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Booster Main Engine Selection Criteria for the Liquid Fly-Back Booster

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ABSTRACT

The Liquid Fly-Back Booster (LFBB) Program seeks to enhance the Space Shuttle system safety, performance and economy of operations through the use of an advanced, liquid propellant Booster Main Engine (BME). There are several viable BME candidates that could be suitable for this application. The objective of this study was to identify the key criteria to be applied in selecting among these BME candidates. This study involved an assessment of influences on the overall LFBB utility due to variations in the candidate ~~rocket~~-engines' characteristics. This includes BME impacts on vehicle system weight, performance, design approaches, abort modes, margins of safety, engine-out operations, and maintenance and support concepts. Systems engineering analyses and trade studies were performed to identify the LFBB system level sensitivities to a wide variety of BME related parameters. This presentation summarizes these trade studies and the resulting findings of the LFBB design teams regarding the BME characteristics that most significantly affect the LFBB system. The resulting BME choice should offer the best combination of reliability, performance, reusability, robustness, cost, and risk for the LFBB program.

INTRODUCTION

LFBB SYSTEM DESCRIPTION

The NASA is currently studying the feasibility and benefits of developing a Liquid Fly-Back Booster (LFBB) to replace the Solid Rocket Boosters (SRB) on the Space Shuttle. The immediate goals for an LFBB would be to enhance the Space Shuttle safety and reliability, increase mission flexibility, reduce operating costs, and improve performance. Additionally, an LFBB could be used as a first stage for a commercial reusable launch vehicle and for achieving heavy lift where required for other government missions such as return to the moon and Mars.

There are currently two LFBB configuration alternatives under study by Boeing North American (BNA) and Lockheed-Martin (LM). Figures 1 and 2 show a dual LFBB configuration being studied by both companies and Figure 3 shows the catamaran LFBB configuration being studied only by BNA. For the dual configuration, two boosters are required while the catamaran configuration only requires one booster. Each vehicle concept creates different integration issues which the Space Shuttle that are unique. However, the BME requirements for each are essentially common and the criteria developed here are equally applicable to each configuration. This paper documents the booster main engine (BME) selection criteria being developed as a part of the LFBB study that will be used later if the program is funded.

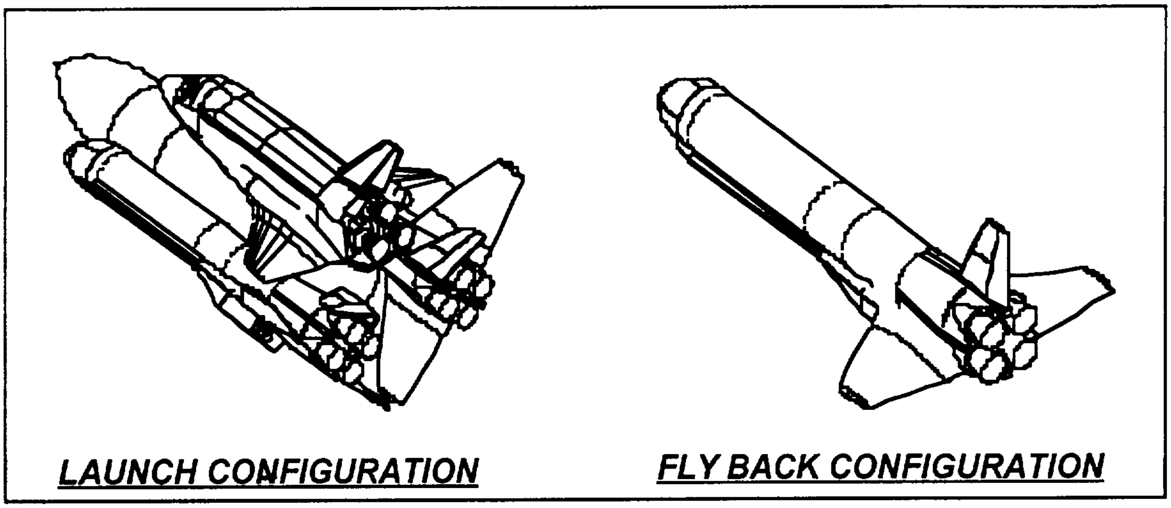


Figure 1. Boeing LFBB - Dual Configuration

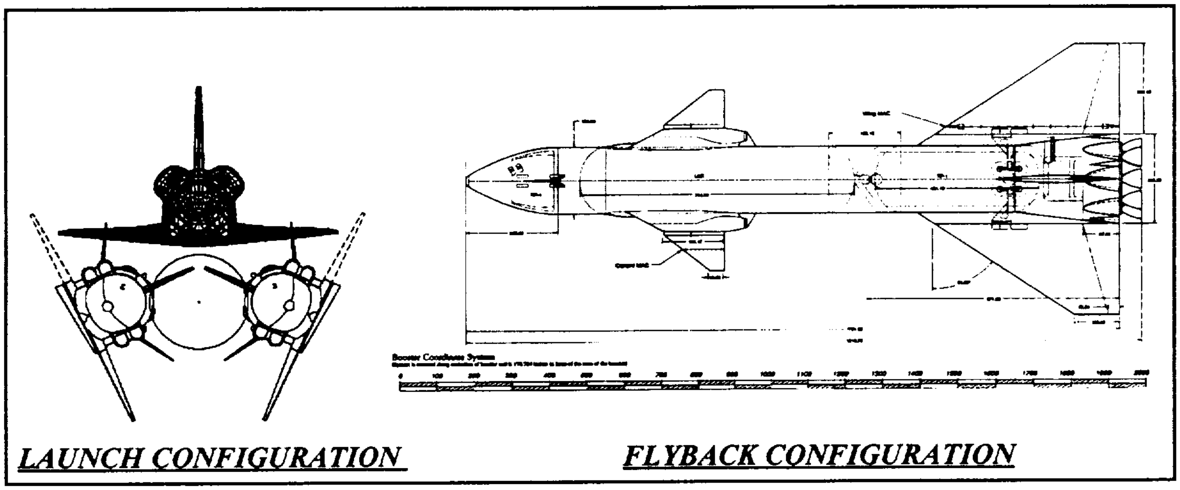


Figure 2. Lockheed-Martin LFBB - Dual Configuration

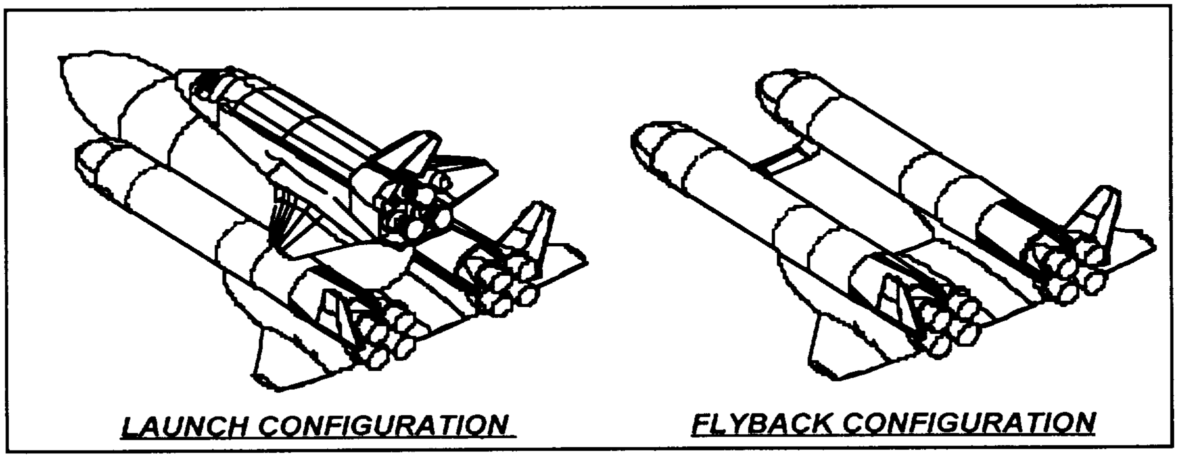


Figure 3. Boeing LFBB - Catamaran Configuration

The LFBB mission profile involves an accent trajectory analogous to the current Space Shuttle when propelled by the existing SRB's. The main accent differencesbetween the existing SRB's and the LFBB involve the ability to complete the mission with a single booster engine-out on either side plus added flexibility for various abort modes. The LFBB main engines cut off and the booster separates from the Shuttle External Tank at approximately 160,000 feet altitude and 5,600 ft/sec velocity. The LFBB then coasts through a ballistic trajectory under reaction control until reaching the regime of hypersonic flight at an altitude of 120,000 feet altitude and 5,000 ft/sec velocity. The airbreathing engines are started at about 30,000 feet altitude and 800 ft/sec velocity as the vehicle decelerates below transonic speeds. The jet powered cruise portion of the mission covers a distance of approximately 200 miles to an autonomous landing back at the launch site. The event sequence for the nominal LFBB mission profile is shown in Figure 4.

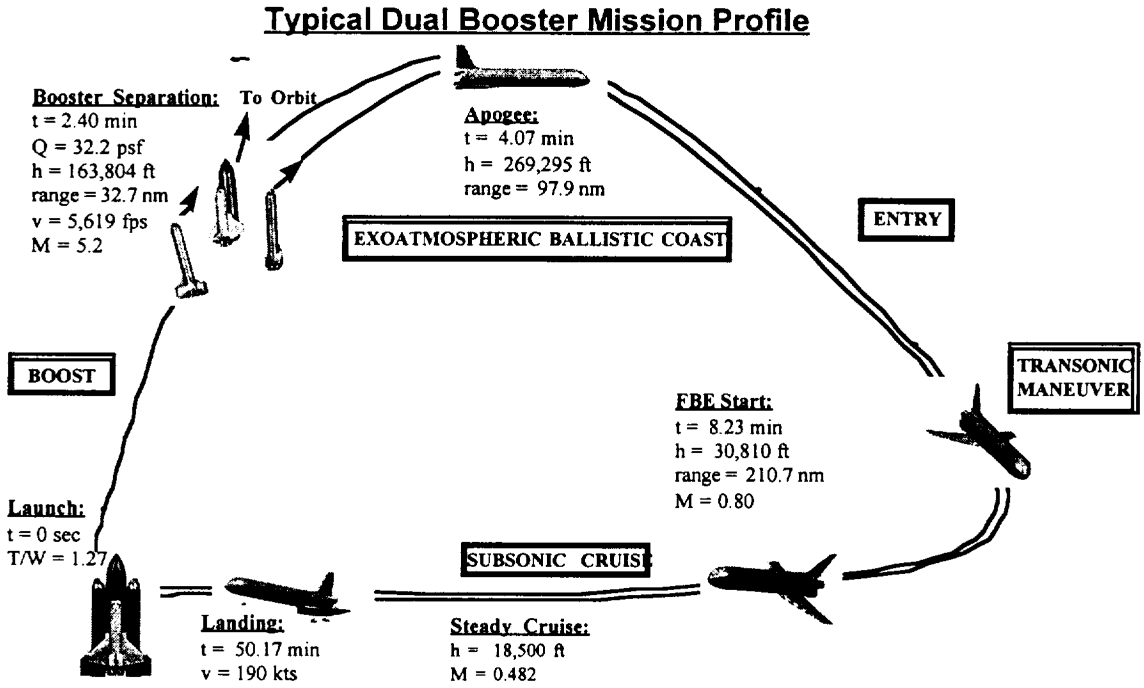


Figure 4. The typical LFBB mission profile covers a broad spectrum of flight regimes

OBJECTIVES

The overall goal of this effort, as stated in the introduction, is to establish the approach for selecting BME for the LFBB. Toward that goal, our first objective was to define the key LFBB system requirements that are most sensitive to variations in rocket engine attributes. Our second objective was to establish a set of selection criteria to guide the BME choice that should offer the best potential for satisfying the key LFBB requirements. Finally, our third objective was to gain a consensus among the various organizations having a vested interest in this BME selection process, including the NASA agencies, the 2 vehicle prime contractors and 3 candidate engine subcontractors.

APPROACH

Recent economic pressures facing the aerospace industry have forced a new thinking into the design process. Engineering in the past, while still having to be concerned about cost, was more driven by performance issues rather than cost. In other words, the system cost what it cost. Either you paid for it or you just did not get it. In a young industry like the launch services industry, it was more important to just make it happen. Now, in the more resources constrained world we operate in, this is no longer acceptable. The engineer must accept an approach of design to cost where resources are very restricted and return on investment expectations are high. This becomes the overwhelming basis for any selection criteria. "Lessons Learned" derived from similar launch vehicle and rocket engine development programs were used to identify the major criteria parameters. Data from these programs were used to define the key BME characteristics that were considered likely to be important for the LFBB. It was important that the parameters be anchored into the reality of existing reusable systems such as the Space Shuttle to make sure that no unexpected costs show up later in the program.

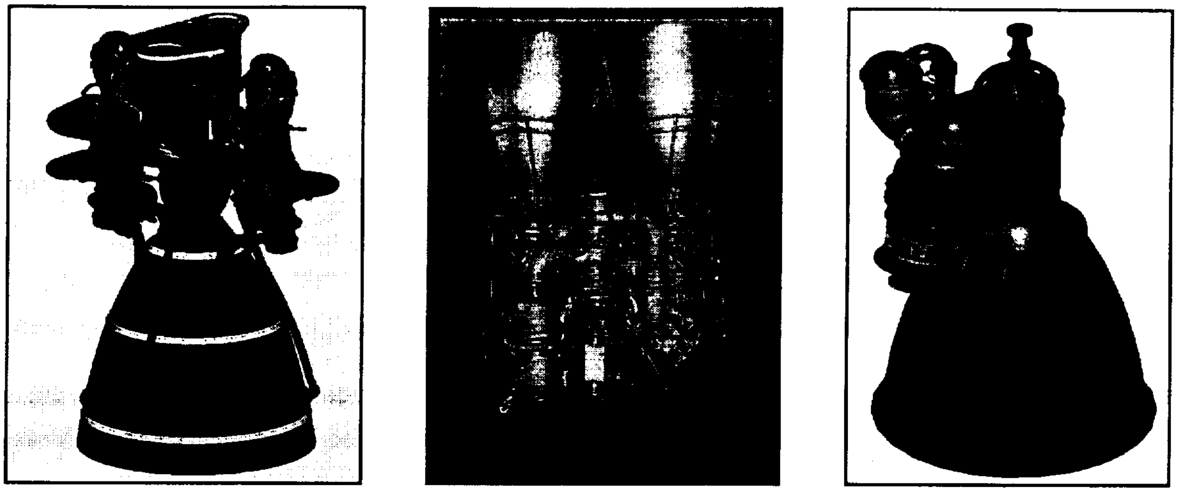
The selection criteria are divided into two basic groups. The first group involves "Must Have" capabilities to satisfy the minimum requirements to enable a viable LFBB concept. The second group of BME selection criteria involve quantifiable attributes which can serve as discriminators between the BME candidates. In most cases, the "Must Have" criteria can also serve as discriminators once the minimum threshold requirements have been satisfied. Once the set of BME selection criteria had been defined, coordination among the many industry and Government organizations involved in the LFBB program was accomplished through a series of meetings facilitated by the NASA/MSFC Program Office.

The system trade studies and sensitivity analyses portion of this effort involved the use of existing analytical tools to assess the affects of variations in the key BME characteristics on launch vehicle system weight, size, performance, reliability, cost, etc. The results of these trade studies have been summarized in the form of vehicle system partial derivatives and sensitivity curves that allow reasonable approximations of the affectsof relatively small changes in BME characteristics on LFBB system level outcomes. These sensitivities will be used later in the study to assign weighting factors to the identified criteria. They also helped to go back and verify the validity of an identified criteria. If it was determined that a parameter had no bearing on the selection process, it was removed from the criteria. In this way the criteria has been evolving through the study. This evolution will continue until the program determines that sufficient data are available to freeze the criteria and move toward a selection of the BME.

SCOPE AND LIMITATIONS

This effort focused on assessing the impacts of variations in the characteristics of three BME candidates on the two LFBB configuration alternatives under study by Boeing North American and Lockheed-Martin. Initial screening assessments were performed on a wide variety of BME candidates, and then focused on a short list of three candidates that looked most promising, i.e the Aerojet AJ-800, Pratt & Whitney RD-180S and the Rocketdyne RS-76. A fundamental constraint on this evaluation process involved the competition sensitive nature of the data on these three BME candidates. A "firewall" approach has been used to assure total segregation of these sensitive data among the propulsion subcontractors. In some cases, this requirement to segregate competition sensitive information has resulted in constraints on the availability of certain key technical or cost data, resulting in a limited or incomplete assessment of the primary BME candidates.

BME CANDIDATE DESCRIPTIONS



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

Figure 5. All of the BME candidates use LOX/Kerosene propellants with oxygen-rich, staged combustion cycles

The three candidate BMEs are similar in that they all are based on staged combustion cycle/oxygen-rich preburners and the use of liquid oxygen and kerosene-based propellants (RP or JP). All engines allow sufficient throttling capability to accommodate the LFBB engine-out requirement. Thrust levels, performance efficiencies, and mixture ratios for the engines allow each of them to meet mission requirements.

Each engine has a unique configuration with the following differences. The Aerojet AJ-800 is derived from the Russian NK-33 engine (current planned for use on the Kistler K-1 reusable launch vehicle) and incorporates dual NK-33 powerhead/turbopump assemblies (one on each side of a new thrust chamber).

The Pratt & Whitney RD-180 is derived from the Russian RD-170 rocket engine (used on the Energia and Zenit launch vehicles). The RD-180 is currently being prepared for ground testing at NASA-MSFC in support of the Lockheed Martin commercial Atlas III and Air Force EELV launch vehicles. It incorporates a single powerhead/turbopump assembly and two of the existing RD-170 type thrust chambers.

The Boeing Rocketdyne RS-76 rocket engine is a new design which would incorporate a single powerhead/turbopump assembly and a single thrust chamber. It can incorporate optimized features based on LFBB and Space Shuttle Requirements.

Each engine is in a different stage of development, and each must be carefully evaluated to compare their relative maturity, potential risk, and cost to meet the LFBB program needs.

RESULTS AND DISCUSSION

BME SELECTION CRITERIA

To meet the LFBB system goals, the BME's must offer a robust propulsion capability which provides extremely high reliability, performance and thrust-to-weight, while at the same time affording generous margins of safety and historically low development, certification, production and operations costs. The key BME features that enable the LFBB system concept involve:

- Operating under highly derated conditions to increase reliability and durability.
- Throttling to allow mission completion with an engine-out.
- Integrated Heath Monitoring to avoid catastrophic failures and allow maintenance on demand.
- Self cleaning engine cycles that avoid labor intensive maintenance operations.

The process of evaluating the three engine candidates against any developed criteria involves assessing the effectiveness of each engine at meeting these general features. The resulting "trade space" for BME characteristics is shown in Figure 6. For each engine the balance achieved in the "trade space" is different but the overall effect on the vehicle level trades may or may not be different. It is the purpose of the criteria described above to help sort out the effects.

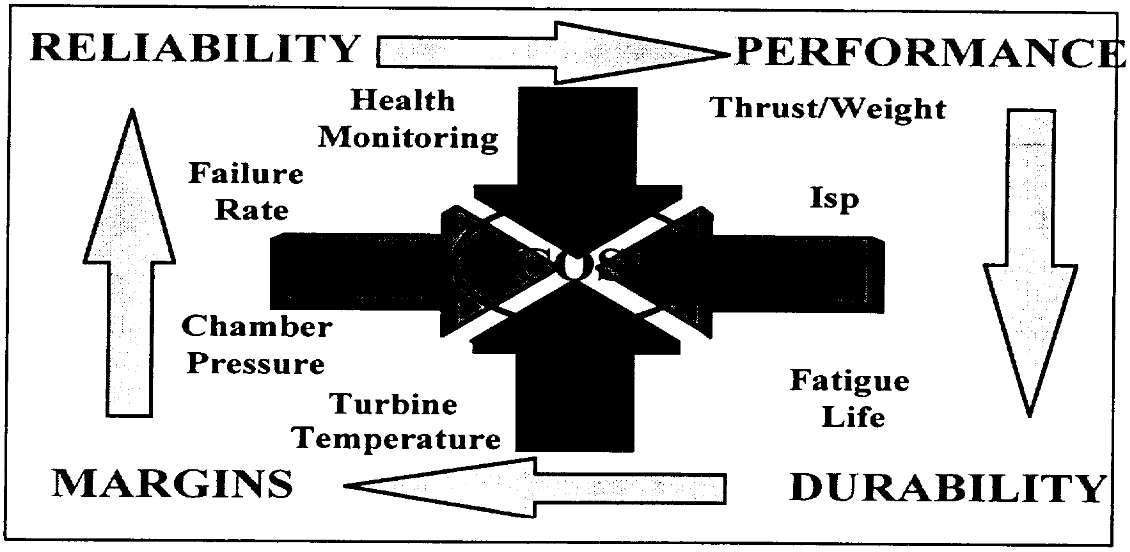


Figure 6. The "Trade Space" for LFBB parameters as affected by BME characteristics.

The engine selection criteria can be divided into two basic groups; "Must Have" and Discriminators (attributes). The "Must Have" criteria are go / no go limits that must be satisfied to enable the physical viability of an LFBB launch vehicle. Table 1 lists the critical BME " Must Have" values. Once the "Must Have" criteria are met, these parameters become discriminators as to their effects at vehicle system level. Additionally there are a number of other discriminators at the engine level that are important for the LFBB. These BME discriminators BME listed in Table 2.

Table 1. BME "Must Have" Criteria serve as enabling parameters for the LFBB.

LFBB Enabling Parameter	Measures of Effectiveness	LFBB System Threshold Value	BME "MUST HAVE" Values
Safety	Mission Success	Engine Out Capability	Throttle range .> 1.67
	Vehicle Loss Rate	< 1/250	< 1/1520 for each of 8 engines
			Catastrophic Fraction < 10%
Reliability	Shut Down Rate	< 1/178	< 1/1425 for each of 8 engines
	Pad Abort Rate	< 1/40	< 1/166 for each of 8 engines
Performance	Thrust/Weight	> 1.20 at sea level	> 95
	Gamble Angle	> +/- 8 degrees	Same
	Gimbal Rate	> 10 deg/sec	Same
	Engine Isp	> 337 sec (vacuum)	Same
	Ullage Pressure	30 psia	NPSH < 30 psia
Affordability	LOX/Kerosene	Mixture Ratio	~ 2.7

Table 2 BME Discriminator Criteria serve as a basis for comparing candidate engines.

Top Level Criteria	Specific Parameter Measured
Engine Reliability	Launch Probability
	Mission Success Probability
	Catastrophic Failure Fraction of Unsuccessful Operation
Acquisition Cost	DDT&E
	Production
Annual Operations Cost	Flight Facility Engine Maintenance Operations
	Sustaining Engineering, Logistics, etc
	Engine Overhaul
	Acceptance Test Facility Costs
Operations Turnaround Between Flights (effect on vehicle availability, i.e. schedule)	Scheduled Maintenance
	Percentage of Unscheduled Maintenance
	Line Replaceable Unit (LRU) Replacement Time
	Engine Replacement Time
Programmatic Considerations	
- Cost and Schedule	Funding Profile
	Development Schedule (How long it takes to have engine available to support flight)
- Program Risk	Prior Hardware Heritage (existing, derivative or new engine)
	Parallel Program Applications (Alternative uses)
	Domestic Sources for Hardware (NASA Policy)

BME SELECTION PROCESS

The BME selection process is still under development at this time. There are a number of programmatic options for selecting the BME that are under active study by the vehicle contractors and the NASA. The government could select the BME and provide the engine as Government Furnished Equipment to the final selected vehicle contractor in a manner analogous to the SSME for the Space Shuttle. In the current environment for doing business, this is unlikely but possible. A joint selection process could be pursued by the Government and the vehicle contractors for a single BME that would work with either vehicle concept. This would remove the BME selection process as a potential discriminator in the vehicle competition and could allow for early start for engine development. This approach raises issues about potential changes in the BME performanceand price between the time the joint engine selection decision is made and the time to execute a subcontract with the winning vehicle system contractor. The Government could allow the vehicle contractors to independently select their BME as a subcontractor for their specific vehicle concept. The BME selected by each vehicle contractor would then become a key element of their proposal, and would thus affect the subsequent winner of the LFBB system competition. It is anticipated that each vehicle contractor will make a recommendation to the NASA Program Officeduring the next year regarding the preferredBME selection process that would be most suitable for their specific LFBB system concept. The examples in this paper are not intended to be exhaustive but only representative of the BME selection process alternatives. Regardless of the specific BME selection process to be used by the LFBB program, the criteria documented in this paper are expected to be the basis for that eventual BME selection.

LFBB SYSTEM SENSITIVITIES

The sensitivity of the LFBB vehicle concepts to changes in BME characteristics were estimated by NASA/MSFC, Boeing North American and Lockheed-Martin in support of the on-going LFBB system concept definition studies. These sensitivity studies focusedon the unique attributes and characteristics of each of the various vehicle concepts as affected by each of the 3 BME candidates. The resulting set of LFBB system level partials provide a convenient means for quickly estimating the effectsof relatively small changes in the BME parameters. These partials were developed by simulating the LFBB system performance for a baseline condition and then noting the effectsof perturbations to this baseline involving small changes in each of the BME parameters (Ref. 1). Specific values have been calculated for each vehicle concept when propelled by each candidate BME. These vehicle and BME specific partials would be inappropriate for inclusion in this paper as they are both too voluminous and competition sensitive. An "average" set of the specific partials has been derived from the specific data to show relative sensitivities and trends without violating the competition sensitivity nature of the detailed results. Tables 3 and 4 summarizes these "average" vehicle system sensitivity to changes on BME parameters.

Table 3. Average Effect of a 1 second change in BME Specific Impulse on LFBB System Weights (Ref. 1)

	2 Duals	Catamaran
Booster Dry Weight (LBm)	690	725
Propellant (LBm)	12,550	13,450
GLOW (LBm)	13,500	14,500
Payload to Orbit (LBm)	505	512

Table 4. Average Effect of a 1 LBm change in BME Dry Weight on LFBB System Weights (Ref. 1)

	2 Duals	Catamaran
Booster Dry Weight (LBm)	12.8	12.9
Propellant (LBm)	29.6	32.5
GLOW (LBm)	26.0	49.0
Payload to Orbit (LBm)	2.38	1.23

The development cost sensitivity analysis was produced using a cost model (Ref. 2) developed and anchored in historical liquid engine program costs. The database used to anchor the model covers engines as small as the Pratt & Whitney RL10 to as large as the Rocketdyne F-1 (Ref. 3). All basic engine cycles are represented and some of the recent data does reflect some new ways of doing business. The model has excellent agreement with the historical data with a maximum difference between estimated and actual ranging between 2 and 12 percent. The parameter presented in this paper is the effect of engine operational life on the development cost. This effect is predicted because the certification philosophy for the STS is to demonstrate two samples for two times the intended operating life. Therefore, if an BME is to operate for a life of 30 missions, the certification testing to demonstrate this would be two engines with 60 representative hot fire tests each for a total of 120 tests. As the operating life goes up it is apparent that the amount of testing goes up by a factor of four. Figure 7 is a plot of this effect on a nominal engine development cycle. The effect of going from an engine life of 20 missions to 60 missions adds approximately $90M to total development cost. In the current environment of limited resources for development, this cost must carefully be traded against the benefits that a longer life engine adds to the operations costs.

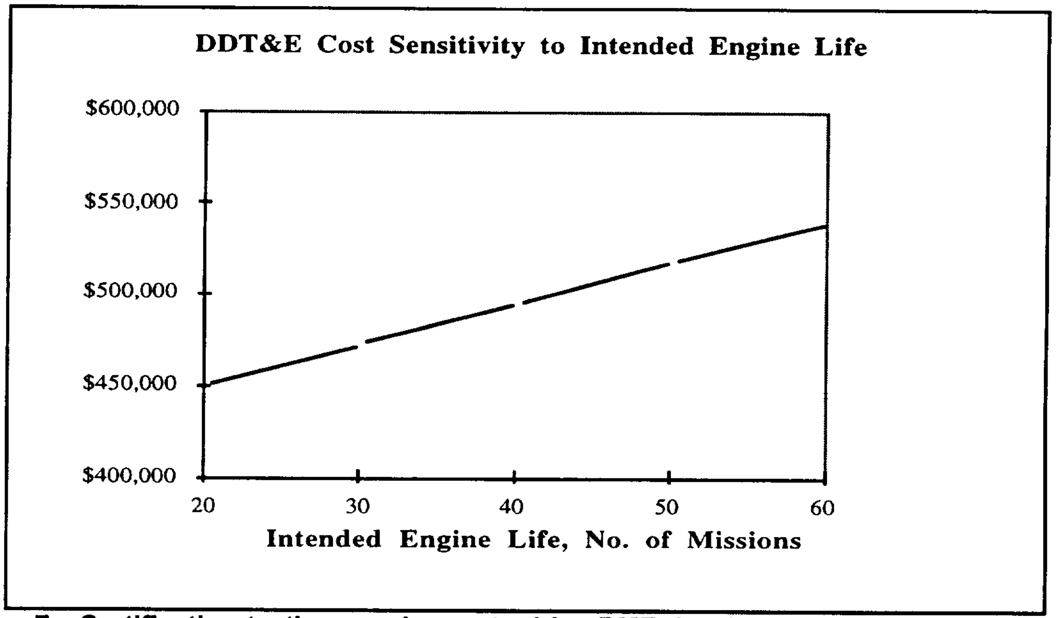


Figure 7 Certification testing requirements drive BME development costs to g row linearly with increasing engine operating life.

The engine life is only one of several significant parameters that affect engine development cost. For the BME, the primary development cost areas appear to be design engineering labor and test hardware costs. Test hardware costs have historically been a very large percent of total DDT&E cost. The design engineering labor costs remain a large number with the percent increasing as other categories are reduced. It appears that DDT&E costs are being traded between numbers of tests required to develop an engine versus design engineering labor. With very expensive hardware, it is cheaper to minimize tests and thus hardware at the expense of increased engineering labor to understand the design and eliminate failures early. Parameters that affecteach of these areas are; engine cycle, thrust level, engine complexity, design methodology, design maturity (is it a new engine or a derivative of an existing engine), and manufacturing technology maturity. All these factors must be assessed in any BME selection criteria. It is important that the BME selection process force the identification of all input data affecting these parameters.

The operations cost sensitivity analysis was produced using a model for predicting the annual operations costs which is anchored in the operations cost of the Phase II SSME (Ref. 2). The SSME is the only reusable liquid rocket engine of this type ever developed and operated and is therefore the only source for anchoring any operations model. The SSME data used was obtained from the 1994 NASA Program Operating Plan budget cycle.

Engine operations costs are broken down into five categories: production, rebuild or overhaul, on-site test, on-site flight, and off-site engineering. The cost estimate input parameters include: production cost estimate, rebuild/overhaul cost as percentage of production cost, launch rates, engine life and overhaul life, number of greenruns required per engine, material costs per test (propellants, etc.), test stand personnel requirements, facility support personnel requirements, on-site flight processing man-hours, and engine manufacturer off-site program support manpower requirements. Sensitivities for each of these areas can be examined. Figure 8 shows the influence of the engine operating life on annual operations costs. Like the trend with overhaul time, there is a decreasing benefit with increased engine life between 30 and 60 missions. The gain from 30 to 60 missions is only about $7M annually while the development cost addition shown in Figure 7 above was about $50M. This would require at least 7 years of operation to realize a return on the added development cost. Again, a system level benefits versus cost analysis will be performed by the vehicle contractors in conjunction with the government to set the specific design criteria that the engine subcontractors will be asked to meet.

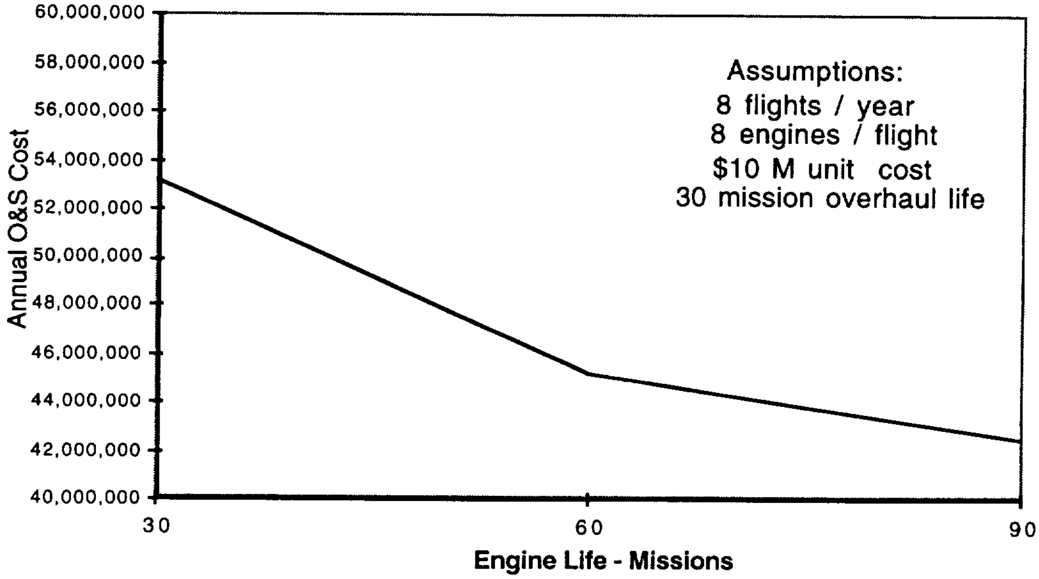


Figure 8. Sensitivity of annual operations and support costs to engine life for a 30 mission engine overhaul rate.

Figure 9 shows the influence of the number of missions between engine overhaul on annual operations costs. This figure indicates a significant decrease in benefit for increased time between overhauls above 15 to 20 missions. This holds true whether the program is using a 30 or 60 mission engine flying 8 times a year or 15 times a year. The flight rate must be increased to over 30 flights per year before the model shows any significant benefit to increased overhaul time beyond 20 missions. Overhaul time will have a similar affect on development cost as does engine life. A system level benefits versus cost analysis will be performed by the vehicle contractors in conjunction with the government to set the specific engine life design criteria that the engine subcontractors will be asked to demonstrate.

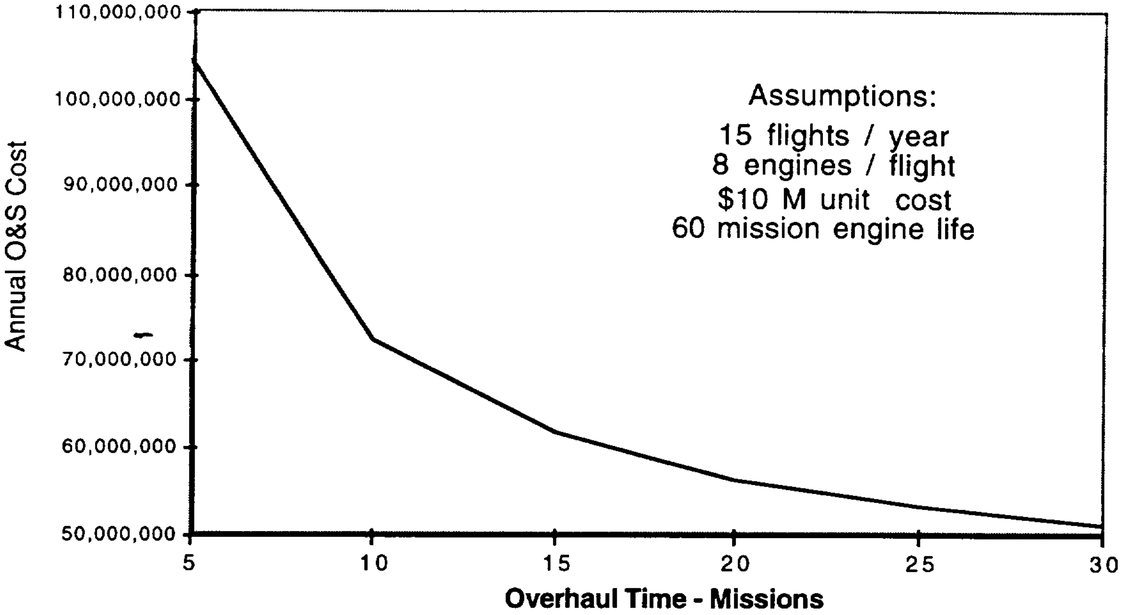


Figure 9. Sensitivity of annual operations and support costs to overhaul Time for a 60 mission engine life.

SUMMARY AND CONCLUSIONS

There are several viable BME candidates for use on a new LFBB for the Space Shuttle. Each BME candidate has its own unique solutions for meeting the LFBB requirements. A set of BME selection criteria has been defined that can be used to screen these unique attributes regardless of the final BME selection process chosen by the program office. This approach allows a BME selection that should satisfy the overall LFBB program goals to enhance the Space Shuttle safety and reliability, increase mission flexibility, reduce operating costs, and improve performance. This approach is also flexible and can be easily modified as the LFBB program evolves. Finally, the sensitivities of the LFBB system concepts to variations in BME characteristics are well understood and will be used in finalizing the BME design requirements.

REFERENCES

1. Space Transportation System standard vehicle performance analysis tools
    ASTRO: Ascent performance trajectory design and analysis
    DADS: Trajectory Simulation tool used to develop DOLILU II I-loads
    XE0034: Entry trajectory design and analysis
    DOLILU: Shuttle day of launch I-load update processor
    POST: Generic vehicle trajectory design and analysis tool
    LVSIZING: Customized MS-Excel tool for launch vehicle sizing
   Unpublished Report, February 12, 1998, Contact M. R. Hines at Boeing North American for specificinformation.

2. Ryan, R. M. and Neely, M. A., "Liquid Rocket Engine Cost Models," Unpublished Report, 1996, Contact R. M. Ryan at NASA/MSFC for specific information.

3. Rocket Engine Development Team (REDT) Final Briefing "Engine Development at Reduced Cost, Schedule and Risk" to T. J. Lee, NASA/MSFC Center Director, 10 June 1993, Contact G. M. Lyles at NASA/MSFC for specific information.