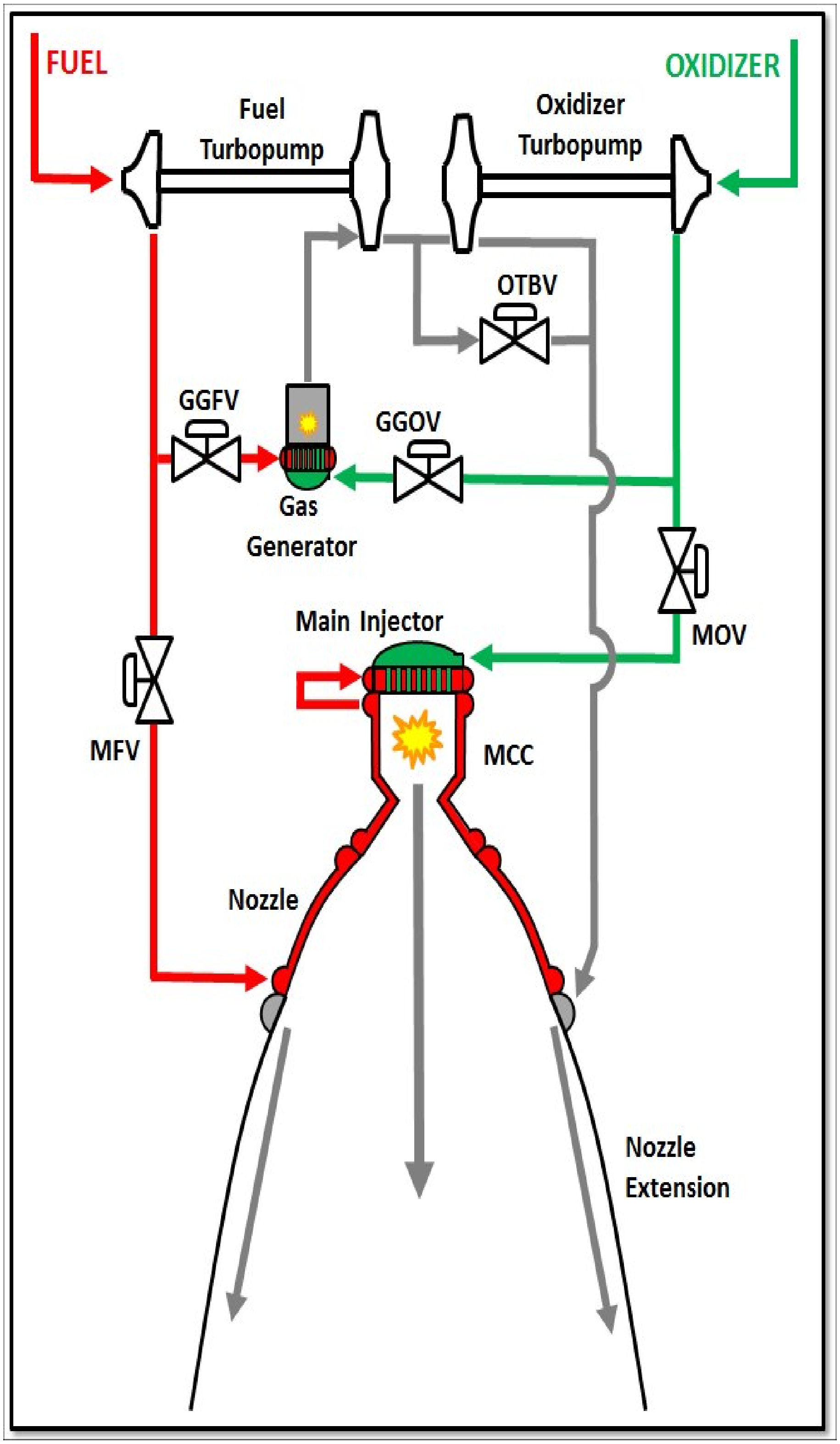
Liquid Rocket Engines (J-2X, RS-25, general)

Tag: engine design

Welcome to the J-2X Doghouse: All a Matter of Balance — and Power

One of the most important analytical tools used in development of a rocket engine is called a "power balance." A power balance is, stated simply, a simulation of the steady-state, internal conditions and functioning of the engine. It can, on one extreme, be accomplished with a spreadsheet or, on the other extreme, take the form of a complex computer program with hundreds of theoretical calculations bolstered by dozens upon dozens of embedded, empirical relationships customized for a particular hardware configuration. But first of all, let's talk about what a power balance is from a purely conceptual point of view. You start with a schematic of the engine:



Where:

MCC = Main Combustion Chamber

GG = Gas Generator

MFV = Main Fuel Valve

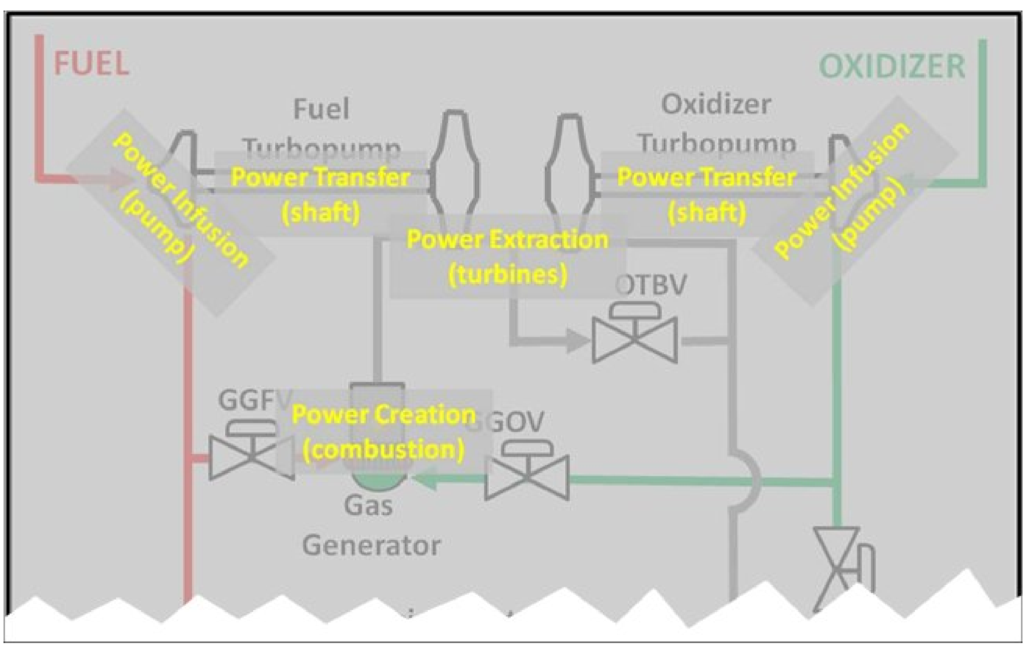
MOV = Main Oxidizer Valve

GGFV = Gas Generator Fuel Valve
GGOV = Gas Generator Oxidizer Valve
OTBV = Oxidizer Turbine Bypass Valve

Next, you break down these pieces of the engine, the components, into descriptions with regards to how they relate to power, pressure, and temperature:

- Pumps: Convert shaft power into fluid power in the form of elevated pressure
- Turbines: Extract power from the turbine drive gases and converts it to shaft power
- Gas Generator and Main Combustion Chamber: Generate power from combustion
- This power is in the form of elevated temperature (combustion = fire = hot)
- Ducts, Valves, and Injectors: Control fluid movement in order to get propellants and combustion products where they need to be, i.e., plumbing. Each of these items reduces pressure in the fluids flowing through them
- Cooling Jackets: Here too pressure is lost as the fluid flows through the cooling passages, but temperatures are elevated as heat carried away (i.e., as cooling takes place)

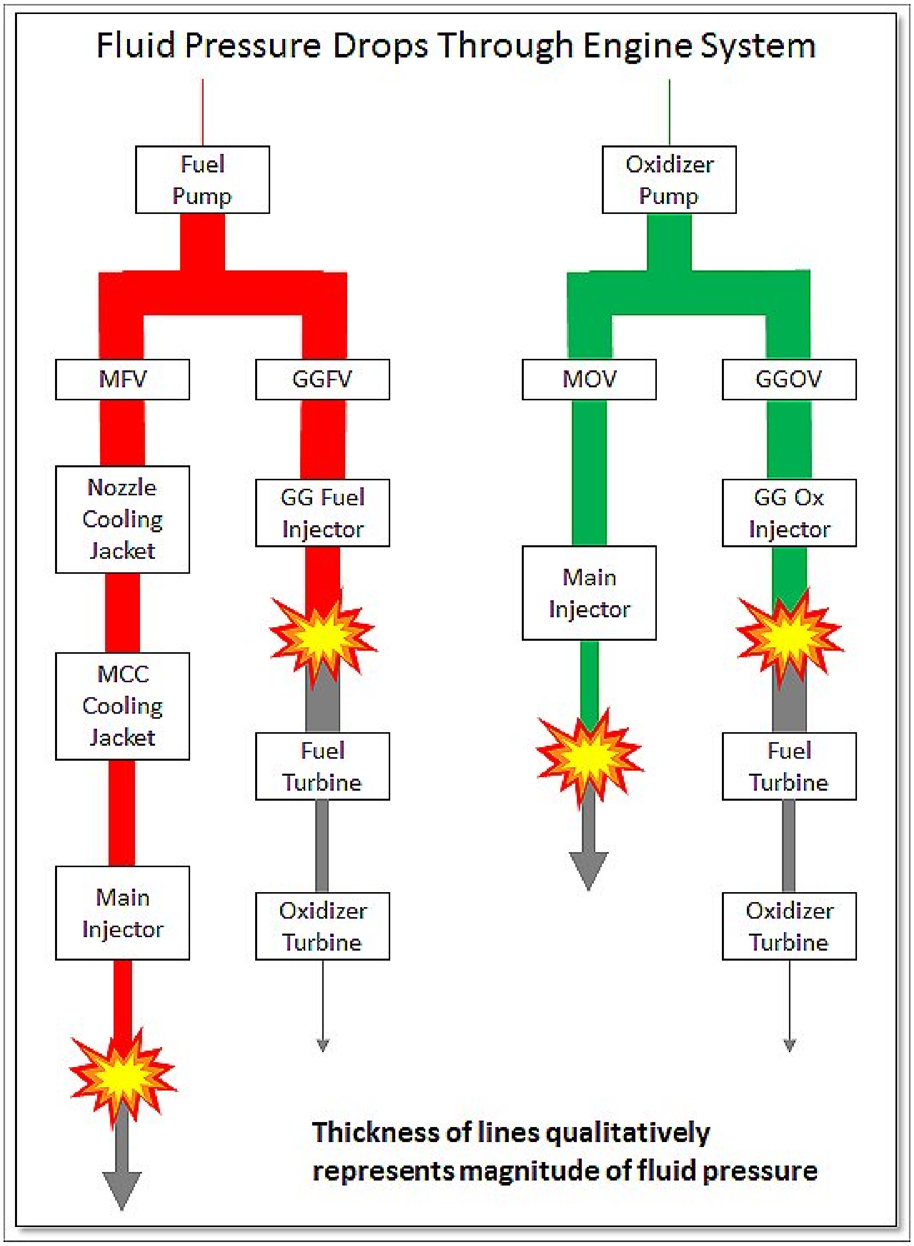
Thus, in terms of the most significant power considerations, here is what is going on with the rocket engine:



You'll note that all of the power stuff happening in the engine is happening up on the top portion of the original schematic (and I've chopped away everything else). In other words, the major power transfer stuff happening in the components that make up what we call our "powerpack" testing. See? That's why and that's where the name comes from. Pretty clever, huh? The whole idea is to get power to pumps so that they can makes lots and lots of fluid pressure so that they can push lots and lots of propellants through the system and into the combustion chamber. That's the whole point of the rocket engine, push stuff to the combustion chamber to make thrust.

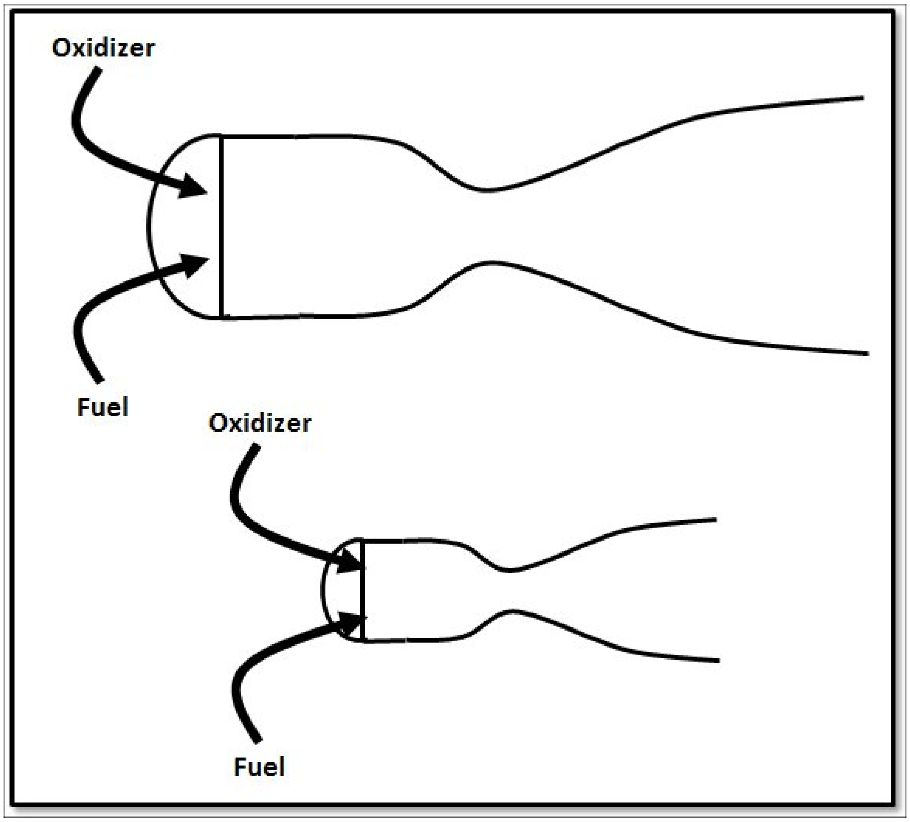
So, how much pressure do you need? That's a matter of how much stuff you've got to push the propellants through and how much pressure you want in the chamber at the end. I sometimes think of it like that great old board game Monopoly ®. You pass "Go" and get $200. Remember that?

Well, in a rocket engine, your pump is "Go" and at that point you get an allotment of pressure. Then, as the fluid goes through the system, from component to component — ducts, valves, cooling jackets, injectors — you have to pay rent in the form of a loss of pressure. That's like landing on the various squares around the board. Paying all that rent is just fine. You can't really avoid it. But you have to make sure that you save enough money to stay at the hotel on Boardwalk in the end without going bankrupt. In other words, you need to get your propellants into the chamber at the residual pressure that you desire. Here's a representation of this pressure management process within the J-2X on both the fuel side and on the oxidizer side:



The explosion-looking symbols in that diagram represent combustion zones. One is the gas generator, where you make the power to drive the pumps, and the other is, of course, the main combustion chamber, where you make your thrust. The gray lines represent combustion products coming out of those combustion zones.

One last question that needs to be considered is this: How much combustion chamber pressure do you want (and/or need)? In other words, when your propellants arrive at the main combustion zone, at what residual pressure do you want that combustion to take place? Sounds like a simple question, right? Well, of course, you want it to happen at the "optimal" pressure. But what does that mean? That is not an easy question to answer. In terms of energy release, within certain bounds, the chamber pressure does not much matter (or, at most, it's a secondary factor). What it really comes down to, believe it or not, is engine size and weight and a handful of manufacturing considerations.



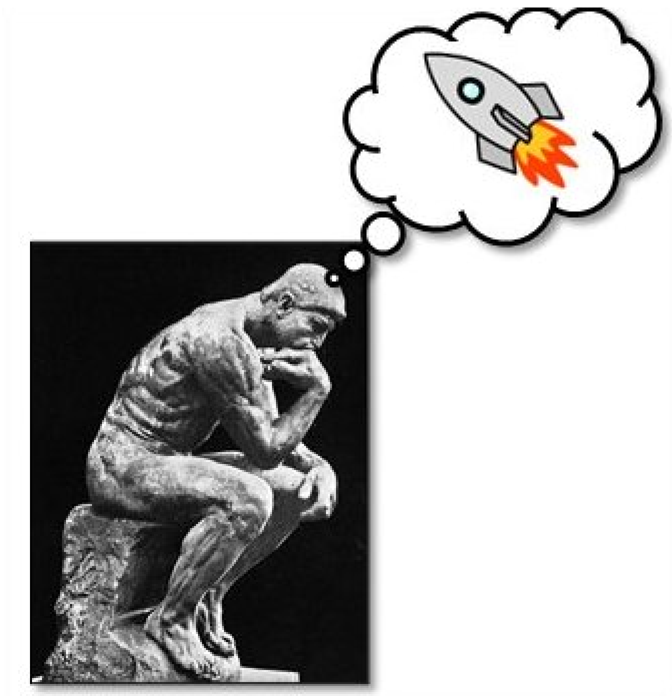
In the drawing above, I have tried to show two combustion chamber and nozzle combinations where the one on top has a throat diameter and nozzle exit diameter twice as large as the respective measurements in the lower version. Thus, both engines using these combustion chambers and nozzles would have the same ratio of nozzle exits area to throat area. It's just that the one on the top would have a throat with four times as much area (area being proportional to the square of the diameter). Would it surprise you to learn that these two engines could generate the same thrust if the one on the bottom had four times as much chamber pressure as compared to the one on top? Yep, it's true. If the top engine has, say, 500 psi (pounds per square inch) chamber pressure and the bottom one has 2,000 psi, then these two rockets are — to first order estimates — operating at the same performance level.

What does that mean? That means that you could have a great big, bulky rocket engine or you could have a small, "tight" one. It would seem that the small one feels more efficient except that with that high chamber pressure you have to generate all that extra pressure in your pumps. That takes a lot of pump power and therefore turbine power. And containing all of that pressure throughout the engine system means thicker walls on your ducts and valves and everything else. Thicker walls mean heavier pieces. So maybe that "tight" engine is really more wasteful. So instead, maybe the big bulky engine sounds like a good idea since it's easier on your turbopumps. Except then you realize that it's too big to fit on your vehicle and, by the way, that monstrously big nozzle weighs a ton and nobody has machining tools large enough to produce the thing. So maybe the bulky one isn't right either. Blah, blah, blah… It's enough to give you a headache! But those kinds of discussions back and forth are what are known as trade studies and they are the foundation for what your engine will eventually become. There is rarely a simple, obvious answer since everything has impacts on everything else.

So, how does all of this get back to the power balance? Well, you take all of those notions discussed above and start applying the following:

- Calculations that describe how much energy is released by the combustion of your propellants.
- Calculations that relate pump speed and pump design features to fluid pressure increases.
- Calculations that relate turbine-drive gas conditions and turbine design features to power extraction.
- Calculations that describe pressure losses for fluid flowing through ducts, valves, cooling jackets, and injectors.
- Calculations that relate fluid flow and fluid conditions to heat transfer processes in cooling jackets

Once you have all of these relationships, then you can perform a power balance. You use your power balance to inform your trade studies. Bigger or smaller? Faster or slower? You just have to realize in using it that you can't get anything for free. The power that you generate in your gas generator uses up some of your propellants (for a gas generator cycle engine) so they can't go through main injector with the purpose of generating thrust. You cannot perfectly extract the power from the turbine drive gases. And, you also cannot pump with perfect efficiency. These considerations all have to be taken into account in your calculations. But the result will be an analytical model that can tell you the pressure and temperature of the propellants throughout their journey through the engine. It will tell you shaft speeds of the turbopumps. And it will give you overall performance of your rocket engine.



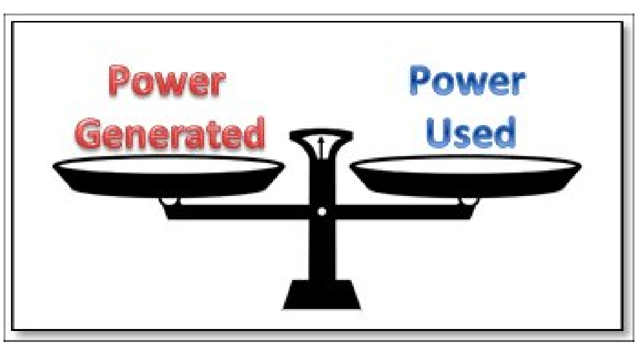
So, let's say that you've been given the job of designing an engine from scratch. You have a thrust requirement and a specific impulse requirement. Let's say, further, that you know what your propellants are supposed to be and let's even go so far to say that you've been told that it ought to be a gas generator cycle engine. Okay, so now what do you do?

Here's one approach (...one of many, many possible):

- Pick a chamber pressure.
- Because of your thrust requirement and specific impulse requirement, you can start with a pretty good guess as to your propellant flow rates.
- Next, generate your schematic layout of the engine and the various components and piece together your simulation of the system.

- Then, figure out how much pressure your pumps need to generate and, therefore, how much power you need your gas generator to create.
- Balance that pump power needed with turbine power to be extracted; you've now set your gas generator conditions.
- Based upon how much propellant that you're "losing" down the gas generator / turbine drive leg, you can figure out how much nozzle expansion ratio you need to get to your specific impulse requirement.
- You'll probably go around a bit in circles with the previous few steps — also known as iterating — until you get a completely self-consistent set of answers (It's essentially a process of making educated guesses, seeing if everything balances out, making new guesses based upon any lack of balance, and again seeing if everything balances. With a good solution scheme, you'll eventually arrive at a place where all your guesses work and your system is balanced.)
- You now have a rocket engine design.

But, is it what you want? Can you build it? Does it fit with the vehicle? Will it be too heavy? Are the component performance factors within reasonable expectations (i.e., rules of thumb carried around by the various component experts)? Is the design close enough to a legacy design so that you might be able to leverage previous, related experience? Or, perhaps, is the design all so new and different that the necessary development program will be quite extensive (and therefore expensive)? It may be that there are a whole bunch of reasons why your design, frankly, stinks so you need to go through the whole process again. In the end, after several cycles through, you almost never come up with a design that makes everyone happy from every perspective, but you come up with one that is sufficient, acceptable, and reasonable. So that's the design that you go and design, develop, and test.



Hopefully, I've shown you that a power balance, an analytical simulation of the internal workings of an engine, is an integral tool in the conceptual design of a rocket engine. Once you've got some general idea of some key parameters you need, the power balance fills in the details, sets the necessary parameters for your turbopumps, captures your fluid splits and conditions, and establishes the general sizing for your main combustion chamber and nozzle. It uses physics and physics-based empirical relationships — combining the disciplines of fluid dynamics, heat transfer, combustion science, and hardware mechanics — for all of the major components of the engine to balance the power generated against the power used and, in so doing, describes conditions throughout the engine.

(This, by the way, is my favorite kind of analytical modeling simply because it combines so many different disciplines and yields such a broad and useful tool. I was lucky enough to be assigned to power balance modeling activities for the Space Shuttle Main Engine when I started working. And that experience has informed everything else I've done for the last 20+ years.)

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