PROPULSION SYSTEM ADVANCES THAT ENABLE A REUSABLE LIQUID FLY BACK BOOSTER (LFBB)

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ABSTRACT

This paper provides an overview of the booster propulsion system for the Liquid Fly Back Booster (LFBB). This includes, system requirements, design approach, concept of operations, reliability, safety and cost assumptions. The paper summarizes the findings of the Boeing propulsion team that has been studying the LFBB feasibility as a booster replacement for the Space Shuttle. This paper will discuss recent advances including a new generation of kerosene and oxygen rich pre-burner staged combustion cycle main rocket engines. The engine reliability and safety is expected to be much higher than current standards by adding extra operating margins into the design and normally operating the engines at 75% of engine rated power. This allows for engine out capability. The new generation of main engines operates at significantly higher chamber pressure than the prior generation of gas generator cycle engines. The oxygen rich pre-burner engine cycle, unlike the fuel rich gas generator cycle, results in internally self-cleaning firings which facilitates reusability. Maintenance is further enhanced with integrated health monitoring to improve safety and turn-around efficiency. The maintainability of the LFBB LOX / kerosene engines is being improved by designing the vehicle/engine interfaces for easy access to key engine components.

INTRODUCTION

The objective of the Liquid Fly Back Booster (LFBB) Program is to enhance Space Shuttle system safety and reliability, improve performance and mission flexibility, and reduce operating cost. A liquid rocket booster replacement for the existing solid rocket motors would enable greater safety by allowing engine-out operations, with abort options which begin much earlier in the trajectory. The economic objective is to make the fly back booster return to base autonomously and be fully reusable with minimum between flight maintenance. The lower cost of operations, higher reliability and the extension of the Space Shuttle operational lifetime is intended to offset the cost of LFBB development. There has been major advances in propulsion technology that offers significant improvements in the use of rocket engines as reusable liquid propellant booster system elements. This paper documents those advances which have been incorporated into the Boeing LFBB concepts.

LIQUID FLY BACK BOOSTER (LFBB) FEASIBILITY STUDY

Boeing was placed under contract by NASA to study the feasibility of replacing the solid rocket motors of the Space Shuttle vehicle with liquid rocket boosters having an autonomous fly back capability to the launch site. The objective of the program would be to enhance both safety and economy over the current solid rocket motor propulsion. A critical element of the program was to identify liquid rocket propulsion elements that will make the LFBB feasible.

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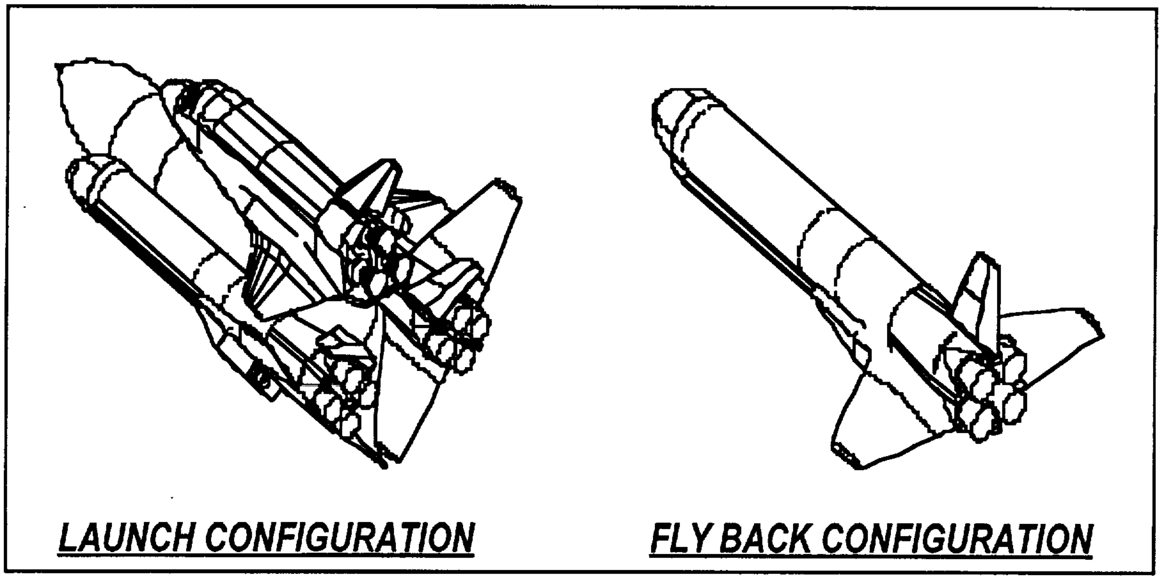
The only large reusable rocket engine employed to date has been the Space Shuttle Main Engine (SSME). The SSME is an excellent and efficient rocket engine, but it requires use of low density liquid hydrogen (9 ounces per gallon) that results in excessive propellant tank size for an LFBB. The size envelop of the LFBB requires use of a denser propellant combination than that used by the SSME. In addition, the LFBB Booster requires much higher thrust levels than the SSME can provide. Therefore, three propulsion challenges must be resolved before an LFBB is feasible. First, that engine must be large enough to supply the thrust required of a new Space Shuttle strap-on booster. Second, a low maintenance but highly safe and reliable engine must be selected. Third, the engine must utilize higher density propellant than is used by the SSME.

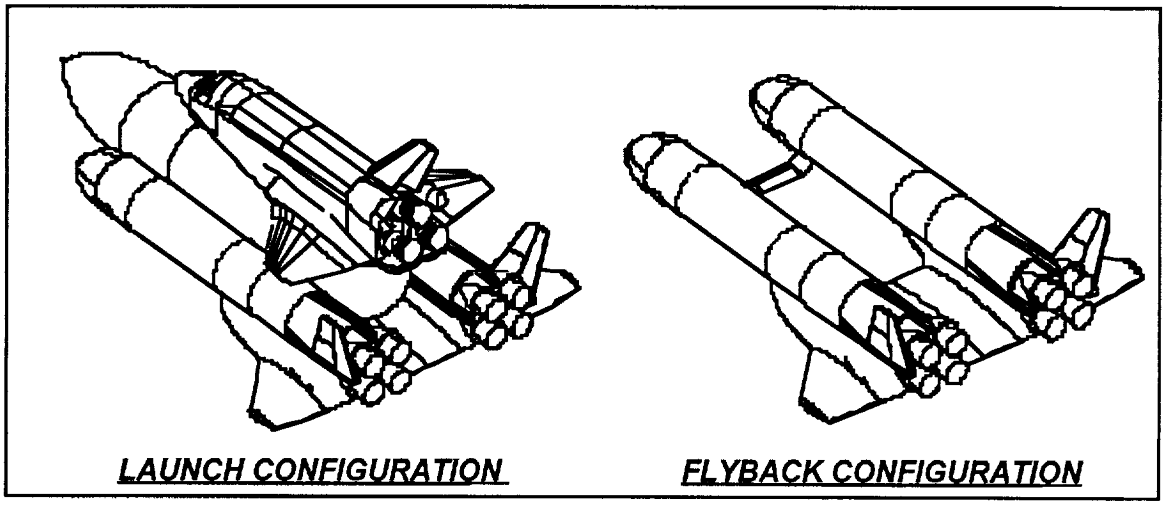
Two configurations of the LFBB were studied, a dual configuration in which a pair of boosters loft the space shuttle, and a catamaran configuration in which two dual-like booster rockets are joined in parallel. Parametric mass property models were maintained for each of the engine candidates, with each engine assessed against two configurations (a dual and a catamaran). Ascent models were used in conjunction with the mass properties models to size each of the configuration and engine combination, in order to achieve the same required overall performance.



LAUNCH CONFIGURATION

FLY BACK CONFIGURATION

Figure 1. Space Shuttle with Dual Configuration LFBB



LAUNCH CONFIGURATION

FLYBACK CONFIGURATION

Figure 2. Space Shuttle with Catamaran Configuration LFBB

SYSTEM REQUIREMENTS

The propellant selection was limited by the requirement to fly with the Space Shuttle and then fly back to the launch site. The performance of liquid hydrogen was attractive, but the high bulk would require large volume propellant tanks that would be incompatible with operations within the Vertical Assembly Building (VAB) at Kennedy Space Center (KSC), the ascent aerodynamic interaction with the Space Shuttle Orbiter, and with efficient jet-powered cruise back to the launch site. The requirements for a common, dense, non-toxic propellant combination led to the selection of liquid oxygen and kerosene as the propellant of choice.

Many of the propulsion requirements might be satisfied with one or two very large engines per dual LFBB, except then there would be no possibility of operating the mission with one engine out. The Rocketdyne F-1 engines that powered the Saturn V Apollo Moon missions were examined early in the LFBB Program. The F-1 engine operated at a thrust level where only two engines per LFBB dual configuration vehicle would be needed. The use of only two F-1 engine sized engines per Dual LFBB would pose an unacceptable hazard by turning even the most benign engine shutdown into a catastrophic vehicle failure. One of the most important requirements set for the LFBB program was to make a booster engine failure non-catastrophic to the greatest extent practical, and to make benign failure events into operationally successful missions.

A problem with the fuel rich gas generator cycle engines as an LFBB candidate is that the engine gas generator cycle causes a large quantity of oily soot to accumulate internal to the engine. This soot must be cleaned out before an engine can be reused. Such cleaning is labor-intensive and requires environmentally dangerous chemicals to complete effectively. The gas generator cycle engines were never designed with the intent to be reusable engines.

REQUIREMENT FOR ENGINE-OUT OPERATION

As reliable as the eight LFBB engines must be, there will be the occasional engine failure. Most of these engine failures will not be catastrophic. But even if the engine failure is not catastrophic, can the mission proceed safely? The answer is yes, if and only if the remanding engines have enough power reserve to continue the mission at the planned vehicle thrust level. In fact, such a single engine shut down need not even result in an abort, if the remanding engines can be throttled up enough to maintain planned vehicle thrust levels.

Obviously, a single engine on a dual LFBB system, or one-half of a catamaran LFBB system, cannot provide balanced thrust with an engine failure. Even with two or even three engines on a dual LFBB or on each catamaran half, the failure of one engine would require a very large engine power increase. When four engines are used, with each engine is normally operated at 75% power level, can the loss of one engine be compensated for. The use of more than four engines per side allows for compensation, but increases the risk of failures to unacceptable levels. Reliability is inversely proportional to the number of engines. The trade study included use of cost models and Monte Carlo simulations to determine the most reliable solution consistent with a cost effective design. The use of four engines on each of the two dual LFBB systems, or eight engines per catamaran LFBB, became an LFBB program selection.

Lift-off drift in the vicinity of the launch pad imposes a vehicle system requirement for a Space Shuttle system thrust-to-weight of greater than 1.2, in order to avoid impact with launch tower structures. This, in turn, translates to a thrust level requirement of 800,000 to 900,000 pounds thrust per engine at full throttle, or 600,000 to 675,000 pounds thrust per engine at 75% throttle. Actual minimum thrust requirements are dependent on engine specific impulse and thrust to weight ratio.

THROTTLE UP AND DOWN REQUIREMENTS

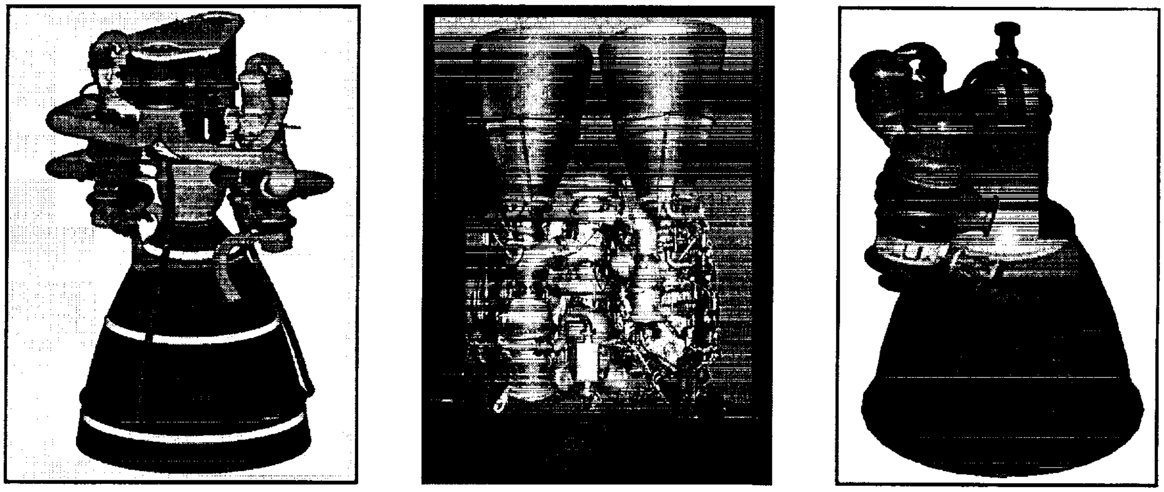
The requirements for the new LFBB propulsion system included high performance engines with high mission reliability, and ability to throttle down to about 62% of rated thrust. This lower thrust limit is set by a Space Shuttle vehicle acceleration constraint of less than 3.0 g. The engines are sized to operate at 75% thrust level at liftoff.

If the health monitoring instrumentation detects an imminent failure, the LFBB system must execute two simultaneous actions. First, the failed engine must be quickly and safely shut down. At the same time, the remaining three companion engines must be throttled up to as high as 100% power. The loss of thrust from the failed engine as it is throttled downward to zero power level must be matched very closely by the combined rate of thrust increase for the three remaining engines to balance the loads across the External Tank.

LFBB ENGINE CANDIDATES

Each of the configurations were assessed with three different candidate engines. The engines are the Aerojet AJ-800, the Pratt and Whitney RD-180, and the Rocketdyne RS-76. All three final LFBB engine candidates use oxygen rich pre-burner combustion cycle (ORPBCC) technology. The Pratt and Whitney RD-180 is derived from the Russian RD-170 engine that powers the Zenit launch vehicle. The RD-180 will also be used to power the Atlas III. The Aerojet AJ-800 is derived from the Russian NK-33 design, which powered the first and second stage of the Russian N-1 moon rocket, and will power the Kisler K-1 commercial reusable rocket vehicle. The AJ-800 is twice as powerful as the NK-33, and it uses a new combustion chamber and two independent NK-33 pump assemblies to achieve this high power level. Rocketydne is offering a new “clean sheet’ engine design approach. The RS-76 engine system is a fully reusable oxygen-kerosene staged combustion cycle engine with an oxidizer rich preburner and a single-shaft main turbopump.

An important finding of the Boeing LFBB study was that all three candidate engines meet the requirement to throttle up in balance with the shutdown transient of the failed engine. All three candidate engines are expected to meet the safety, performance and reliability requirements for an LFBB application. The candidate engines are shown in Figure 3.



Aerojet AJ-800 **Pratt & Whitney RD-180S** **Rocketdyne RS-76**

Figure 3. The Three LFBB Engine Candidates

OXYGEN RICH PRE-BURNER STAGED COMBUSTION CYCLE

An important advance in rocket engine technology is the oxygen-rich pre-burner staged combustion engine. The previous generations of American LOX/kerosene engines used a fuel-rich gas generator cycle to power the engines. All three of the above LFBB engine candidates utilize the oxygen rich pre-burner staged combustion cycle.

Gas generator cycle engines mix propellants in proportions that are very fuel rich. The fuel rich mixture creates gasses that are much cooler that those found in the main combustion chamber. These gasses must be hot enough to power the turbines without exceeding the temperature limits of the machinery. The hot gas turbine powers the pumps. The exhaust gasses are then either fed into the combustion chamber, the nozzle or dumped overboard. The fuel rich cycle has the advantage of creating lighter molecular weight exhaust gas (lighter molecular weight turbine gasses effectively increases overall specific impulse), and in being reducing (not oxidizing) when operating in turbines.

The mixture had to be very fuel rich in order to obtain a low temperature gas that would not exceed the operating limits of the turbine. When the hot gas had passed though the turbine, it was exhausted either into the thrust chamber (closed cycle), the nozzle (as was the F-1) or to the outside (open cycle as with the Atlas MA-5). The major problems that made this type of engine impractical as a reusable engine were internal soot deposition and combustion stability. The oily soot left over in an engine represents a high risk of causing a failure if any amount reached the components that carry LOX. Extensive cleaning is essential before each new engine firing. The major problem is that cleaning the inside gas passages is very difficult, costly and requires use of chemicals that are not environmentally friendly.

Soot problems are caused by incomplete combustion of the fuel, leaving large quantities of partially burned hydrocarbon. This soot clogs passages and inhibits heat transfer, including proper operation of heat transfer sub-systems like a heat exchanger. In contrast to the fuel rich gas generator cycle, the oxygen rich pre-burner completely consumes all the fuel, leaving a hot gas stream consisting of oxygen, water vapor and carbon dioxide. The lack of any soot or particulate deposition means that the ORPBSC cycle leaves the machinery clean at shutdown. A clean engine at shutdown is critical for fast, low-cost between flight maintenance.

BENEFITS OF OPERATING AT LOW POWER SETTING

A key requirement of the LFBB Program has been safe operation even if an engine must be shut down in flight. The implementation of this requirement is the use of four booster engines per solid rocket motor being replaced, with the reserve capacity to achieve full thrust even with one engine out. The booster main engines are sized to require only 75% of the available thrust level during the ascent trajectory. The booster engines must operate at 100% power level only if one engine must be shut down.

Operating engines at lower power level is less harsh than full power operation. The operation at lower power has two likely effects, the wear and tear is reduced in a manner that should increase reliability and reduce maintenance requirements. How much is maintenance reduced and reliability increased by operating engines at 75% power instead of 100% power? That answer remains undetermined but reliability analysis shows the engine should be four times as reliable at 75% thrust as it is at 100% thrust (SSME tests history shows that reliability drops off even steeper between 104% and 109%). The wear and tear on the engines should also be reduced by the same factor of four. This reliability and wear improvement is expected to result in lower maintenance cost and fewer failures.

INTEGRATED VEHICLE HEALTH MONITORING SYSTEM (IVHMS)

The economic targets for the LFBB requires high reliability with low maintenance effort in between flights. It is not feasible to routinely tear down engines for inspections just on suspicion that a problem may be lurking. The condition of the engine must be known, both during and after a flight. The IVHMS (Integrated Vehicle Health Monitoring System) function is to provide information that assists maintenance decision making. The IVHMS also aids in rapid turn-around by enabling a maintenance-on-demand capability. Knowing the health of the engine from the history of the most recent flight will enable the use of the same type of maintenance practices that are employed on commercial airlines.

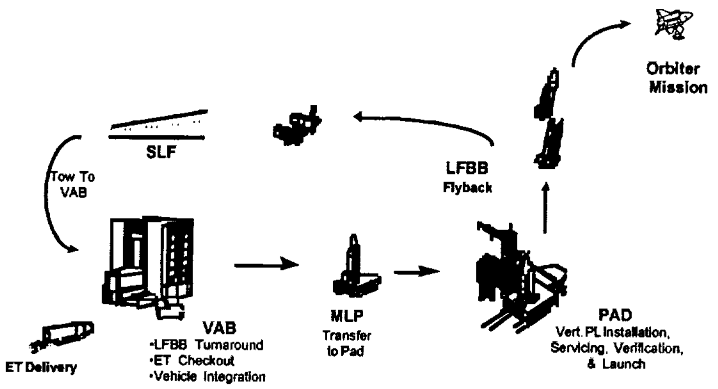
A critical function of the IVHMS is to detect in-flight problems that could lead to catastrophic failures in time to execute appropriate corrective action. Corrective action means shutting down an engine before it fails catastrophically. Shutting down an engine is, in itself, a failure. The essential function of the IVHMS system is to assure that a failure is only a benign engine shut-down, not a loss of vehicle catastrophe.

SAFETY ENHANCEMENTS

There are two major LFBB safety enhancements to the overall safety of the Space Shuttle Program. First, the LFBB would add the capability of successfully completing the missions even with a booster engine failure. The current solid rocket motors cannot change their thrust profile, be shut down, or jettisoned from the space shuttle from ignition until burnout. Liquid rockets are fully controllable, and provide more options on which safer abort strategies can be based. The second major safety enhancement is elimination of a major quantity of highly flammable solid propellant from the Space Shuttle while the vehicle is being processed. Each solid rocket motor carries 1,107,000 pounds of propellant [1], where the main hazard is fire resulting from electrostatic discharge. The current system involves stacking solid rocket motors in the VAB, along with a large work force and billions of dollars in ground and flight assets. While the safe ground assembly of large solid rockets has been ongoing at KSC since the first Titan-IIIC launch in1965 [2], there have been accidents elsewhere in which catastrophic damage and loss of life occurred. NASA has an excellent safety record handling large solid rocket motors, but eliminating the hazard of having over a thousand metric tons of propellant within the VAB would be very desirable.

CONCEPT OF OPERATION

The Concept of Operation for a LFBB differs radically from the current Solid Rocket Motors. The current Solid Rocket Motors must be retrieved from the ocean, disassembled, cleaned, shipped back to Utah, refurbished, loaded with propellant, shipped back to Florida, reassembled, and mated back to the Space Shuttle. In contrast, the LFBB flies back to the launch site on it's own power, is refurbished, and is mated to the Space Shuttle before any propellant is loaded aboard. The number of steps, turn around times, transportation requirements and overall cost are all significantly reduced with an LFBB system replacing the Solid Rocket Motors



- Integrated Vehicle Controlled By Orbiter/JSC/MCC Until LFBB Staging
- Standalone Booster Controlled By KSC/LCC
  - Responsible For Standalone Booster At All Times; Grnd & Flt Ops; No Handoffs
  - Autonomous Flyback With Ground Override Limited To Selection Of Programmed Flight Modes
  - Controlled By Launch Team From Same LCC Console(s) As Launch
- Range Safety System In Conformance With AFM 127-1
- No Adverse Impact To Shuttle Hold, Scrub-Turnaround, Abort, or Launch-On-Time Capabilities

Figure 4. Space Shuttle Concept of Operation with LFBB

ECONOMIC IMPROVEMENTS

The economic improvements brought about by the LFBB include an annual savings of about $400 million for seven flights over use of solid rocket motors. The use of LFBBs has the added benefit of reducing the time it takes to mate the booster, external tank and mobile launch platform from 28 days to only 11 days. The quick turn around will allow NASA to achieve space shuttle launch rates of 10-15 flights per year. [3]

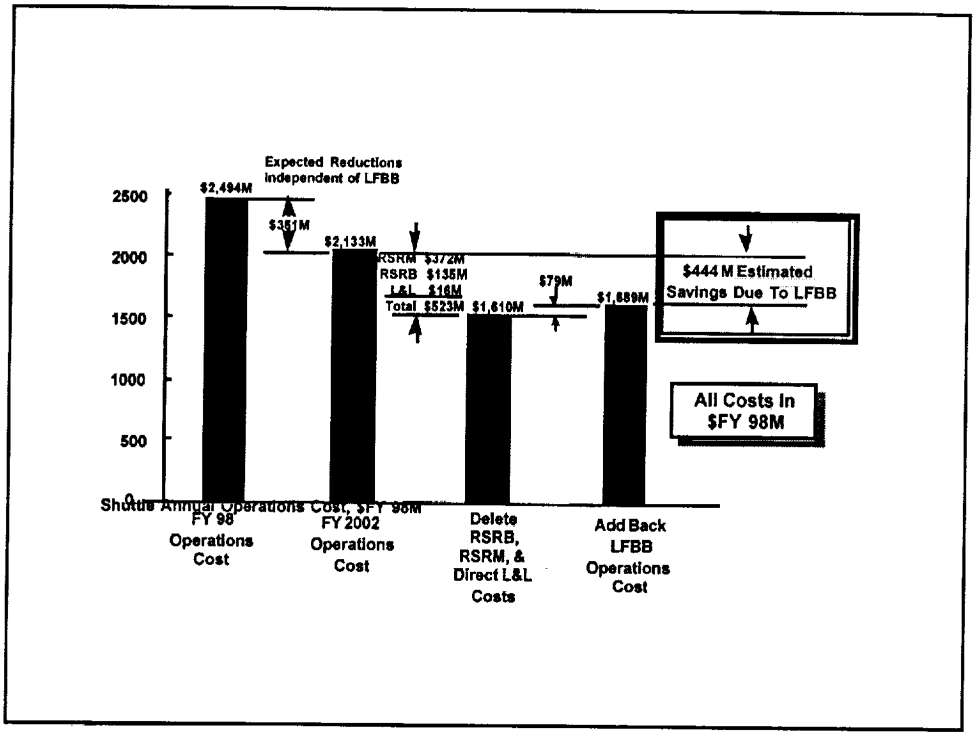


Figure 5. LFBB Cost Savings Analysis Summary with Annual Savings Estimate of $444 M

These improvements come, in part, because the LFBB does not require disassembly and re-assembly for each mission. The critical propulsion innovations, flying a lower than rated thrust level mission for lower wear, and use of pre-burner cycle engines that come back clean, make the faster turn around operations practical.

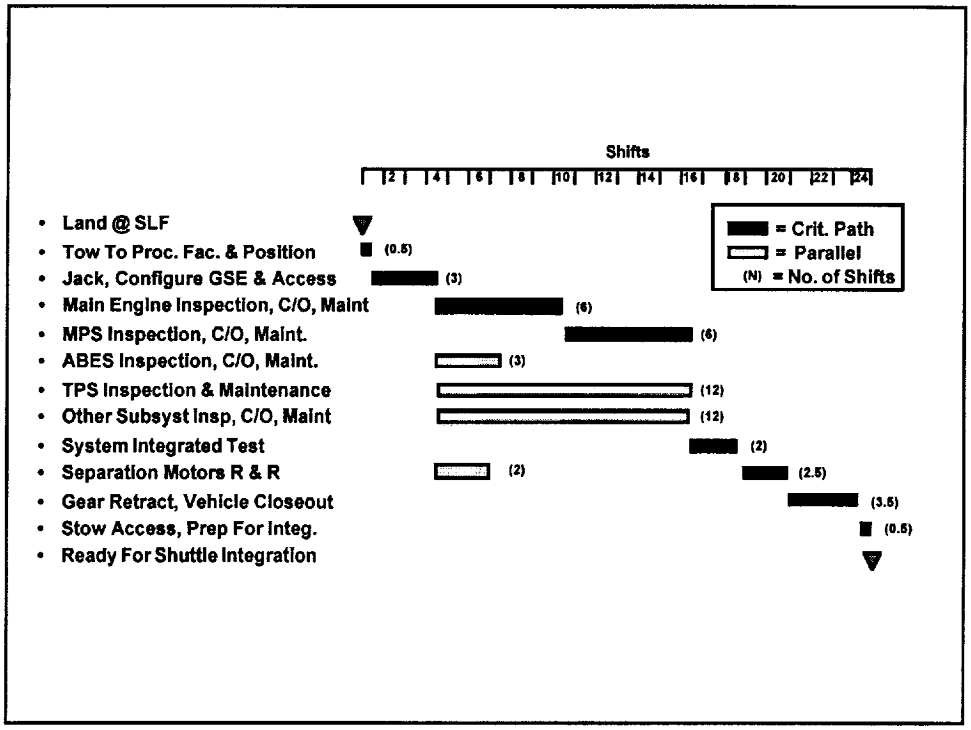


Figure 6. Main Propulsion & Engine Operability is Key to Achievement of a 24-Shift Turnaround

SUMMARY AND CONCLUSIONS

The most important conclusion is that an LFBB booster propulsion system is, technically and economically feasible. An important portion of the feasibility has been enabled by the new generation of oxygen rich pre-burner combustion cycle engines. These engines provide high thrust to weight, are "self cleaning" compared to the fuel-rich gas generator cycle systems. Both safety and reliability would be improved over the current practice of using Solid Rocket Motor Space Shuttle booster propulsion. Ground handling safety would be enhanced by eliminating the huge solid propellant grains that are in place in the Vertical Assembly Building.

REFERENCES

1. Isakowitz, Steven J., "International Reference Guide to Space Launch Systems," second edition. AIAA 1991, page 279.

2. Ibid pp293

3. Howard, Bob "Liquid Fly Back Boosters to Improve Space Shuttle Performance, Boeing News, March 27, 1998.