually characterized by trade studies conducted among several different approaches on a purely qualitative basis.

Therefore, the current status of the design lies somewhere between a CoDR and a PDR. In order to bring the design to the PDR level, several detailed, but preliminary, analyses should be completed on the final configuration. The first of these analyses is a CFD simulation of the combustor. The shape of the combustor directly relates to two very important aspects of the pump, the combustion pressure drop and the combustion efficiency. The CFD analysis would provide further insight into whether or not the initial estimates are realistic and supportable or if the concept needs to be refined. A more detailed CFD analysis would also be conducted as part of the detailed design to adjust the design and verify the combustor properties.

The next analysis that would be beneficial is a basic structural analysis to demonstrate there are no glaring weaknesses in the final configuration under random vibration and shock loading. The structural analysis would also identify the best location and methodology for mounting the pump, as well as, identify locations where the structure is overly conservative. As a side benefit of the structural analysis, the projected mass estimates could be refined to within +/-10% of the final values.

The third analysis would be a thermal analysis to identify any areas of concern regarding the thermal properties of the materials selected. The thermal analysis would work well in conjunction with the structural analysis to ensure that the material properties after the materials are heated up, are adequate for the design to be a success.

Along these same lines, the thermal analysis may identify potential weight saving areas where the temperatures do not require high temperature nickel based alloys.

Finally, a preliminary analysis of the shaft dynamics and the seals would have to be conducted to verify or dispute the performance modeling assumptions regarding the seal leakage rates and the bearing parasitic losses. Of course, in any shaft dynamic modeling, the identification of the shaft/system modes is important to the overall system performance and stability. Therefore, initial evaluations of the basic shaft dynamic properties would help answer the questions regarding whether or not the concept is even feasible.

Overall, it is regrettable that the additional analyses were not executed as planned, but it is also recognized that it may be beneficial to work the concept in a serial manner. It is common in concurrent engineering approaches to develop all the models for a concept based on a preliminary physical design concept using basic calculations. In a concurrent design approach, the performance, structural, thermal and parasitic loss evaluations are conducted at the same time. More often than not the approach ends up with conflicts between the desires of the various disciplines that have to be reconciled before a design iteration occurs. By allowing the design of the Combustion Driven Drag Pump to be driven by a parametric model, taking into account many of the basic principles of all the disciplines may eliminate common design conflicts. However, before that can be asserted as fact, the full design and development of the Combustion Driven Drag Pump has to be completed, so one may look back on the development history and determine if the approach was beneficial or detrimental.

CHAPTER 9

RECOMMENDATION FOR FUTURE WORK

9.1 Further Design Refinement

Based on the results from the design trade studies, it is clear that the performance of the Combustion Driven Drag Pump can be influenced in a number of ways by the various design parameters. The initial study identified the major contributors to the overall performance of the pump, as well as, the general trends. However, one element of the study that was defined in a generic manner that affects the design and overall performance of the pump is the propulsion system definition. How the pump is integrated into the overall system and the rocket itself influences how the pump is intended to function.

For example, if the pump is integrated into the system to provide pressurized propellant to several rockets and/or thrusters of different types, then how the turbine exhaust is handled becomes more complicated. Conversely, if the pump is integrated closely with a rocket, then the operating conditions are well defined and the pump performance can be tailored toward that specific application. The possibilities for integrating the pump and using it in a productive manner are numerous, which is why the study only focused on a generic application of the pump in a manner that was simple to evaluate.

Because of the variety of potential uses, any implementation of the Combustion Driven Drag Pump will need to be tailored for the particular application. The results herein are the starting point for the development of the actual product, not the end. Therefore, future work is necessary to design the final details of the concept, if only to make sure the concept is optimally developed for each particular application.

9.2 Transient Simulation

One of the most important next steps is to determine if the pump can be started and stopped in a reasonable manner. Multiple approaches are available for starting the pump. The first is to open the valves and allow the propellants to migrate through the pump to the combustor where they would react, produce a high temperature, high pressure gas and begin to drive the turbine. The first method is commonly referred to as a bootstrap start [1]. A second method is to use a secondary gas to impinge on the shaft and cause it to start rotating, so when the propellants are introduced, the pump is already acting like a pump [3]. The second method is normally called an impingement start. A third method is to attach an electric starter that can spin the shaft until the propellants take over [20].

The second and third methods are similar in that they require additional mass and they decrease the efficiency of the pump. Conversely, the first method only uses propellant, which would end up producing thrust. Thus, the first method is preferred, but not necessarily guaranteed to function properly. The clearest method for determining how to start the pump is to develop a transient simulation where the polar moment of inertias, thermal masses, propellant masses and torques are simulated to estimate the transient performance of the pump. The same simulation could also be used to predict the shutdown, deceleration and acceleration characteristics of the pump. The initial NPSS™ based simulation can be modified to create the desired transient simulation.

9.3 Detailed Component Analysis

Beyond the need to design the pump for particular applications, is the need to conduct a more thorough analysis of the pump. It is not enough to design the pump for generic requirements as used for the initial concept study. A more detailed set of specific design requirements must be used. More detailed design requirements would stem from having more specifics on the application of the pump and how it is intended to be used in the system. The details of the overall system could be used to develop the specific structural requirements, thermal environments and operating characteristics for the pump. Improved requirements would pave the way for conducting similar design optimization studies as defined herein with specific metrics to meet, which could be linked to analyses of the structures, thermal characteristics, shaft dynamics and fluid flows. Furthermore, the analysis efforts can be addressed by using the NPSS™ functionality called zooming, where higher fidelity component models can be incorporated into the simulation to directly evaluate the component impacts at the system level. Particular areas of interest in each of these analyses are described below.

9.3.1 Structural Analysis

The structural analysis for this study was basic in that only the hoop and shear stresses were considered for the pressure vessel. The calculations were applied to basic material properties using simple calculations. Since determining the basic impacts of changing various design parameters was the goal of the study, the simplified approach was appropriate. The next step would be to complete a preliminary structural analysis to support a PDR level review. However, for an actual detailed design, a full finite element analysis using tools such as ANSYS or NASTRAN is warranted. If nothing else, the vibration and shock requirements of an actual application would require the analysis effort to quantify the structural margin throughout the pump and its support structure. In addition to the vibration and shock loads, a thermostructural analysis would provide evidence that the design would meet actual application loads with margin under the worst-case environmental loading and operating conditions.

9.3.2 Thermal Analysis

Thermally, the pump has very few requirements. However, there are three areas of concern that call for a full thermal analysis. The three areas of concern are important enough to drive the need for a preliminary analysis prior to PDR and a complete analysis during detail design. The first area of concern is the material selections within the pump. The pump is baselined primarily with INCO 625, which is a high temperature nickel based alloy. The selection of INCO 625 was primarily to ensure that the pump material could withstand the combustion temperatures. However, it might be possible to change many of the components to lighter materials if the temperatures and stresses show that they can withstand the thermal and stress environments.

The second concern from a thermal standpoint is the heating of temperature sensitive areas. As the press disks are the only non-metallic material in the pump, the temperatures of the press disks have the lowest allowed material temperature limits. The bearing temperatures are also of concern, since the lubrication is accomplish through use of the propellants. The thermal environment, particularly of the MMH side bearing, is important to understand not just from the perspective of adequately cooling the bearings, but from making sure that, the MMH does not reach its auto decomposition temperature.

Finally, the thermal analysis is critical to the understanding of how the thermal environment affects the pump. The thermal environment is composed of two elements. The first is the ambient environment. In space, the ambient conditions can be extremely hot when facing the sun or extremely cold when in the shadow of a planet facing away from the sun. Both conditions could make operating the pump a challenge. The other thermal environmental element is the soak back from the rocket after firing. When the rocket stops firing, the residual heat in the rocket heats the propellant in the injector and upstream of the injector. The heating effect will heat the propellant trapped in the pump.

The two thermal environments could conceivably vaporize the propellant both in bulk and locally. Vaporizing the MMH could cause it to decompose exothermally, causing what is known in the industry as an unintended rapid disassembly or explosion of the pump, rocket or propulsion system as a whole. Generally, this is an undesirable outcome. In the event of local vaporization, of either propellant, stresses near the pocket of hot propellant will increase as the pressure increases. Naturally, the increased stresses accompany decreased material strength as the material in the area increases in temperature. The thermal gradients themselves could cause non-trivial stresses within the pump. Localized heating may be more difficult to deal with, as the likely outcome may be weakened structural integrity or small leaks. Since both would be difficult to detect, the impact may be difficult to react to and understand.

Interestingly, the other half of the thermal environment can be just as damaging. If the pump becomes too cold, then the propellant may freeze as it enters the pump or travels through some of the small passages. The effects of frozen propellant can be as extreme as vaporized propellant. If only one of the propellant paths freezes or becomes partially blocked by frozen propellant, then the combustor in the pump may run at dramatically hotter or cooler temperatures, depending on which propellant is blocked. Similarly, the rocket itself may run at hotter or colder temperatures. In both cases, the hotter temperatures would be destructive to the pump or rocket, while the colder temperatures would decrease the performance of the system and jeopardize the mission.

Even in the unlikely event that frozen propellant does not result in a loss in performance, the non-symmetrical loading on the shaft due to frozen flow passages may damage the pump. Both environments need to be understood and compensated for in the pump system, either through increased emissivity coatings to cool the pump and/or with pump heaters to prevent the pump from freezing. Both options are common in the spacecraft industry and are easily implemented if the requirements are fully understood.

9.3.3 Rotor Dynamics

The shaft is a rather complicated assembly and detailed design and application requirements may alter some of the basic features of the shaft. In the absence of a rotor dynamics model, the interfaces have been arbitrarily set, as have many of the geometric features not directly related to the overall performance of the pump. However, sufficient flexibility has been maintained in the overall design that significant changes in the shaft, its construction and the geometry of the shaft elements can be implemented without decreasing the benefit of the pump. A detailed analysis of the shaft dynamics and bearing loads is necessary to help define the actual interface requirements and bearing requirements. Additionally, the shaft dynamics analysis will provide a check on the parasitic losses associated with the drag of the bearings on the shaft.

9.3.4 Secondary Flow Analysis

The analyses described up to this point have been related to the static or non-performance related aspects of the pump. Each of the analyses do not materially affect how well the pump performs its primary function of raising the pressure of the propellants. From this point forward, the described analyses have a direct impact on the overall performance of the pump, starting with the secondary flow analysis.

The secondary flow analysis addresses the functionality of the various seals within the pump. A detailed analysis needs to be conducted to ensure that the pump does not have excessive leakage from one flow to another. However, it has been observed by many experts in the seal business that one truism about seals is that they all leak [3]. Therefore, it is important to understand how effective the seals are and what impact leaking seals have on the overall performance of the pump.

The first leakage would be from the high pressure turbine exhaust to the high pressure propellant discharges or vise-a-versa. It is envisioned that the seals separating these flows would be effective labyrinth seals. The current design has a lower pressure at the turbine exhaust than at the propellant discharge. Thus, the seal would leak from the oxidizer and the fuel discharges into the turbine exhaust. A small amount of leakage is acceptable and planned for in the design. However, a large amount of leakage would result in a failure of the pump in that the propellants leaking into the turbine exhaust would vaporize and add pressure to the turbine exhaust, thereby decreasing the pressure ratio across the turbine. A lower pressure ratio means lower turbine work and lower pump pressure rise. Additionally, the oxidizer would react with the fuel rich turbine exhaust adding heat and pressure. The backpressure on the turbine would decrease the amount of work done by the turbine and slow down the shaft. Therefore, only a small amount of parasitic loss as described above has been accounted for in the simulation. Any additional losses would decrease the effectiveness of the pump.

Similarly, leakage from the high pressure propellant discharge to the propellant inlet would have a similar effect on the effectiveness of the pump. For this seal, the pump has been designed with spiral grooves on the faces of the outer shafts to discourage the flow from migrating toward the centerline. Additionally, the bearings will serve as another barrier to the propellant movement. However, as observed earlier, the seals will leak [3]. Again, the simulation accounted for some leakage to the upstream injectors.

In both cases, the simulation has estimates for the parasitic losses associated with the leakage through the seals. However, a detailed analysis is needed to determine if the current design can maintain the desired leakage levels, and if so, how does the leakage vary from one operating condition to the next. The outcome is likely to be a more detailed design approach to the seals and an update of the leakage assumptions in the pump simulation.

9.3.5 Combustor CFD

For the combustor of the pump, the general approach was to provide doublet impingement of the oxidizer and the fuel streams at the inner radius of the combustor. Using hypergolic propellants, such as MMH and MON-3, provides an interesting challenge to the design of the combustor. The first is that the reaction rate is very rapid because the reaction starts with the pure liquid forms of both propellants and then accelerates [58]. The driving philosophy behind the generic combustor design illustrated in the study was to provide a rapid area of expansion to accommodate the rapid heat release from the reaction of the propellant to minimize Rayleigh losses.

Following the heat release rate section is a region of gradual acceleration as the gases travel away from the inner radius toward the turbine. Since the flow is also moving away from the centerline and has a significant tangential component, the flow slows down to conserve angular momentum. Therefore, a first cut at a radial outflow, hypergolic propellant, combustion chamber should have a shape similar to that used in the initial trade studies. However, the actual shape did not have a significant effect on the overall performance of the pump system, except that larger outer radii of the combustor made the pump weigh more with a larger overall diameter. Unfortunately, the simulation did not have a complete set of geometry/performance interaction characteristics, as a more detailed CFD analysis is needed to properly define them.

An actual design for the combustor would have to take into account the basic features above as well as Rayleigh losses, mixing losses and acceleration losses. Therefore, a CFD model coupled with a thorough combustor design effort would have to be undertaken to ensure that the pressure losses and combustion efficiencies used in the pump design trade studies are achievable. It is possible that the simulation performance assumptions will need to be updated to reflect the true capability of the combustor, especially with respect to the off design point operating characteristics.

9.3.6 Turbine CFD

Designing the turbine took an interesting path during the study. The initial concept was to design a radial outflow turbine with traditional turbine blades. However, as the simulation developed it became clear that the volumetric flow rate through the turbine would be too small for a traditional bladed turbine design. A partial emission turbine was considered for the design and has heritage with Transtar [15] and the XLR-132 [1], but was discarded as likely to place extra stress on the bearings. Thus, the design changed prior to the first simulation run to a Hero turbine.

Ensuring that the turbine provides the correct performance is integral to the overall performance of the pump. With a traditional turbine, it is a rather simple effort to create a mean-line style code to evaluate the performance at the design point and at the off design conditions. However, with a reaction turbine the mean line approach is not practical. Jets of gas providing torque, rather than aerodynamic pressure differences on turbine blades, characterize the Hero turbine [70]. The result is that the Hero turbine requires a full CFD analysis to estimate the losses in the gas stream at both the inlet and exit points to the turbine. The acceleration of the gases through the turbine is rather straightforward and can be adapted from traditional rocket textbooks. To complicate the analysis though, is the fact that the inlet to the Hero turbine contains gases that are rotating in the same frame of reference as the turbine. Hence, a CFD analysis linked to the combustor would provide the most realistic representation for the turbine.

9.3.7 Collection Scroll CFD

The collection scrolls did not play a critical role in the overall performance of the baseline pump concept. However, as the design iterations progressed, it became apparent that they had the potential to provide a significant improvement capability for the pump. Therefore, a thorough design review and analysis of the collection scrolls could provide a benefit to the pump that has not been fully captured in the initial studies up to this point. The design of collection scrolls is important, as a possible risk mitigation against potentially optimistic projections of performance in other aspects of the performance modeling. A full CFD analysis would be able to quantify the overall performance of the collection scrolls and would provide information that could be used to guide future performance improvement efforts.

9.4 Design Review

An additional benefit to the overall success of the Combustion Driven Drag Pump would be the presence of detailed design reviews. To date, the concept has been reviewed for novelty and resulted in the filing of a provisional patent application. The patent application was dropped in favor of a defensive publication or public disclosure to ensure that the concept cannot be patented by others. However, neither the provisional patent application, nor the defensive publication provided much technical feedback or critique of the concept itself. A true review of the technical merits is warranted. A peer level or higher review is especially necessary in light of whether or not the concept has any utility.

At present, the Combustion Driven Drag Pump is only a concept with preliminary trades conducted to optimize the initial design. To go to the next level, a more thorough and rigorous review process is needed. A valuable part of the design and development effort is the discussion of the concept with peers and customers. Peer reviews evaluate the technical merit of the concept and to help solve the technical challenges that face the successful implementation of the design. Reviews by customers or potential customers ensure the development of the concept is moving in the direction that would meet particular goals at the system or spacecraft level.

Further development of the Combustion Driven Drag Pump is dependent upon conducting peer reviews and design reviews. A plan for conducting reviews along with further analyses is shown in Figure 9.1. As can be seen, the peer reviews follow completion of individual design efforts, and design reviews follow major updates to the performance projections of the pump concept. The plan for detailed design is shown in Figure 9.2, which also includes the procurement of long lead items and the development of the work instructions. Finally, in Figure 9.3, the notional schedule for manufacturing, assembling and testing the pump is laid out, culminating in a final report on the effort. Naturally, the actual calendar time associated with the milestones is heavily dependent upon the funding profile and application.

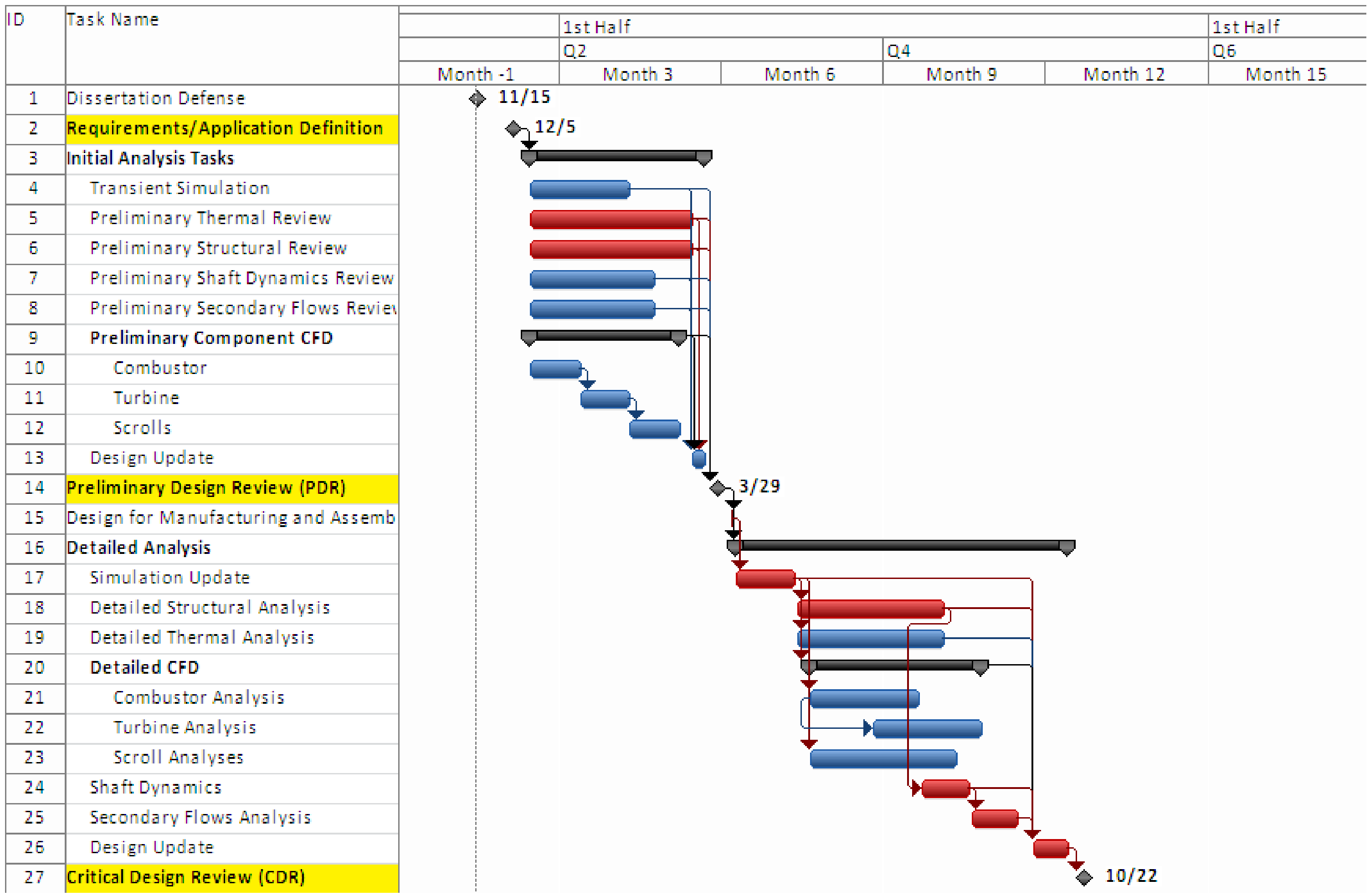


Figure 9.1 Timeline for Further Developments – Design and Analysis

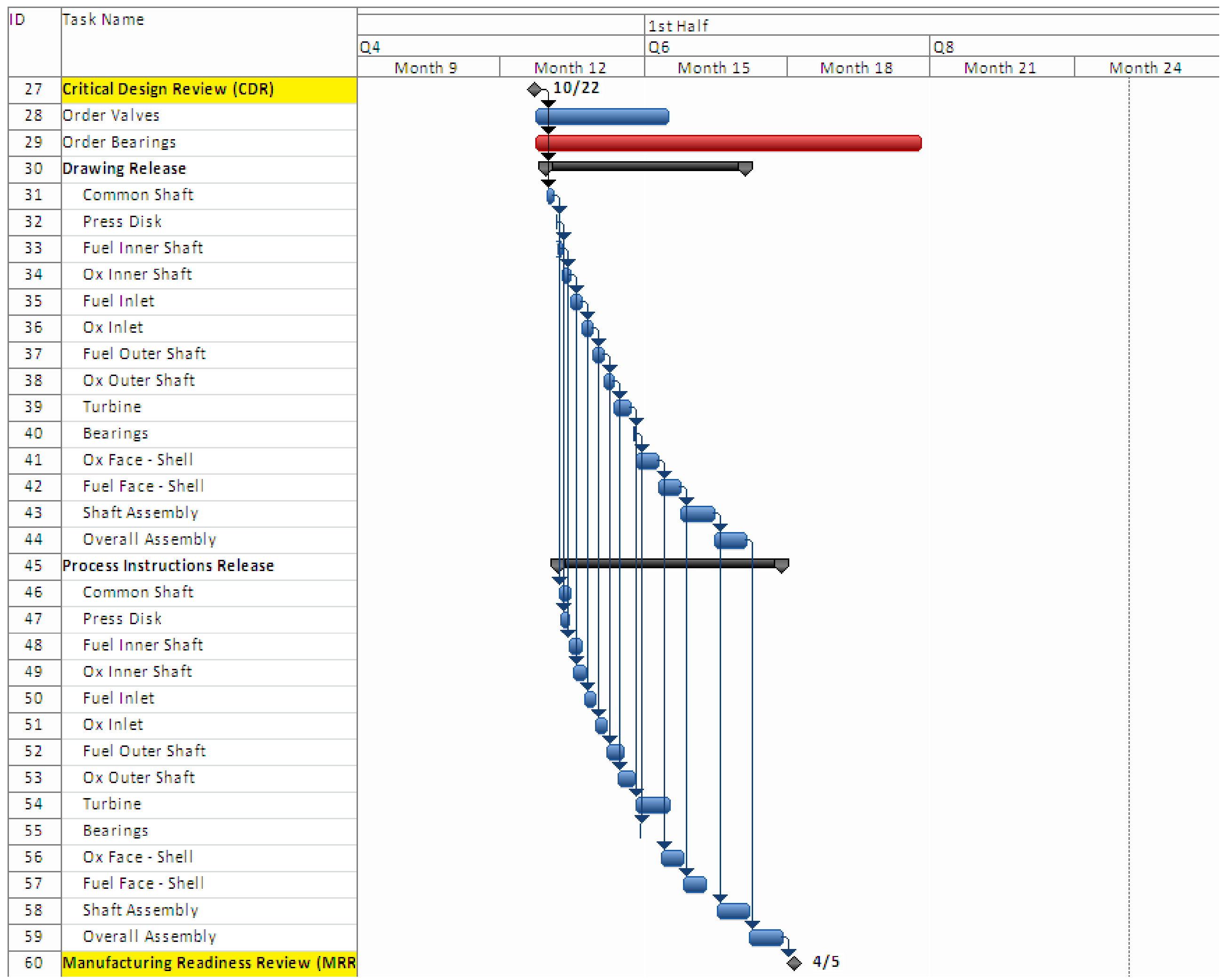


Figure 9.2 Timeline for Further Developments – Detailed Design

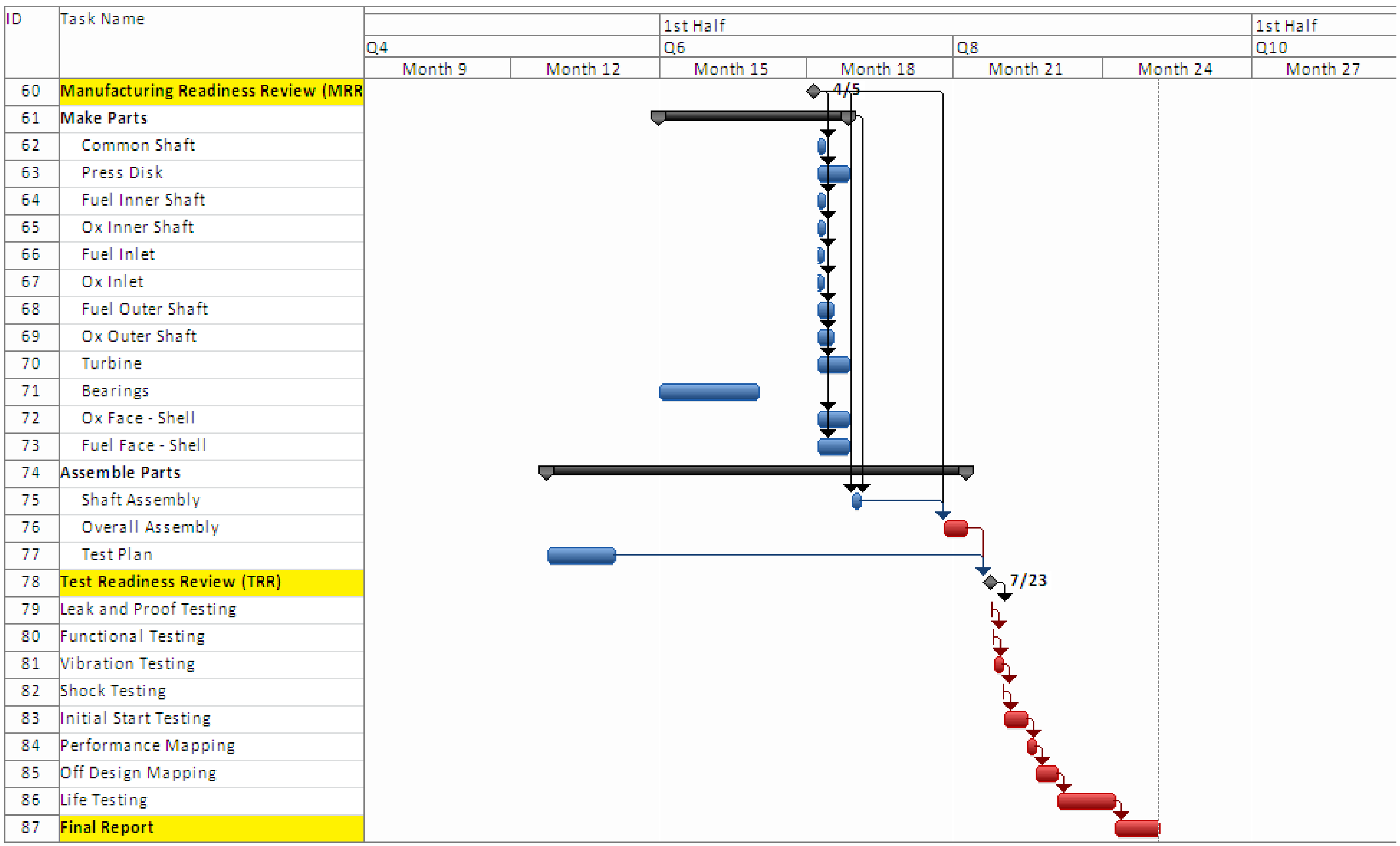


Figure 9.3 Timeline for Further Developments – Manufacture, Assembly and Test

CHAPTER 10

CONCLUSIONS

At the beginning of the study, the objective was identified as develop a pressurization system that would be both simple and robust to meet both the technical needs and the cultural challenges in the small rocket propulsion industry. As developed, the Combustion Driven Drag Pump meets the requirement of being simple, and because of its simplicity the Combustion Driven Drag Pump can be a versatile device for space propulsion applications. The overall value to the industry is a subject that is both technical and political in nature, so it is somewhat unclear as to whether this objective was met or can be met. However, the end conclusion is that the Combustion Driven Drag Pump is feasible and would provide a technical improvement over existing systems.

10.1 Simplicity

Development of the concept for the Combustion Driven Drag Pump followed an organic path governed by restrictions in the rocket propulsion industry and technical challenges facing pumps for use with small bipropellant rockets. The industry culture criteria dictated that the pump needed to be simple and robust, while the technical criteria emphasized performance and size. The simplicity requirement drove the overall approach and more or less defined the configuration, while the technical requirements drove the integration and optimization of the pump elements.

A simple pump would be a pump with the fewest complicated features to manufacture and the smallest impact on the overall system. During the development of the Combustion Driven Drag Pump concept, several alternative approaches were considered but were discarded as being too complicated. These approaches included electric motor driven shafts, positive displacement or gear pumps and turbomachinery pumps. Using a drag pump driven by a combustor appeared to be the simplest to manufacture and assemble.

By design, a Combustion Driven Drag Pump has significant resistance to factors that prove challenging for other concepts, such as tip clearance or inefficiencies associated with low pressure drive gases. However, the Combustion Driven Drag Pump is still only a concept with element level heritage in different fields to demonstrate physically that the principles are sound for use in rocket propulsion. The biggest challenge to the development of the Combustion Driven Drag Pump is not the technical issues, which have been demonstrated for the most part, but the perception that the Combustion Driven Drag Pump is new and hence risky. Thus, a portion of the study was to illustrate that many of the elements of the Combustion Driven Drag Pump are, in fact, low risk by nature and contain some heritage in other industries.

The other element of the study was to highlight the simplicity of the pump design at a reasonable size and still provide a performance benefit. The design was illustrated through the development of the solid models and the performance was defined with the simulation. The performance simulation was a key element to understanding the concept and verifying that it is simple in nature. Because of the importance of the simulation in understanding the concept and helping guide its development, a powerful simulation approach was selected for the study. Using NPSS™, the simulation was developed to be able to quickly evaluate different design choices and to grow with further development of the concept. The NPSS™ model is inherently capable of adding additional components, additional functionality and improving the fidelity of the modeled components by directly including detailed component simulations such as finite element analyses like CFD.

10.2 Versatility

The Combustion Driven Drag Pump concept, as described in the study, shows that the pump can produce the desired performance for one specific type of application. The question remains as to whether or not the pump concept can be adapted to other applications. The first alternative is the use of different fuel and oxidizer combinations. In the current design, hypergolic propellants produce the best results, as an igniter is not needed for the combustor. Thus, other hypergolic propellants, such as pure hydrazine and pure nitrogen tetroxide, are likely to produce the same type of result but require some design modifications. For example, replacing MMH with hydrazine would require changing the hydraulic dam geometry to accommodate the 20% higher density of hydrazine and would require changes to the fuel flow split to maintain a specified turbine rotor inlet temperature in the pump combustor.

However, propellants, such as oxygen and methane, which are increasingly being considered for similar applications, would require some significant modifications to the concept to incorporate an igniter. One option for incorporating an igniter is to use lead slugs of hypergolic propellants. Another option is to leave open the outer portion of the turbine such that a groove would exist for an igniter to pass through, but that may lead to additional leakage and structural stresses. The best option may be to change some of the materials in the shaft so a voltage difference can be created within the combustor structure. Applying a current to two different portions of the pump, such that it creates a spark is likely to be the easiest to implement.

Next, using the pump other than to pressurize a single rocket could be beneficial, so the question is whether that is possible. In the current version of the concept, the exhaust gas from the turbine is piped into the rocket along with the high pressure propellants. An alternative approach might be for the pump to provide high pressure propellants to high pressure manifolds feeding multiple rockets. The exhaust could be used to pressurize the fuel tank, which in a dual mode system provides high pressure capability for the monopropellant rockets in addition to the bipropellant rockets. Alternatively, the exhaust products could be stored in a separate pressure vessel and used as a warm gas thruster supply for very low thrust levels.

Fourth in the list of what can be done with the Combustion Driven Drag Pump is whether the pump can be adapted for different cycles. Clearly, the pump is well suited for the staged combustor cycle, and it is not difficult to imagine that the pump can be easily adapted for a gas generator cycle. The expander cycle, however, is a little more difficult to envision. In an expander cycle, the heated propellant drives the turbine. Adapting the concept to an expander cycle should be feasible. The adaptation would include increasing the fuel pressure ratio portion of the pump to provide higher pressure fuel at the discharge. Then the fuel returning from the rocket chamber, cooling jacket would be routed through a partial admission/partial emission turbine to drive the shaft prior to injection into the rocket chamber.

Finally, adapting the pump for different rocket types is not difficult to imagine either. The simplest would be to replace the combustor with a catalyst bed for propellants like hydrazine or hydroxyl ammonium nitrate (HAN) for monopropellant rockets. The exhaust would drive the turbine as both of those propellants produce exothermic reactions in the proper catalytic environment. The majority of the propellant flows to the main rocket chamber at high pressure. Conversely, it is not difficult to imagine incorporating the pump into the rocket chamber and use all of the exhaust gas to drive the turbine. The approach would be similar to the Williams International turborocket patent [39] where the turbopump is located within the rocket chamber. The key difference is that all of the propellant can go through the drive turbine.

Clearly, the concept has a degree of flexibility that conventional turbopumps do not currently exhibit, especially at the small rocket level. The flexibility and simplicity of the drag pump are the key features for its selection. However, the selection of the power turbine was to address the overall size and weight of the pump. Interestingly, the drive turbine benefit is only necessary for the higher flow rates associated with the larger end of the small class of rockets. For the smaller rockets, replacing the turbine with an electromagnetic motor is feasible and possibly attractive. Although, the challenges associated with the heavy magnets are still present.

10.3 Value

Establishing the overall value of the Combustion Driven Drag Pump is a difficult proposition. Numerous studies have shown that the performance of a bipropellant rocket with a pump or an elevated feed pressure is beneficial to the overall performance of the propulsion system [11], [23], [28], [38]. However, the launch industry appears to be generally content with the current capabilities of small bipropellant rockets. Thus, the demand for a pump to increase the performance of the bipropellant rocket is currently low. Coupling the low demand with the fact that the pump concept has no heritage creates a real, non-technical, impediment to placing a value on the utility of the pump.

Interestingly, there is a potential change on the horizon that may provide some hope that the Combustion Driven Drag Pump will develop further. The change that is making its way through the industry is that the launch industry is becoming more competitive and commercialized at the same time. Both elements have been in the launch industry for some time but not simultaneously at the levels projected for the future. NASA and the United States government have adopted a stance that commercial concerns need to step up and start taking the lead in the launch industry [30].

Two effects may influence the development of the Combustion Driven Drag Pump. The first is that as NASA and the government step away from the industry, many of the complicated and overburdening restrictions that come with government contracts will gradually lessen as the commercial industry develops its own rules and requirements for successful operation. However, it is unclear as to whether or not the looming shift will drive looser or tighter requirements. It can be observed that lower government involvement typically results in more innovation and fewer requirements but not always.

The other effect is likely to be the more dramatic and influential of the two industry changes looming on the horizon. The second effect is increased competition. The aircraft industry is an excellent example of how increased competitiveness drives evolutionary improvements and innovations. As the government released control of the airline industry, the competitive nature demanded that the aircraft provide benefits that are more economical [31]. Thus, a steady series of improvements have occurred over the course of the last forty years (i.e. Boeing 737 vs. the Boeing 787) in contrast to the space program, where the rockets for Orion are virtually identical to Apollo and Space Shuttle rockets built nearly forty years ago. To put the difference into perspective, the rocket industry is approximately eighty years old with the pinnacle achievement of putting a man on the Moon occurring over forty years ago. The same commercial pressures will place added emphasis on launch operations, where placing payloads into various orbits will demand greater performance from the bipropellant rockets associated with those applications.

The value of the Combustion Driven Drag Pump is real, and it does have value for the industry. However, the current uses do not have strong business requirements to drive performance improvements. In the future, the increase in the competitive nature of the industry may place an emphasis on performance improvement options such as the Combustion Driven Drag Pump and may lead to propulsion innovations.

10.4 Feasibility

The Combustion Driven Drag Pump is feasible in that small combustion chambers have been used in small bipropellant rocket engines for over forty years. Using hypergolic propellants solves many of the problems associated with ignition and combustion of the propellants. The turbine stems from a machine developed centuries ago, and the drag pump runs every day in small gas turbine engines. Collection scrolls are used in modern pumps such as sump pumps and well pumps, as well as, in modern turbopumps.

None of the technical challenges facing the Combustion Driven Drag Pump are new. Each element individually has been tested and is used on a daily basis in some other industry. The only reason that a pump of this nature has not been developed prior to this point in time is because the elements are all used in different industries, and the need for them to be combined into one pump is unique to small bipropellant rockets.

The Combustion Driven Drag Pump does not have a likely use outside bipropellant rockets, but for bipropellant rockets, the pump does promise to provide performance improvements. The concept of the Combustion Driven Drag Pump is simple, flexible and is designed for the challenges in the small bipropellant rocket industry, but more importantly, it has been shown to be feasible through the analysis that was conducted in this study. One of the most important elements in the study was the development of the simulation, which can grow with the development of the Combustion Driven Drag Pump continuing to provide insight into the pump concept.

APPENDIX A

FLAT METRIC RESPONSES OMITTED FROM CHAPTER 6

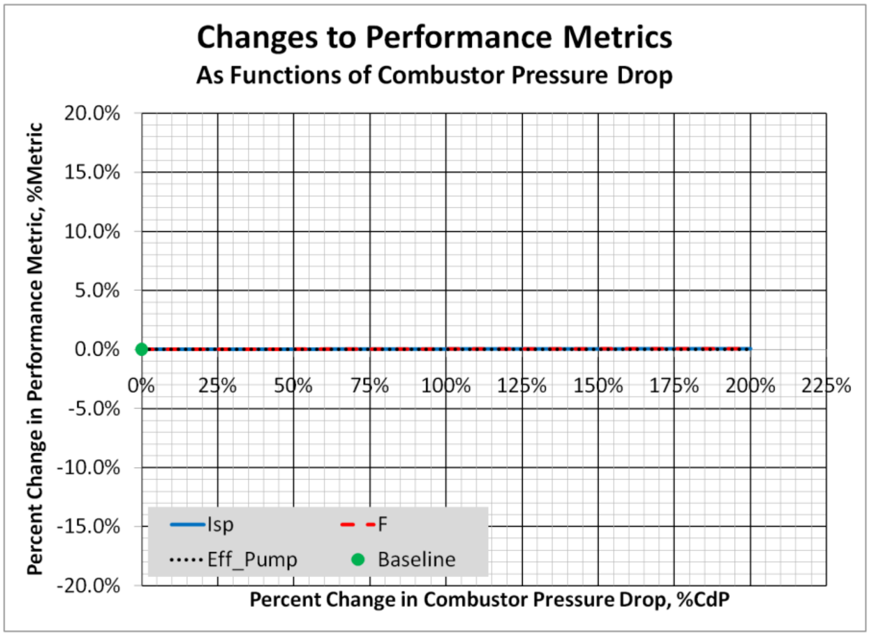


Figure A.1 Round 1 Combustor Pressure Drop Influence on Performance Metrics

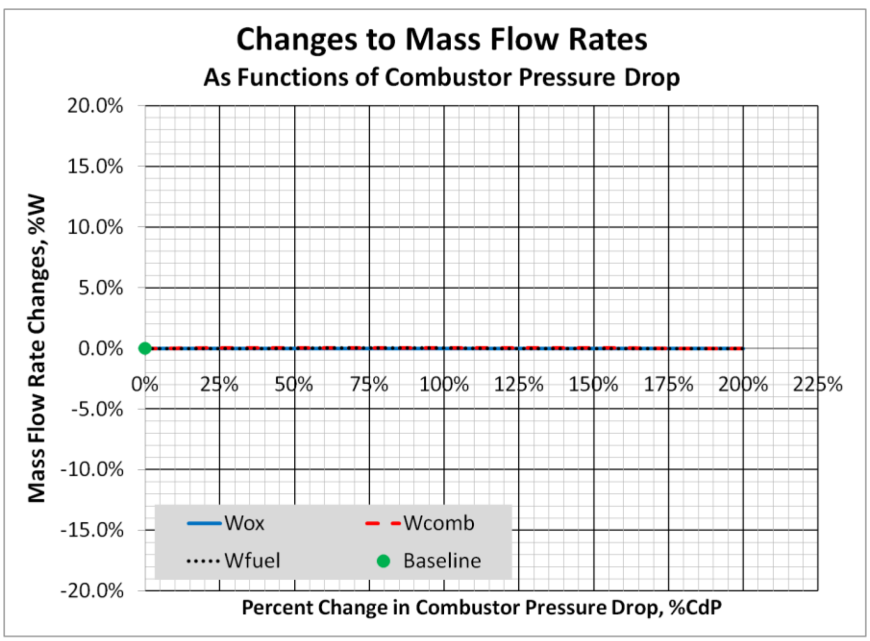


Figure A.2 Round 1 Combustor Pressure Drop Influence on Mass Flow Rates

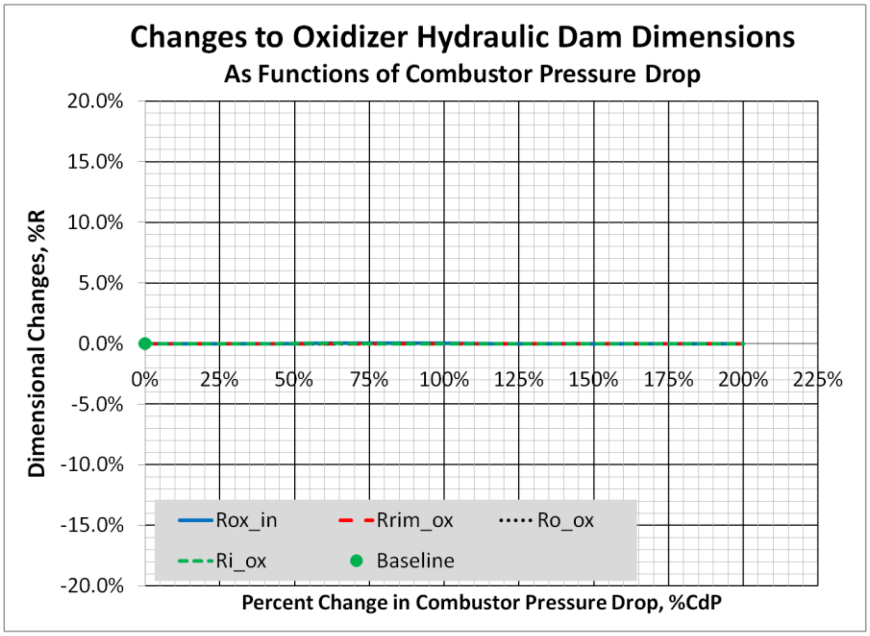


Figure A.3 Round 1 Combustor Pressure Drop Influence on Oxidizer System Dimensions

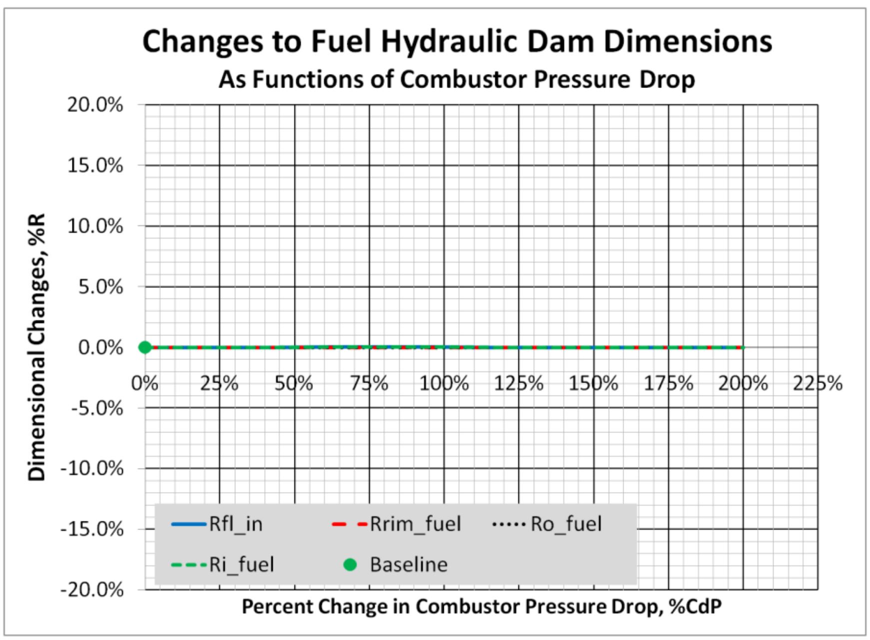


Figure A.4 Round 1 Combustor Pressure Drop Influence on Fuel System Dimensions

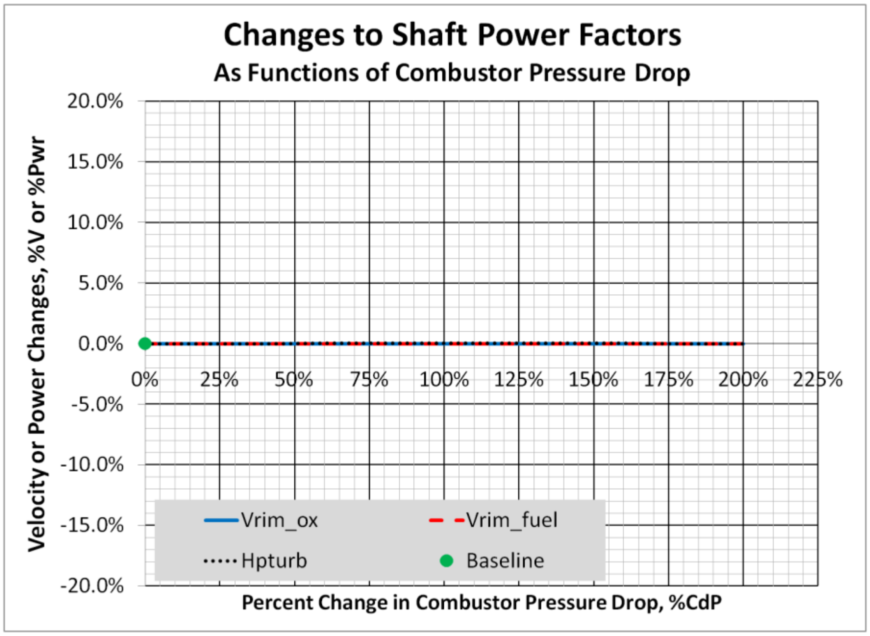


Figure A.5 Round 1 Combustor Pressure Drop Influence on Power Metrics

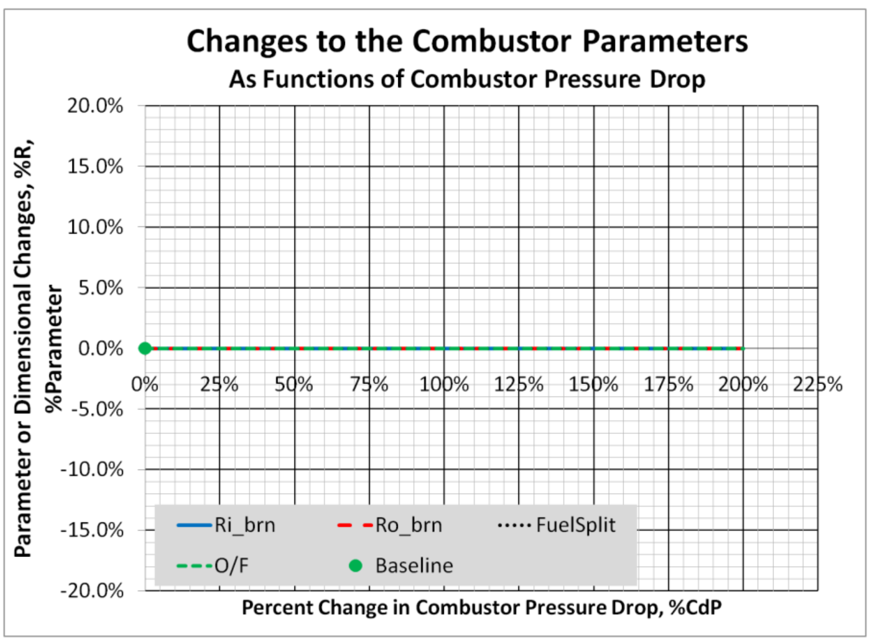


Figure A.6 Round 1 Combustor Pressure Drop Influence on Combustor Dimensions

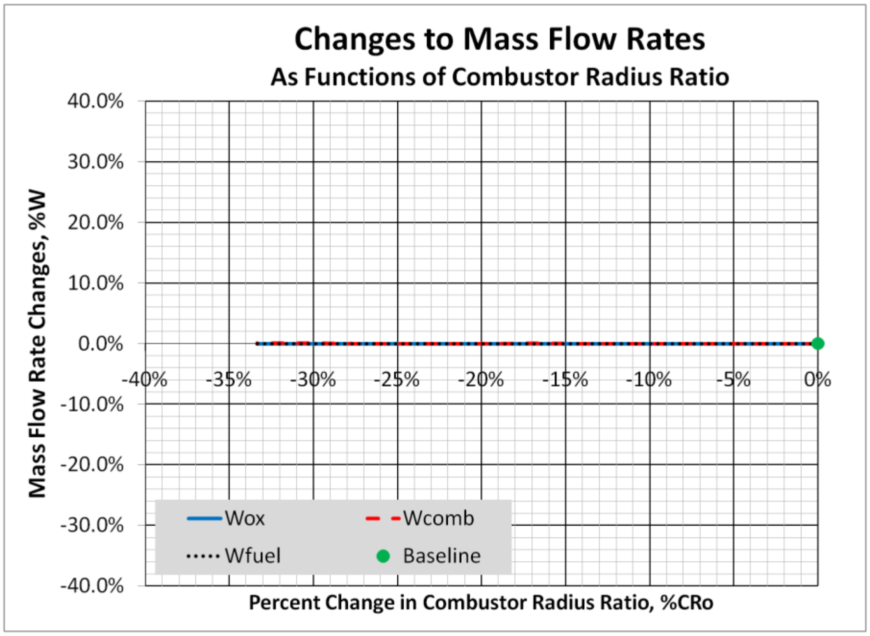


Figure A.7 Round 1 Combustor Radius Ratio Influence on Mass Flow Rates

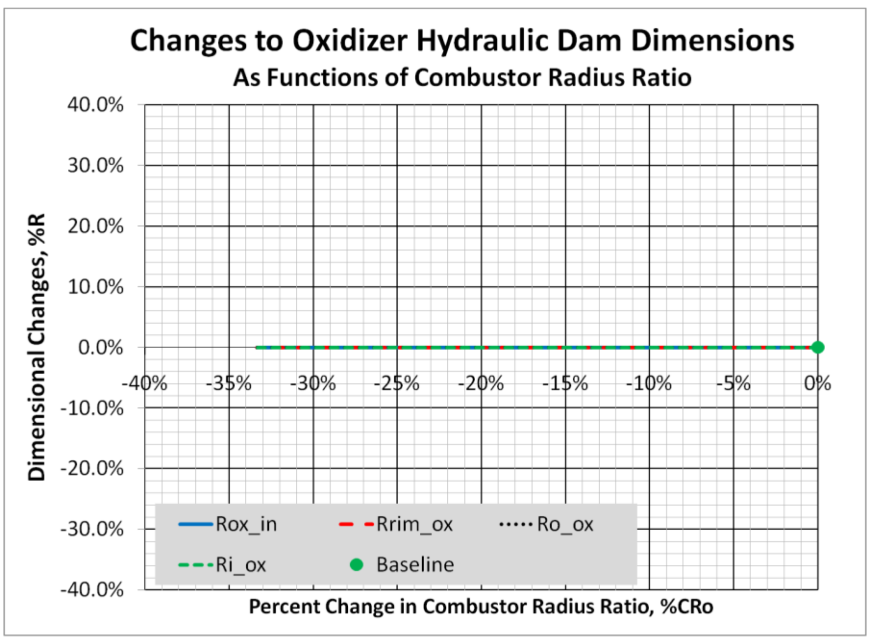


Figure A.8 Round 1 Combustor Radius Ratio Influence on Oxidizer System Dimensions

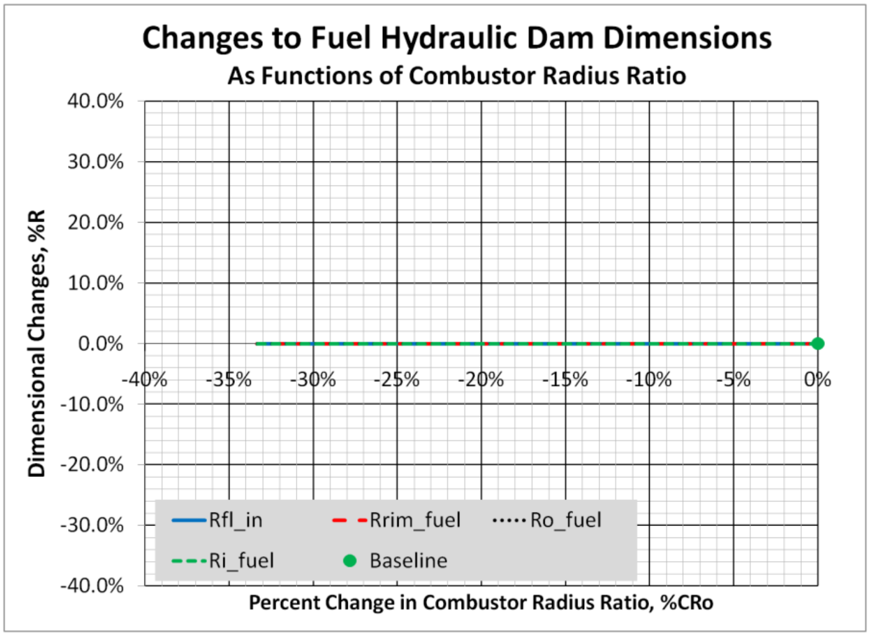


Figure A.9 Round 1 Combustor Radius Ratio Influence on Fuel System Dimensions

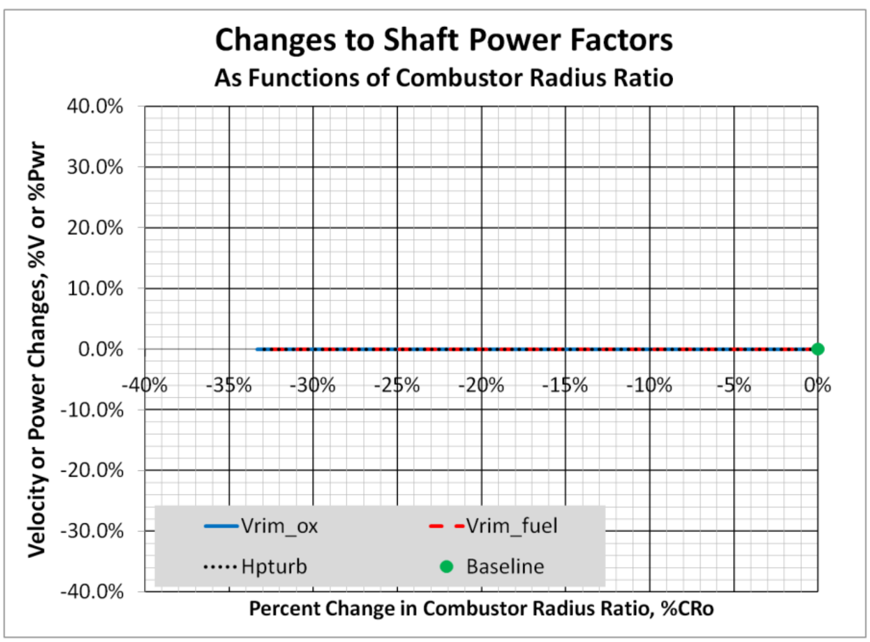


Figure A.10 Round 1 Combustor Radius Ratio Influence on Power Metrics

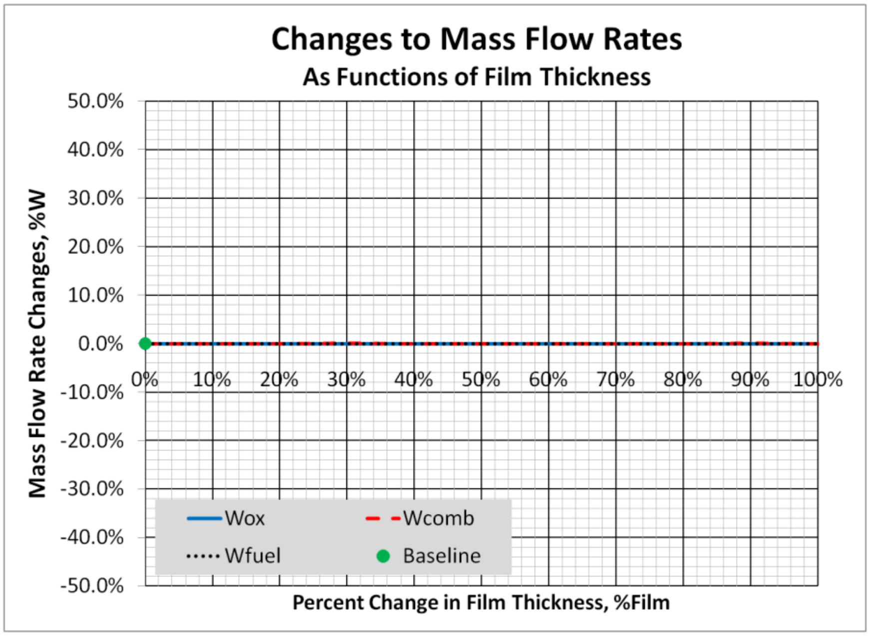


Figure A.11 Round 1 Film Thickness Influence on Mass Flow Rates

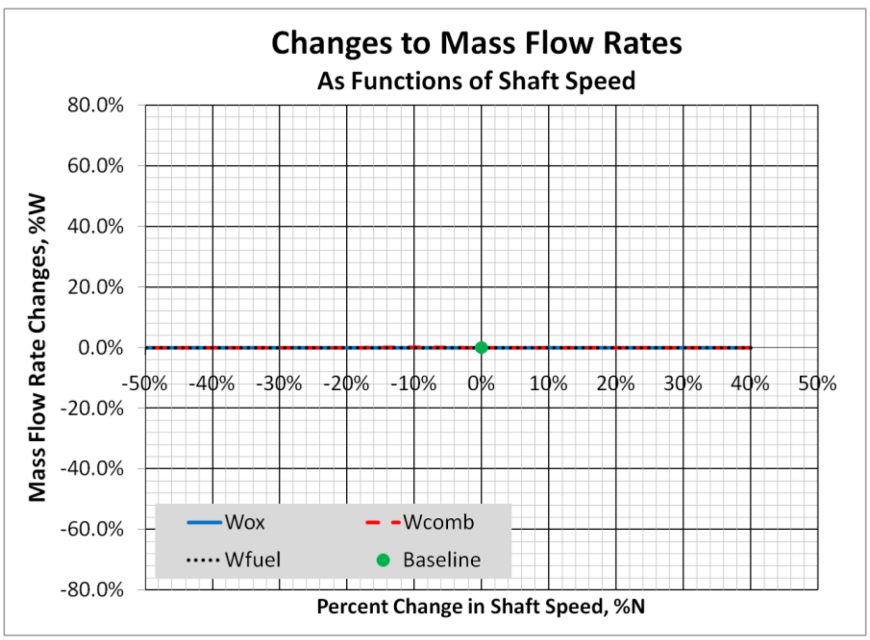


Figure 6.12 Round 1 Design Point Shaft Speed Influence on Mass Flow Rates

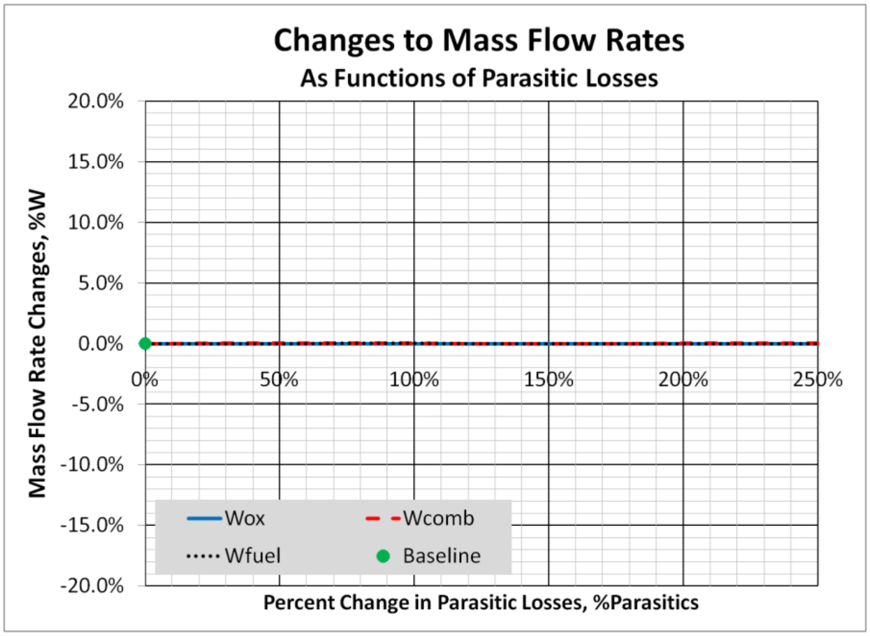


Figure A.13 Round 1 Parasitic Loss Influence on Mass Flow Rates

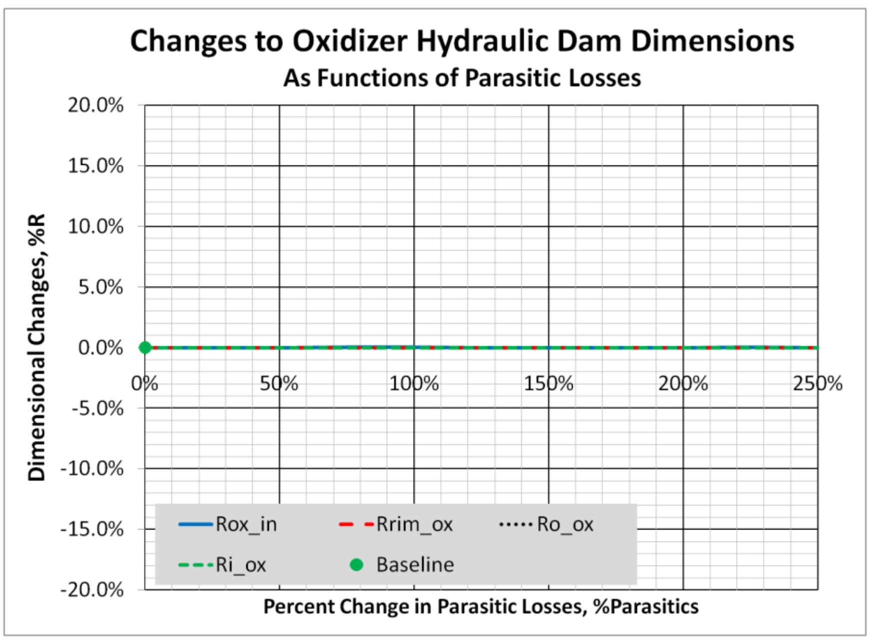


Figure A.14 Round 1 Parasitic Loss Influence on Oxidizer System Dimensions

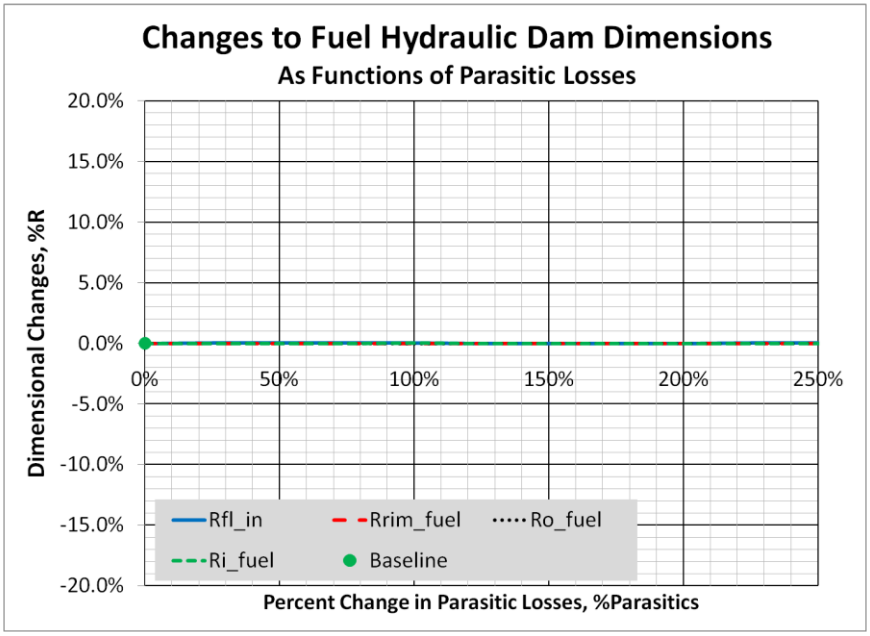


Figure A.15 Round 1 Parasitic Loss Influence on Fuel System Dimensions

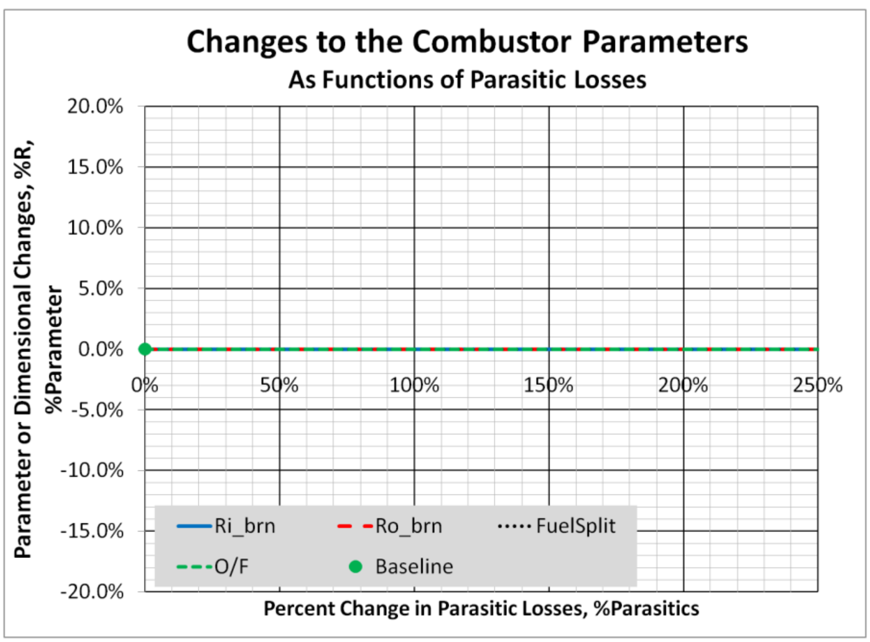


Figure A.16 Round 1 Parasitic Loss Influence on Combustor Dimensions

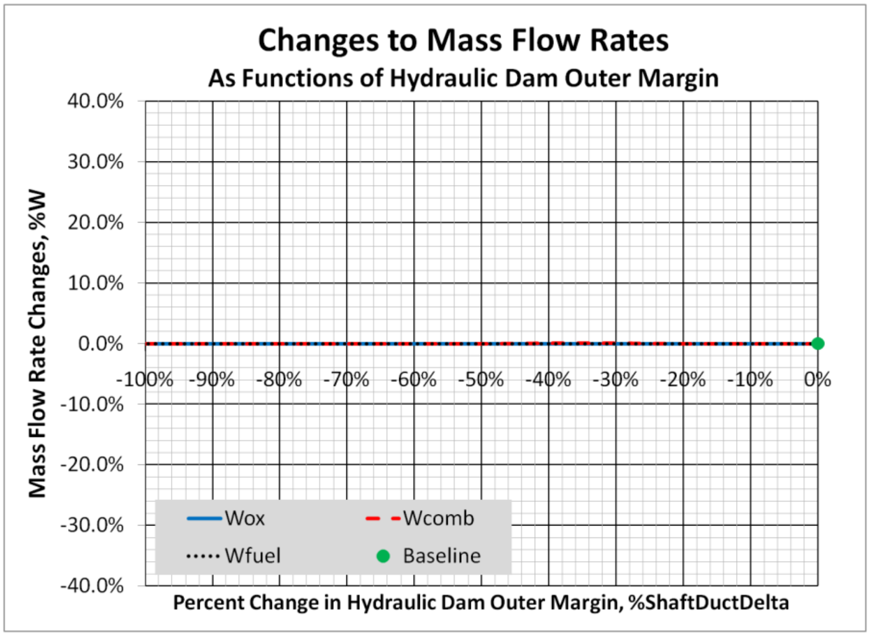


Figure A.17 Round 1 Hydraulic Dam Outer Margin Influence on Mass Flow Rates

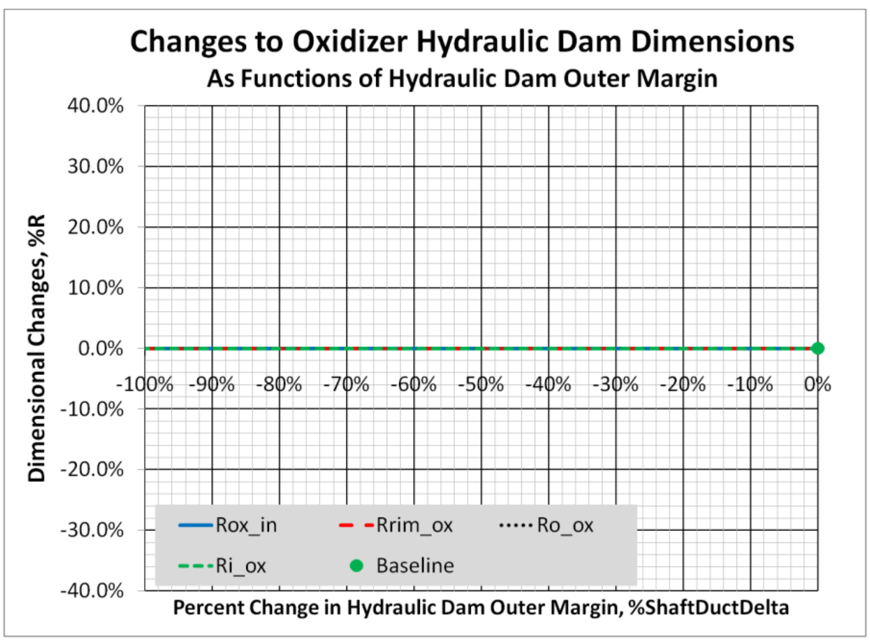


Figure A.18 Round 1 Hydraulic Dam Outer Margin Influence on Oxidizer System Dimensions

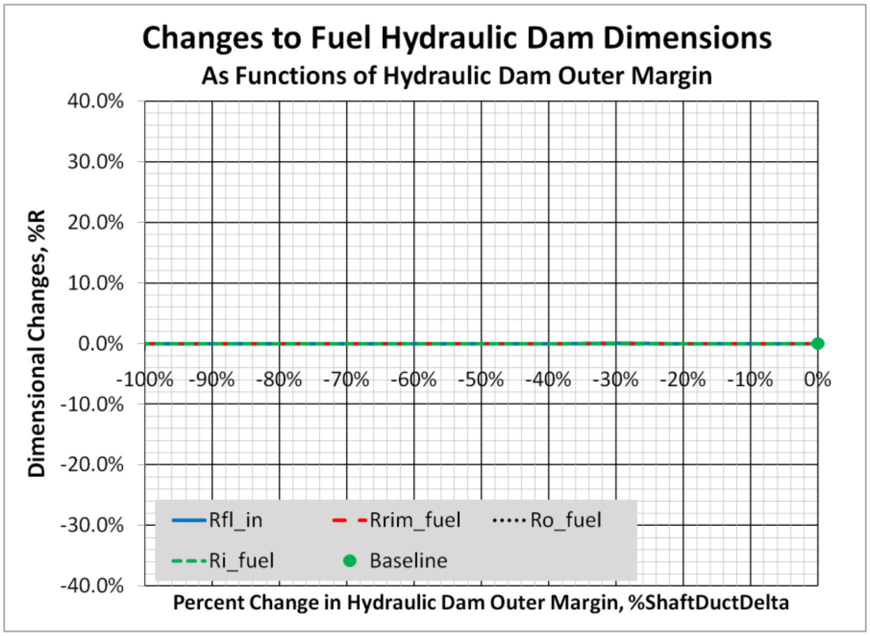


Figure A.19 Round 1 Hydraulic Dam Outer Margin Influence on Fuel System Dimensions

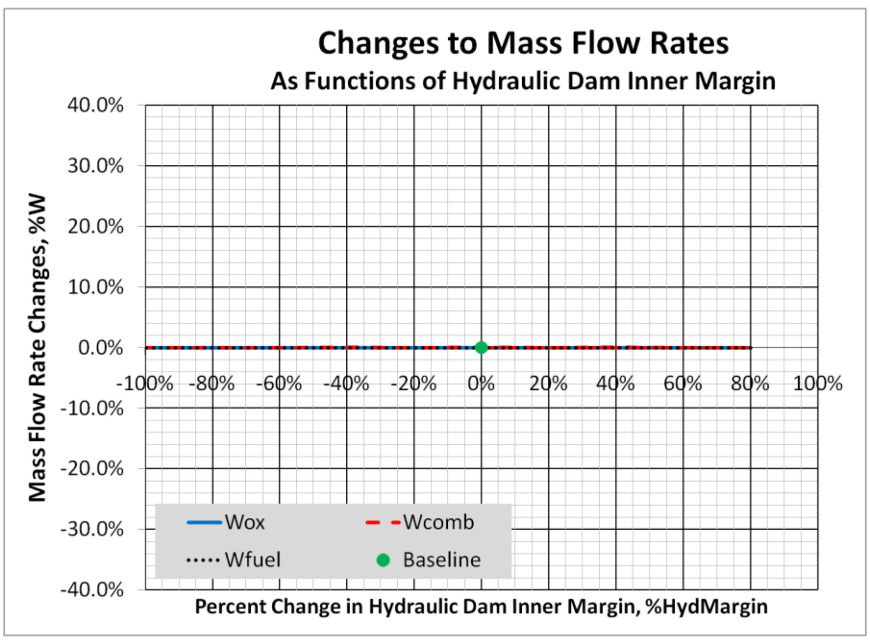


Figure A.20 Round 1 Hydraulic Dam Inner Margin Influence on Mass Flow Rates

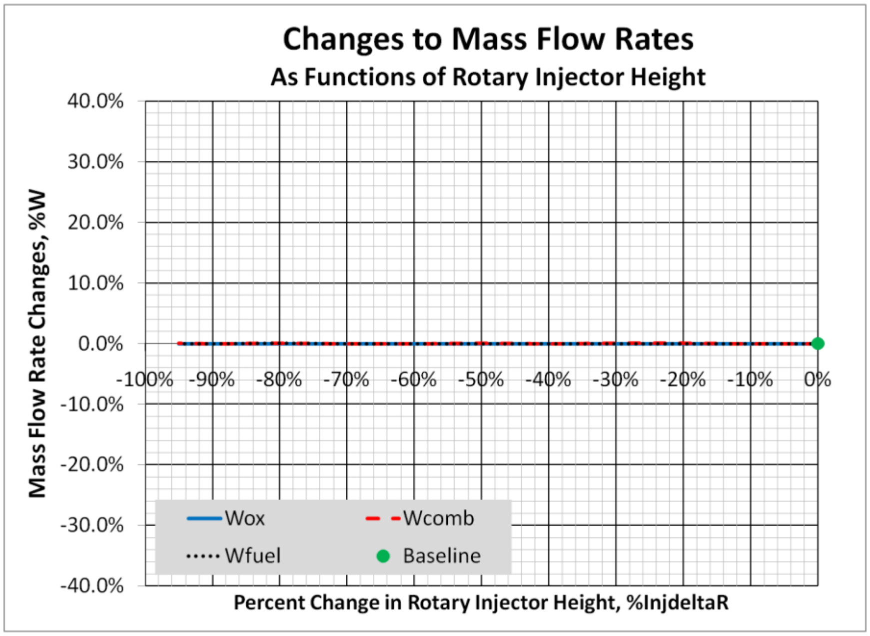


Figure A.21 Round 1 Rotary Injector Height Influence on Mass Flow Rates

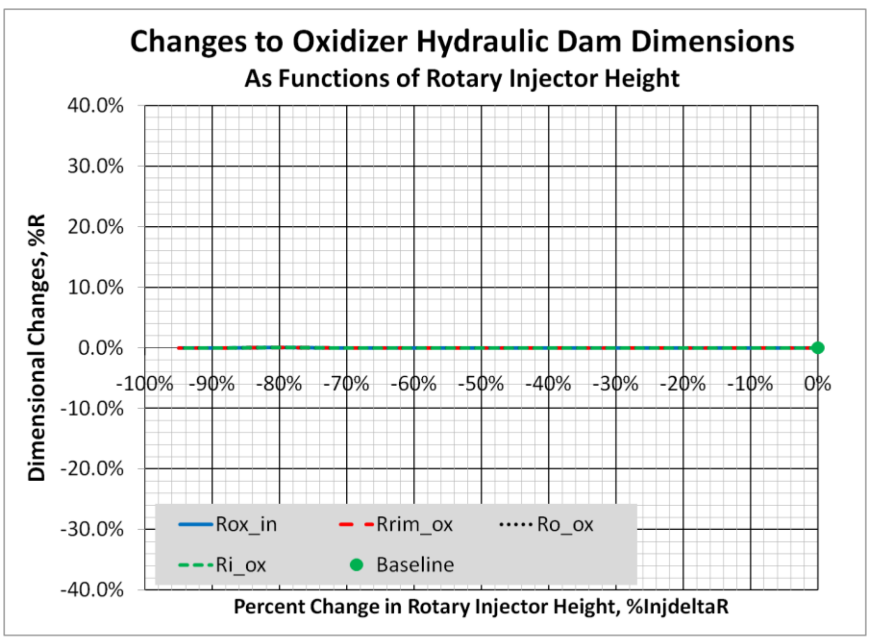


Figure A.22 Round 1 Rotary Injector Height Influence on Oxidizer System Dimensions

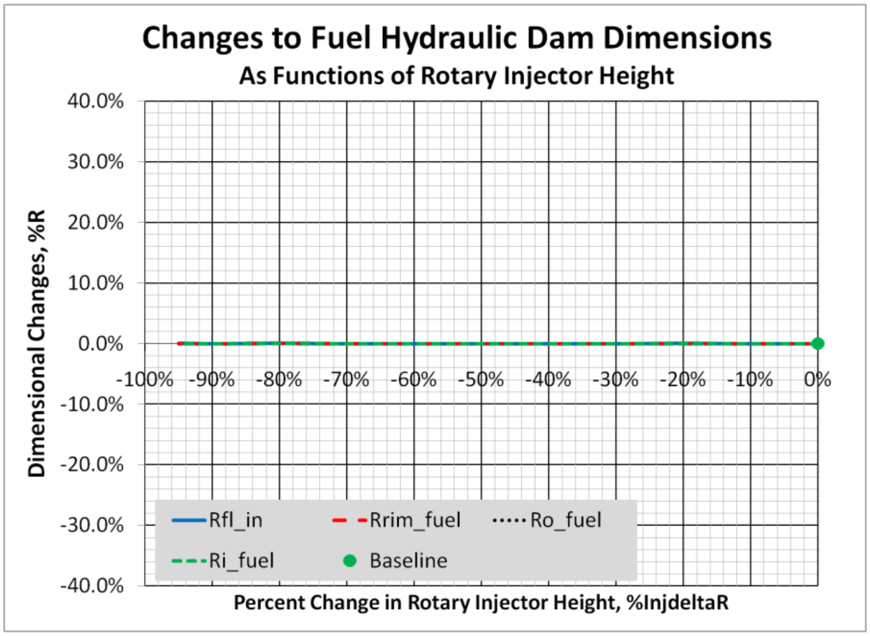


Figure A.23 Round 1 Rotary Injector Height Influence on Fuel System Dimensions

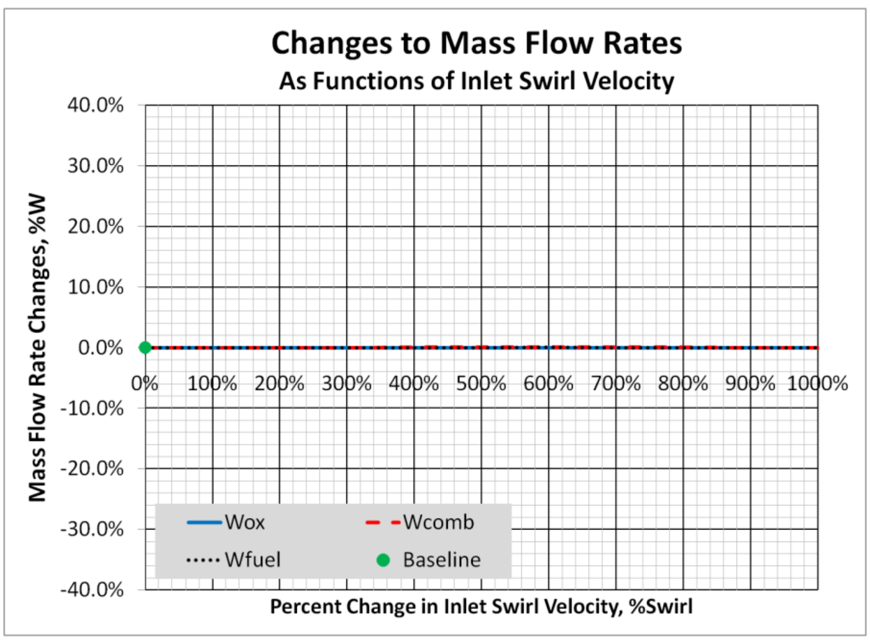


Figure A.24 Round 1 Inlet Swirl Velocity Influence on Mass Flow Rates

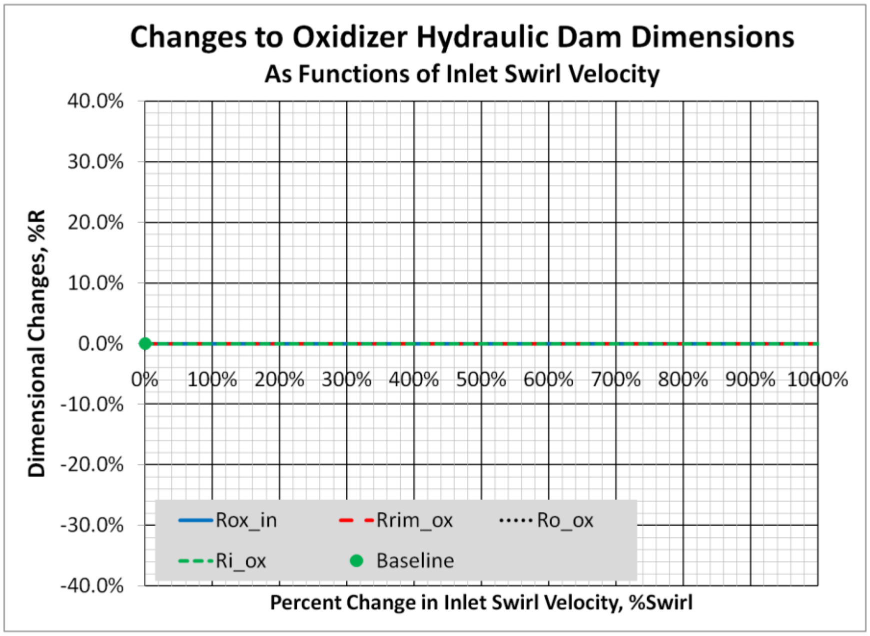


Figure A.25 Round 1 Inlet Swirl Velocity Influence on Oxidizer System Dimensions

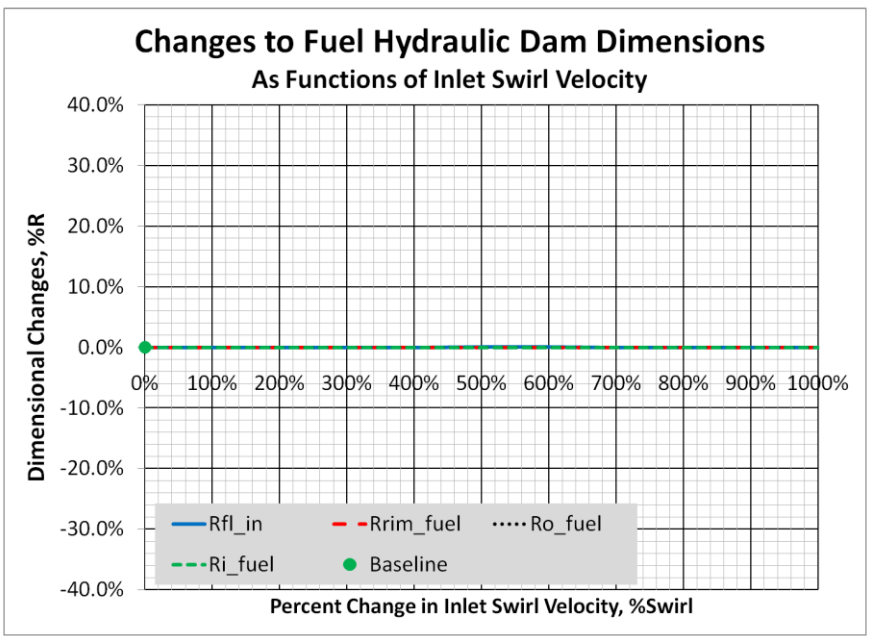


Figure A.26 Round 1 Inlet Swirl Velocity Influence on Fuel System Dimensions

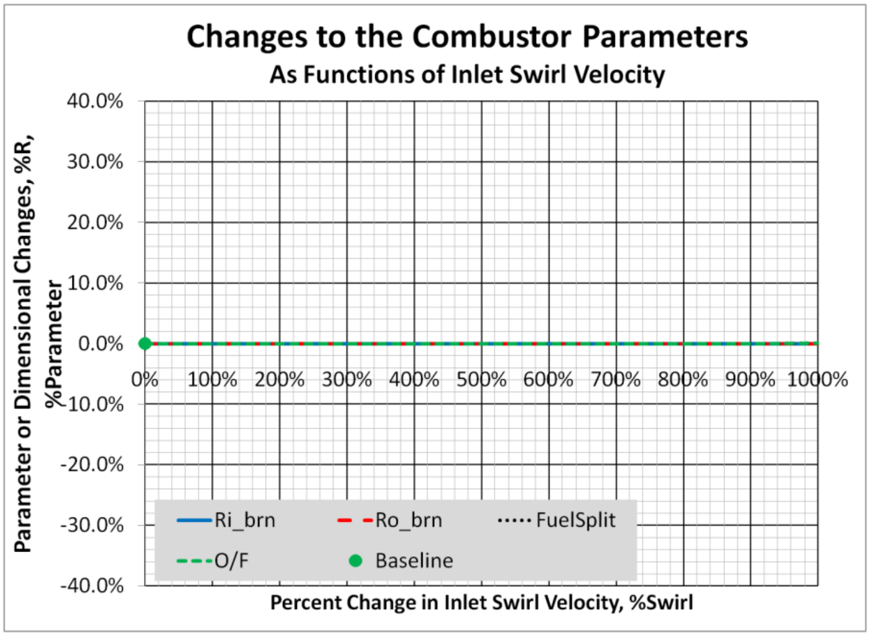


Figure A.27 Round 1 Inlet Swirl Velocity Influence on Combustor Dimensions

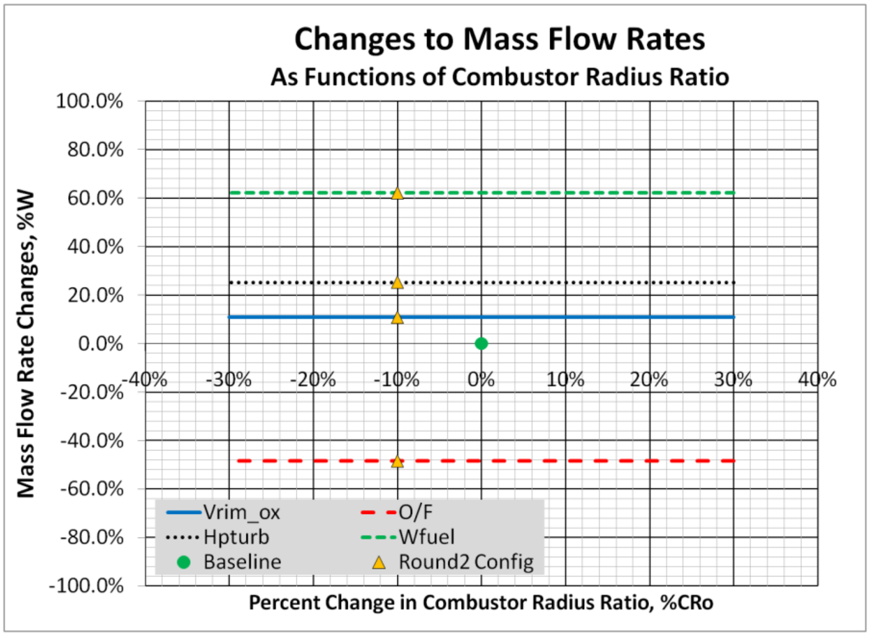


Figure A.28 Round 2 Combustor Radius Ratio Influence on Power and Mass Flow Metrics

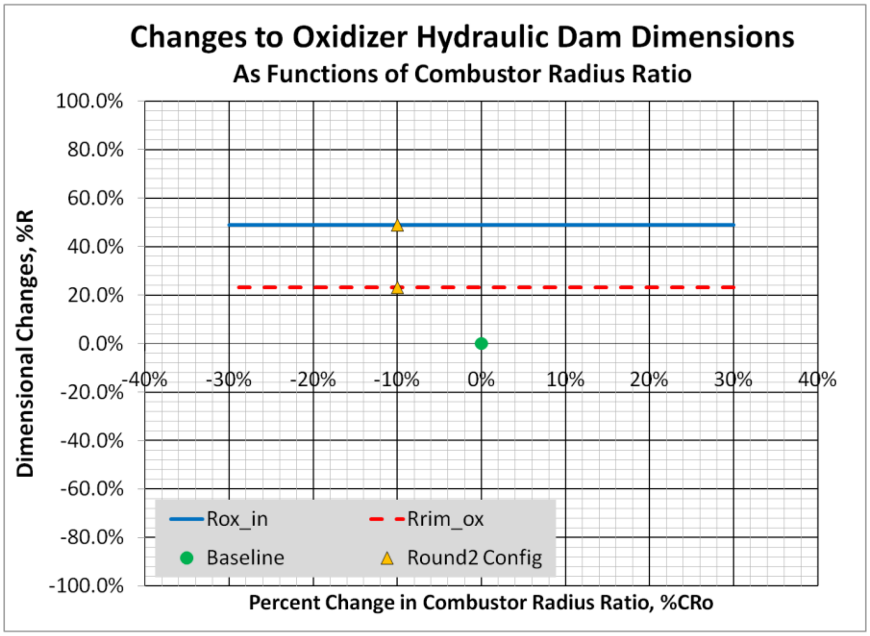


Figure A.29 Round 2 Combustor Radius Ratio Influence on Shaft Geometry Metrics

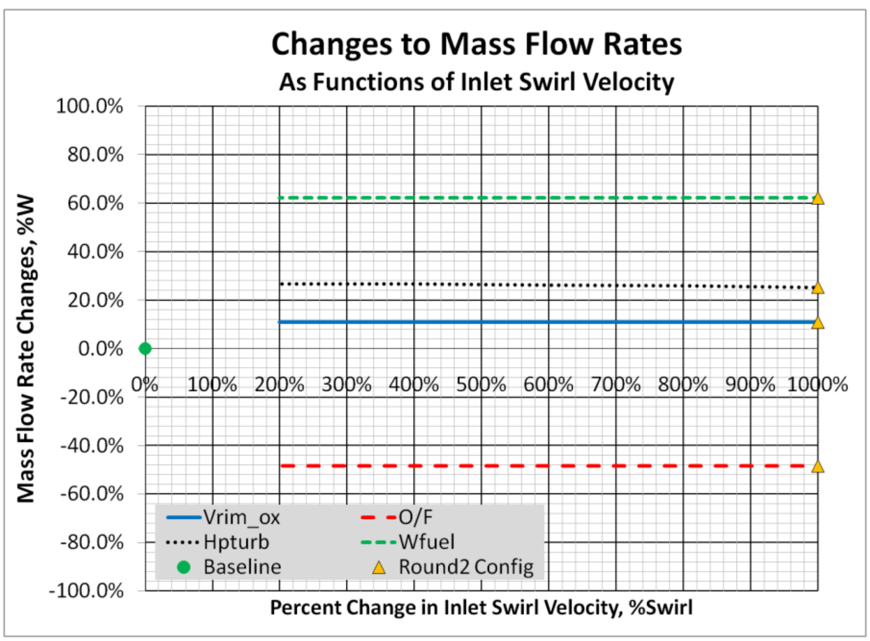


Figure A.30 Round 2 Inlet Swirl Velocity Influence on Power and Mass Flow Metrics

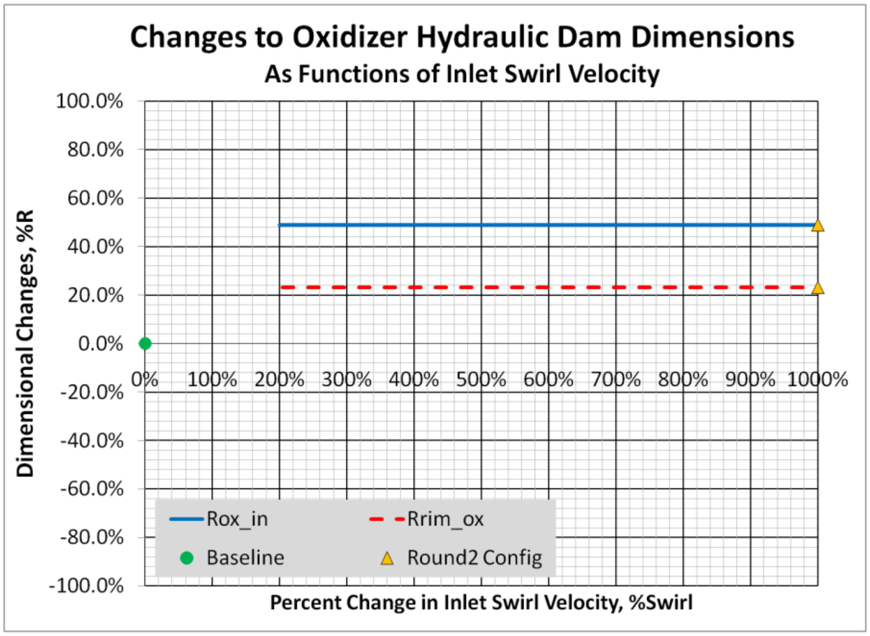


Figure A.31 Round 2 Inlet Swirl Velocity Influence on Shaft Geometry Metrics

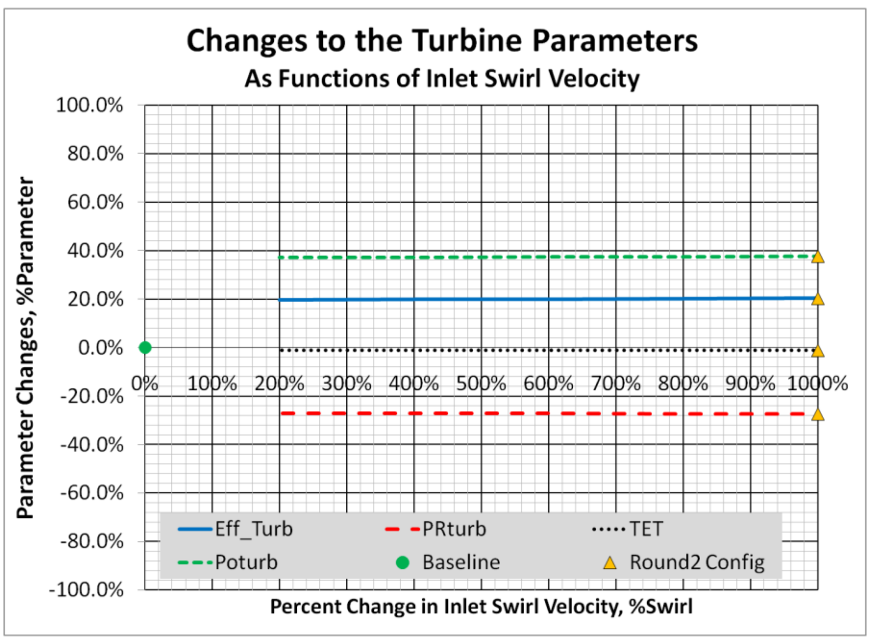


Figure A.32 Round 2 Inlet Swirl Velocity Influence on Turbine Metrics

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BIOGRAPHICAL INFORMATION

Steven Stanley was born and raised in West Texas. In 1993, he completed his Bachelors of Science degree in Aerospace Engineering at Texas A&M University. He went on to the University of Texas at Arlington to work on his Masters of Science degree in Mechanical Engineering. While studying at the University of Texas at Arlington, Steven researched pulse detonation engines. After graduating in 1995, Steven went to work at Williams International in Walled Lake, Michigan, a leader in small gas turbine engines. While there, he analyzed and modeled the performance of small gas turbine engines, ranging in applications from car engines, to business jet engines to cruise missile engines to drone engines. While working at Williams International, Steven completed his Masters of Science in Aerospace Engineering at the University of Michigan in 2003. In 2006, Steven changed propulsion industries by switching from small air breathing engines to small rocket engines when he joined Aerojet in Redmond, Washington. While at Aerojet, working on the next generation of crewed launch vehicles, Steven began working on his Doctorate in Aerospace Engineering at the University of Texas at Arlington and is planning to complete that effort in Fall 2011. Steven currently lives in Sammamish, Washington with his wife of eighteen years, Janna, his five year old son Justin and his three year old daughter Kaitlin. Currently, he enjoys golfing and visiting national parks.