Design of an Expander Cycle Engine with J-2 Equivalent Thrust

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Abstract

Contemporary gas generated systems and steering systems are complex, costly to manufacture, and costly to process prior to launch. Contemporary expander cycle rocket engines are limited to low thrust engine sizes due to the square cube rule. Proposed engine architecture (regeneratively cooled jet vanes) will produce an operationally efficient, expander cycle engine design with thrust levels of approximately 240,000 lbf or more that is integrated with the steering system to produce an engine/jet vane combo which reduces operational and processing cost versus contemporary engine/TVC combos. A full expander cycle engine can obtain equivalent thrust and superior specific impulse over the J-2X gas generator cycle engine while being much lower in manufacturing & processing costs via the use of this architecture. This increase in operational efficiency and specific impulse is accomplished by obtaining additional heat energy for the turbine from regenerative-cooled steering-jet-vanes.

Nomenclature

APU	=	Auxiliary Power Units are devices that produce mechanical power via hypergolic propellants for military aircraft & launch vehicles or kerosene for commercial aviation that are used to power hydraulic pumps.
DD&T	=	Design, Development, & Testing is a term for the cost of researching & producing the first unit of a product.
EMA	=	Electro-Mechanical Actuator
GH2	=	gaseous hydrogen
Isp	=	Specific Impulse is a term for rocket efficiency and is given in units of seconds.
kW	=	kilowatts
LH2	=	Liquid Hydrogen
LOX	=	Liquid Oxygen
LRB project	=	Liquid Rocket Booster project was a concept of replacing the Space Shuttle Solid Rocket Boosters with liquid.
OEPSS	=	Operationally Efficient Propulsion System Study
GN&C	=	Guidance, Navigation, & Control
RL-10	=	Expander cycle LOX/LH2 engine
RS-68	=	Largest gas generator cycle LOX/LH2 engine ever built
Square cubed Rule	=	A term to represent the relationship between the area and volume of an object; as the size of a box doubles in size, its surface area will increase by 4 (2 square) while its volume will increase by 8 (2 cubed).
SSME	=	Space Shuttle Main Engine
T-0	=	Umbilicals that are disconnected at the moment of lift-off
TVC	=	Thrust Vector Control is the use of two actuators to gimbal a rocket engine.

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I: INTRODUCTION

Expander cycle engines have the advantage of providing very high specific impulse and an extremely robust, simple design with inherent safety for controllability. However, due to the square cube rule, expander cycle engines are limited to low thrust applications. Applications for greater thrusts required the use of gas generator cycle and stage combustion cycle engines. However in general, gas generator cycle engines are not as efficient and stage combustion cycle engines are more complex and more difficult to fabricate and control than expander cycle engines. The first hydrogen powered engine to fly in space[I] was the RL10A-1 engine, which was an expander cycle engine that operated at a chamber pressure of only 300 psi (2,068 kPa), specific impulse of 422 seconds and 15,000lbf (66,723N) of thrust. Contemporary theory states, the expander cycle is not practical above 1,100-psi (7,584 kPa) chamber pressure since the vaporized fuel does not provide enough energy to drive the turbine to produce the higher pressures.[II] The proposed technology will circumvent this limit by obtaining heat from jet vanes.

Not only is engine design extremely important for cost considerations, but also vehicle attitude control (pitch, yaw, and roll) and power are just as significant for launch operational costs. A means of steering the launch vehicle often require the use of operational intensive systems using hydraulics and hypergolics. The purpose of proposed engineering architecture is to produce an operationally efficient, expander cycle engine-design with thrust levels ten times greater than possible today while integrated with the steering system to produce an engine/Jet Vane combo with reduction in cost versus contemporary engine/TVC combos. This remarkable feat is accomplished by obtaining additional heat energy for the turbine from regenerative-cooled, servomechanism (or rotary actuators), steering-jet-vanes.

Two particular initiatives that formulated a matrix on launch vehicle design that were built off of lessons learned are Operational Efficient Propulsion System Study (OEPSS) and Space Propulsion Synergy Team (SPST). The OEPSS data book teaches us that hydraulics and hypergolics are the most processing-intensive attributes in launch vehicle preparations. Having a vehicle steering system that is based upon servomechanism (or rotary actuators) will significantly reduce the operational activities required for launch preparations.

II: SIGNIFICANCE OF THE STUDY

During a NASA-KSC sponsored Liquid Rocket Booster (LRB) study by Lockheed in 1987, one of the bidding contractors stated that the engines represented 46% of the $3,224M DD&T costs and 42% of the $51M re-occurring costs of each LRB and the turbine represented 50% of the engine cost (Smith, 1988)[III]; as shown in Figure 7 in APPENDIX 1. Please Note: These costs numbers assumed 12 launches per year with two boosters per launch and four engines per booster. Therefore, the engines are costing $5.4M each even while being produced at 96 identical engines per year!

Presently, the delivery cost of the "50-year-old technology" RL-10 expander engine is $4-5 million each. While each J-2S and the RS-68 gas-generator engines will be delivered to NASA for roughly $20 million and the SSME staged-combustion engine is delivered for $50-$75 million (informed source, 2004)[IV]. As part of the Delta IV launch vehicle, the RS-68 represents $14M (or **19.4%**) of the total $72M (1999$) received for launch vehicle services at a launch rate of 24 per year (astronautix.com).[V]

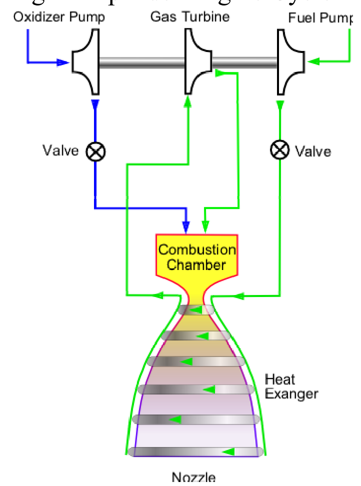
APPENDIX 1 shows that engines are the major cost driver to launch vehicle costs. In fact, the cost of the engines drives the costs of the other hardware. If the turbine can be cheaply machined then the entire cost of the launch vehicle can be reduced by orders of magnitude. Under the current design philosophy, the value of the turbopump is so significant that extensive measures are undertaken to reduce the weight of other launch vehicle components, such as the propellant tank. Therefore, if a SSME equivalent thrust engine, including vehicle attitude control, can be produced for under $1 million the reduced cost propulsion system will have a profound effect on the overall cost of travel into orbit.

III: REVIEW OF LITERATURE

Why Expander Cycle Engine; Technology Background

The expander cycle is an extremely simple rocket engine cycle; it does not require a pre-burner or gas generator; a flow diagram is shown in Figure 1[VI]. The gases that drive the expander engine turbine obtain their heat via regenerative cooling the main combustion chamber and nozzle. Only LOX/LH2 engines have been developed using expander cycle since hydrogen sufficiently cools the combustion chamber while obtaining adequate energy to drive the turbine. However, the low density of hydrogen requires high speed and/or multiple-stage pumps to raise the hydrogen discharge pressure. The pump discharge pressure must be high enough to overcome chamber and nozzle coolant pressures losses and still meet the turbine pressure ratio.

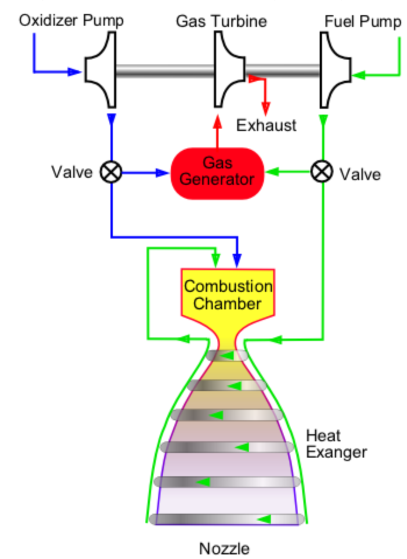
Fig 1 Expander Engine Cycle



Two other turbopump engine cycles are the gas generator and the staged combustion; a flow diagram of each is shown in Figures 2 & 3[VII]. Their high temperature turbines and complex valving operations increase their manufacturing and launch preparations costs.

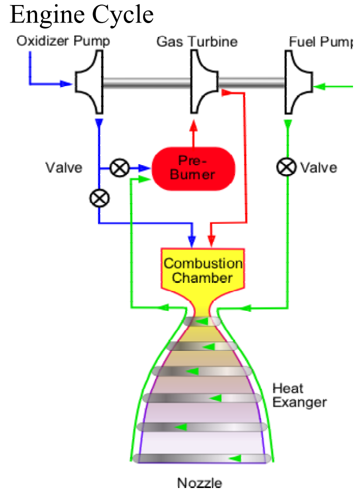
A traditional gas generator cycle engine utilizes a small portion of the propellant to combust outside of the combustion chamber to power a turbine whereas a tap-off gas generator routes diluted reactants from the combustion generator to the turbine. The reactants from the turbine are dumped without contributing to vehicle thrust. The reactants are usually mixed at approximately 1:1 ratio to keep the temperature below the melting point of the turbine blades and therefore, much unburned fuel is dumped. Still, gas generators can maintain good efficiency and require a much smaller turbine by exhausting from the turbine to a much lower pressure than stage combustion or expander cycle engines. The F-1 and J-2 engines from the Saturn V are examples of gas generator cycle engines.

Fig 2 Gas Generator Engine Cycle



Stage combustion is similar to the gas generator engine except the propellants are combusted in a pre-burner. From there, the hot reactants are routed through the turbine(s) before being injected in the combustion chamber where they are combined with additional oxidizer to produce thrust. In both of these engine cycles, the engines can become very efficient by increasing the temperature of the reactants to more than 1,500 deg F before being routed through the turbine. Such high temperatures create major engineering problems in material selection and production.

Fig 3 Staged Combustion Engine Cycle



Other Comparisons between Expander Cycle vs. Gas Generator & Stage Combustion Engines

Expander cycle engines can be designed to obtain some of the highest rocket engine efficiencies. Expander cycle engines are extremely simple to start and inherently safe from run-away conditions. Unlike gas generator engines, which must be spun-started by high-pressure helium or solid rocket cartridge; simply open the fuel valve on an expander cycle engine and the engine will pump. Unlike gas generator and stage combustion, which must be carefully controlled so the proper amount of propellants are mixed in the pre-burner or gas generator or risk explosion; simply close the fuel valve on an expander cycle engine and the engine will shut itself down. Since the gases going through the turbine are at a lower temperature, the turbine blades could be constructed with cheaper materials and cheaper methods. Less valves and no external combustion within an expander cycle engine also mean less parts and less complexity.

Problem with Expander Cycle Engines

The problem with expander cycle engines is that they are limited to under ~60,000 lb of thrust due to the inability to obtain more heat energy to drive the turbine via regenerative cooling means. The square cube rule dictates that as the circumference (or surface area) of an engine doubles; engine thrust will increase by a factor of nearly eight. Since propellant pump power requirements are directly related to thrust and since heat energy to drive the turbine is directly related to the engine surface area, then a point is quickly reached where insufficient heat energy exists to drive the turbines and therefore the pumps. Simply lengthening the nozzle has little effect since a somewhat insulating boundary layer prevents the highest temperature gases from reaches the nozzle walls. The largest expander cycle engine built to date is the European Space Agency's Vinci, which is still under development and will produce just under 40,500 lb of thrust[VIII]. Thrusts greater than 500,000 lb are typical for booster engines.

In a closed cycle, the hydrogen is injected into the combustion chamber as a normal expander cycle engine; while in an open cycle a small percentage of hydrogen is routed through the regenerative cooling system prior to being routed to the turbine then expelled as waste product. The increase in specific impulse is brought about by dumping only hydrogen in the open system verses a 1 to 1 ratio of LOX/LH2 in a gas generator.

Problems with Contemporary TVC's

On most engines, Thrust Vector Control is currently accomplished by using two hydraulic actuators to gimble the engine for pitch and yaw control; a separate thruster or means is employed for roll control. Gimbling engines forbid mounting the propellant pumps **within** the propellant tanks without high pressure flexible propellant feed lines. Mounting the pumps outside of the tanks require a recirculation system and processes that are presently a source of processing and propellant conditioning problems before launch. In addition, the use of hydraulic actuators on board launch vehicles has been a tremendous source of processing problems since they add enormous amount of support hardware; namely, hydraulic pumps, accumulators, hypergolic APU, hypergolic purge systems, cooling systems, and GSE.[IX]

Proposed Solutions - Steering Vanes

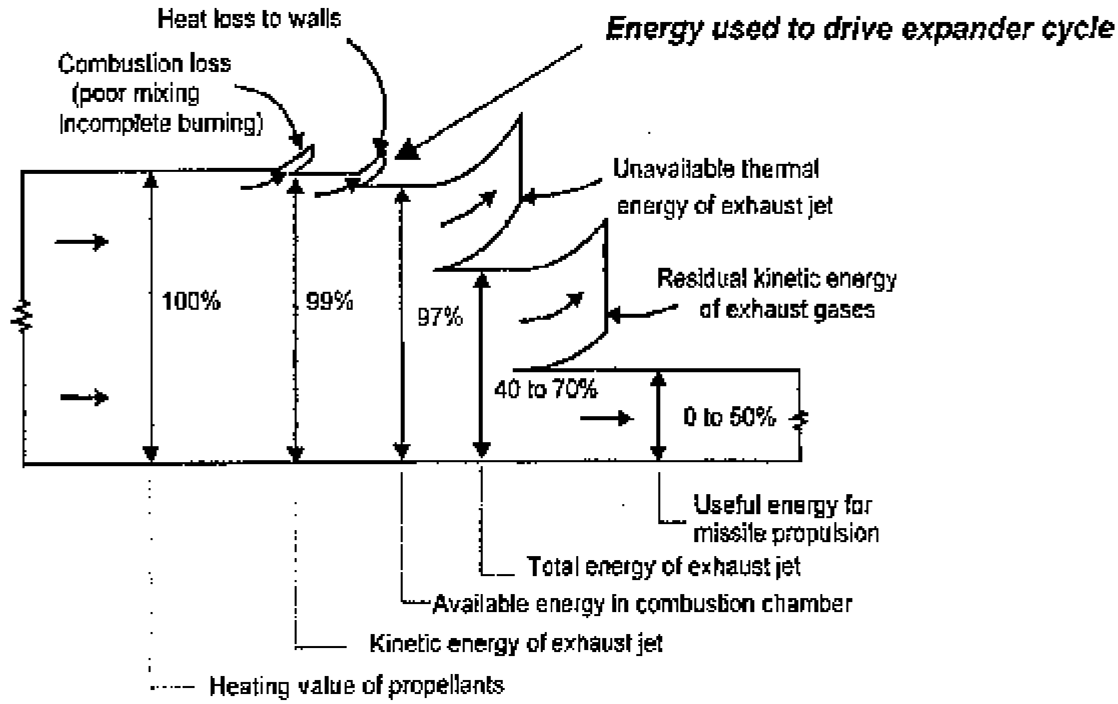
Figure 4: Redstone Missile Steering Vanes

In addition to the normal regenerative cooling of the combustion chamber and nozzle, it is proposed that additional heat energy can be obtained via regenerative cooling steering-jet-vanes, which deflect the engine exhaust. The steering vanes are similar in function to the four ablative carbon jet-vanes used on the Redstone missile[X] during ascent to control pitch, yaw, **and roll**. The steering vanes will be actuated via the use of three Electro-Mechanical Actuators (EMA) or servos. Two of the vanes are not needed for roll control and can rotate with each other. Electrical power for the EMA and other vehicle functions could be provided by battery, fuel cell, or a turbo-generator on the propellant tank re-pressurization system among other methods.

If the jet vanes are rotated about their center point, equal amount of surface area will be exposed on either side of the pivot point, extremely little amount of rotating force will be needed to pivot the jet vanes with incredible responsiveness. The jet vanes can be rotated by a simple servo-motor or pneumatic rotary actuator. This should be compared to hydraulic (or EMA) TVC, which requires a continuous force equal to 1% of the total thrust to gimbal the engine 8 degrees. In addition, the power required to actuate the TVC in a very quick manner is the largest hurdle to replacing the hydraulic TVC with EMA.

How Much Energy is Available?
In Figure #5, Sutton shows the heat source of contemporary expander cycle engines (heat loss to walls) as being only 2% of the total fuel energy to the engine. Based upon this same figure, as much as 57% of the total fuel energy could be available to power the proposed expander cycle engine via the regeneratively cooled jet vanes.

Figure 5: Energy Balance Diagram for Chemical Rocket[XI] (figure has been corrected)



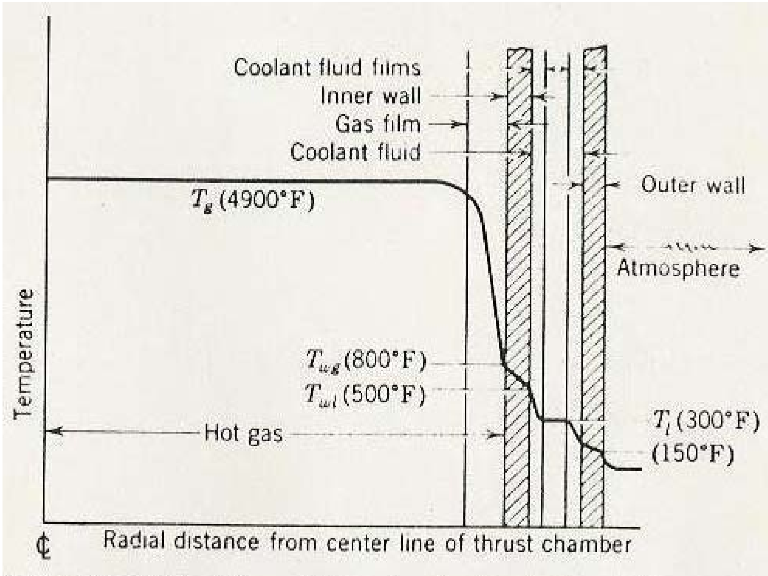
Material Science Considerations

Using the compressible flow table for an ideal gas with k = 1.4 and an area ratio of 28, we find the speed of the flow exiting the J-2 rocket engine nozzle as Mach 5.143 and the T/Tt = 0.1595. If the temperature of combustion of LOX/LH2 is 6,000F (3,696 k), then the static temperature (temperature traveling with the flow) at the nozzle exit will only be 600 deg F (589.5 K). However, the total temperature (the temperature of gas brought to a stop) is equal to simply the temperature of the gas burning. The temperature of LOX and LH2 burning at a 5.5 : 1 ratio is approximately 6,000 deg F. Therefore, the jet vanes must be designed to withstand gas impinging on the top surface at a temperature of 6,000 deg F.

In Figure # 6, Sutton shows the temperature gradient for a regeneratively cooled combustion chamber. Unfortunately for jet vanes installed within the exhaust plume, there is no (or very little) boundary layer (referred to as Gas Film) to buffer the wall jacket from the hot gas jet. This technology quickly becomes a material science problem, as now the jet vane cooling tubes must be able to withstand the full hot gas plume traveling at Mach 5.143.

According to Ellis[XII], Glenn Research Center has developed a rocket nozzle material (referred to as CRCop-84) that can operate at 1,700 deg F and has a thermal conductivity of 162 Btu/(hr-ft-F). CRCop-84 most likely will not survive while being directly impinged upon by the hot gas plume. Any number of methods could be chosen to protect the upper most portion of the jet vane from the hot gas, of which it is proposed to simply wrap the top cooling tube with tungsten wire. Since tungsten has a melting point of 6,192 deg F, it will survive in the jet with no problems. However, constructing tubes strictly out of tungsten is not possible and its thermal conductivity is much lower at 100.53 Btu/hr-ft-F than CRCop-84. After a protecting boundary layer as shown in figure 6 is established, the tungsten wrap may not be necessary.

Figure 6: Temperature gradients in cooled rocket thrust chamber with typical temperature values[XIII]



We must calculate when along the length of the jet vanes that a sufficient boundary layer is established and the tungsten coating is no longer necessary. The equation for determining the Reynolds number is given as:

1) $Re_x = Uo\ x / \upsilon$

Where,

Re_x = Reynolds number in the direction of flow
Uo = Velocity of the free stream jet which was found above to equal Mach 5.143
x = distance from the forward end of the jet vane
υ = Kinematic viscosity = 3.77 x 10^{-5} m^2/second at 200C for steam.

Equation 2) is used to find the speed of sound knowing static temperature (T) is 589.5 k.

2) $c = (kRT)^{0.5} = (1.4 * 287 \text{ J/kg K} * 589.5 \text{ kelvin})^{0.5} = 487$ m/s

Where,

c = the speed of sound

Uo is the free stream velocity equal to Mach 5.143 or 5.143 x 487 m/s = 2,503 m/s.

Since flow is considered turbulent when Re is greater than 4,000, we find the stream turns turbulent when x is equal to just 0.06mm after we substitute υ and Uo into equation 1). As a result, we can assume the flow immediately becomes turbulent. Equation 3) is used to determine the thickness of the boundary layer after a specified distance from the leading edge of the jet vane.

3) $\varsigma = 0.37\ x / (Re_x)^{1/5}$

For (x) equal to one inch (25mm), the boundary thickness will equal 0.020 inch (0.53mm). With this boundary layer, we can again assume the temperature gradient as shown in figure 6.

Engine Cycle Comparison

Tables #1 and #2 show how the gas-generator J-2 engine would compare in performance and design if it were modified with the proposed architecture into an expander cycle engine.

To make an apples-to-apples comparison, the following design aspects have been unchanged:

- Vacuum Thrust,
- Chamber Pressure,
- Combustion chamber, throat, and nozzle dimensions
- LOX pump pressure, flow rate, power, speed, and efficiency
- LH2 pump efficiency and speed
- LH2 turbine inlet temperature, speed, and efficiency
- NPSH for LOX and LH2

The following assumptions were made:

- The information on the J-2 engine was accurately supplied by the reference.[XIV]
- 151 psi was required by the LH2 to transverse the nozzle cooling tubes (this is unchanged)
- 75.5 psi was required by the LH2 to transverse the jet vane cooling tubes
- The LH2 turbine output pressure would be the same as the LOX pump output pressure
- Pump head and power would scale linearly with increase in pump pressure.
- The power supplied by the LH2 turbine to operate the LOX pump via gearing will remain unchanged.
- The size of the jet vanes will be increased until enough heat is captured to run the turbine.

Table #1: J-2 Gas Generator Cycle Engine Modified as Expander Cycle Engine

Engine Type	J-2		J-2 Expander	
Engine Cycle	Gas Generator		Expander Cycle	
propellant type	LOX	LH2	LOX	LH2
Thrust-vacuum (lbs)	232,250		232,250	
Isp-vacuum (seconds)	421			
	Pump			
pressure increase in pump (psi)	1,069	1,220	1,069	1,854
Head increase in pump (ft)	2,172	38,337	2,172	58,258
Flow rate (lb/sec)	467.7	84.2	467.7	84.2
Shaft speed (rpm)	8,698	27,167	8,698	27,167
Efficiency (%)	80%	73%	80%	73%
Shaft Power (hp)	2,302	8,587	2,302	13,049
Required NPSH (ft)	42.3	176	42.3	176
	Turbine			
Shaft Power (hp)	2,302	8,587	n/a	15,351
Inlet Pressure (psi) Total	89.3	652	n/a	1,200
Pressure ratio	2.65	7.2	n/a	1.12
Outlet Pressure (psi)	33.7	90.6	n/a	1,069
Shaft speed	8,698	27,167	8,698	27,167
Inlet Temperature (F)	768	1,200	n/a	1,200
Efficiency (%)	47%	60%	n/a	60%
	Gas Generator			
Total Flow Rate (lb/sec)	7.04		n/a	n/a
Mixture ratio (oxidizer/fuel)	0.94		n/a	n/a
Flow Rate (lb/sec)	3.41	3.63	n/a	n/a
% of Pump Flow Rate (%)	0.73%	4.31%	n/a	n/a

Thermodynamics of the Engine Cycles

In Table #2, the J-2 gas generator is emulated by an expander cycle system. In the J-2 gas generator, LH2 is combusted with LOX to create a mass flow rate of 1,200 deg F steam and hot hydrogen gas. Based upon the presented conditions, the amount of power is calculated by the change in enthalpy for steam and GH2. The gas generator propellants represent 1.276% of the total propellants entering the combustion chamber. For the Closed Expander Cycle J-2 engine, 100% of the hydrogen is assumed to be heated to 1,200 deg F, travel through the turbine, before being combusted in the combustion chamber. For the Open (or Bleed) Expander Cycle J-2 engine, only 5% of the hydrogen is assumed to be heated to 1,200 deg F, travel through the turbine, before being dumped near the end of the nozzle. The Open Expander Cycle J-2 engine has the advantage of requiring much less heat from the jet vanes, much smaller turbine, and much less modifications to the gas generator engine, but it is less efficient than the closed expander cycle.

Table #2: Turbine Modifications

	J-2 Gas Generator	J-2 Closed Expander
Turbine Inlet Steam (lbs/sec)	3.836	0
Turbine Inlet GH2 (lbs/sec)	3.204	84.2
Turbine Inlet Pressure (psi)	652	1,119
Turbine Inlet Temperature (F)	1,200	1,200
Turbine Inlet Enthalpy - Steam (Btu/lbm)	1,627	0
Cp @ Inlet Temp (btu/lbm*F)	3.52	3.52
Turbine Outlet Pressure (psi)	89.3	1,069
Turbine Outlet Temperature (F)	768	1,164
Turbine Outlet Enthalpy -steam (Btu/lbm)	1,414	0
Cp @ Outlet Temp (btu/lbm*F)	3.49	3.52
Total Power from steam (Hp)	1,154.9	0.0
Total Power from GH2 (Hp)	6,859.5	15,302.5
Total Turbine Power (Hp)	8,014.4	15,302.5

According to Sutton,[xv] jet vanes cause a 2 to 3% drag even at zero deflection. One-inch (25.4mm) thick jet vanes at the end of the J-2 nozzle would cover at most 3.2% of the 34.2 square feet nozzle exit. Since the gas generator propellants represented a loss in Isp of only 1.276%, it would appear at first that the jet vanes represent a net lost in performance. However, a streamline jet-vane design could possess a coefficient of drag that will reduce the effective coverage of the nozzle exit area to less than 0.64%. In addition, because increased pump power in a gas generator represents increased loss, gas generator pump power requirements are kept to a minimum. Our modified expander cycles are not as limited by power requirements and therefore, pump and combustion chamber pressures can be increased at little expense. Controlling the jet vanes by electrical means is a godsend for operations compared to hydraulic powered TVC's; especially if a hypergolic APU system is used to power the hydraulic pump.

Recommendations

Additional study is recommended to determine the optimal performance characteristics of a J-2X equivalent expander cycle engine, determine the true manufacturing and processing costs, and determine the optimal size of the jet vanes to power the J-2X equivalent expander cycle engine, as well as materials and design of said jet vanes.

Summary & Conclusions

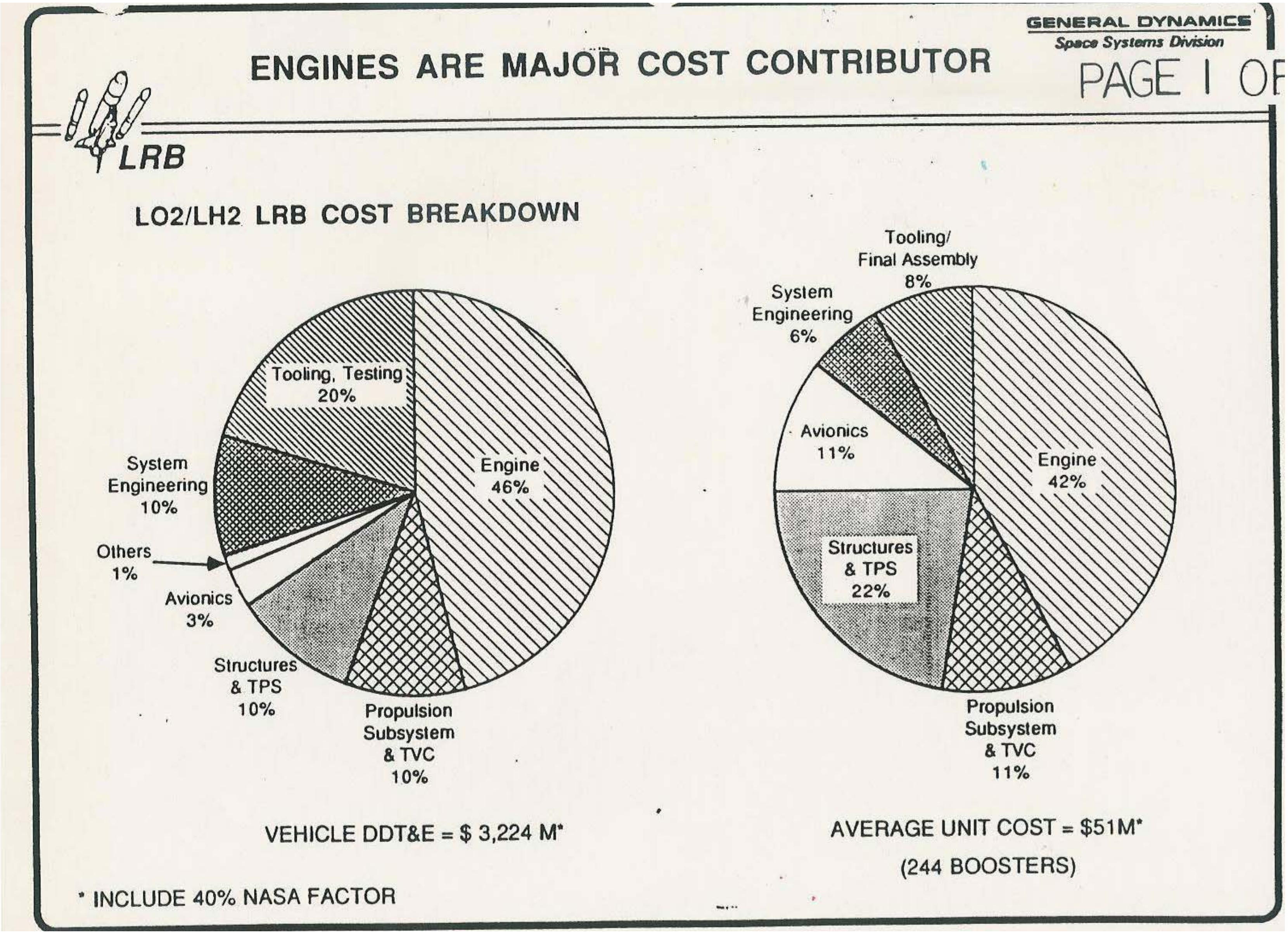
An expander cycle engine is inherently simpler and less costly to fabricate and process than any other type of pump engine as is evident from past rockets. This is the reason why upper stage vehicles (where large thrust is not needed) utilize expander cycle vs the other cycle engines. Rocket engine development represents a huge investment in the US aerospace infrastructure. Such a huge investment should be directed at technologies that advance the state of the art if the industry is to remain globally competitive.

Much more heat energy is available from regeneratively cooled jet vanes than through extending the nozzles due to the fact that an insulating boundary layer builds up along the nozzle wall whereas the jet vanes stick in the center of jet flow. Not only do the jet vanes provide the heat energy to operate the turbines, the jet vanes require far less power to operate than equivalent TVCs. Based upon the chemical rocket energy balance, as much as 57% of the total fuel energy could be available to power the expander cycle turbines via the jet vanes. This 57% should be compared to the 2% presently recovered from contemporary regeneratively cooled nozzle and combustion chamber.

This paper presented a very brief glimpse at the material science and the fluid dynamic analysis needed to optimize the regeneratively cooled jet vanes, as well as present a possible design to combat the 6,000 deg F jet plume impinging upon the top of the jet vanes. Finally, a comparison was made in the engine specifications between a gas generator J-2 engine and an equivalent thrust expander cycle J-2 engine and turbopumps.

Due to the favorable results from this paper, additional study should be conducted into expander cycle engines powered by regeneratively cooled jet vanes.

APPENDIX 1 – Figure 7



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[VII] http://en.wikipedia.org/wiki/Staged_combustion_cycle_(rocket) Figure

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[XIII] Sutton, pg 99

[XIV] Sutton, pg 315

[XV] Sutton, pg 226