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NASA Technical Memorandum 104801

Liquid Flyback Booster Pre-Phase A Study Assessment

Volume 2

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Preface

The Concept

Provide a cost-effective solution to long-term access to space through a fully reusable liquid propellant booster

Which:

- Increases Shuttle safety by enhancing abort capability and failure tolerance during first stage
- Increases Shuttle performance capability to high inclinations and high orbit altitudes
- Significantly reduces Shuttle operations costs
- Provides a development path to mitigate critical Shuttle obsolescence (i.e., computers, integrated navigation systems, electromechanical actuators, etc. are designed to also replace obsolete Orbiter systems)

While:

- Providing a reusable first stage for unmanned launches
- Providing a growth path to a heavy-lift launch capability

All of the above can be accomplished with a single configuration and a single infrastructure including:

- One processing facility
- One vendor/logistics support activity
- One sustaining engineering activity
- Maximum synergism with Shuttle infrastructure

RESULT: COST-EFFECTIVE ACCESS TO SPACE

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Tables

Acronyms

ABE	air-breathing engine
ADTA	air data transducer assembly
ALT	approach & landing test
α	angle of attack
APAS II	Aerodynamic Preliminary Analysis System II
APU	auxiliary power unit
ARF	Assembly and Refurbishment Facility
ASRM	advanced solid rocket motor
ATO	abort-to-orbit
ATP	Authority To Proceed
β	angle of sideslip
BECO	booster engine cut-off
BFS	back-up flight software
BMAD	battery management and distribution
BP	body point
BSM	booster separation motor
C&T	Communication and Tracking
CAD	computer-aided design
CBT	computer-based training
CCAFS	Cape Canaveral Air Force Station
CCF	Consolidated Communications Facility
CCF	catastrophic correlation factor
CFD	computational fluid dynamics
CL	coefficient of lift
DED	design engineering difficulty
DMS	data management system
EIU	engine interface unit
EMA	electromechanical actuation
EPS	electrical power subsystem
EQI	Production Equipment Status
ET	external tank
F&M	force and moment
FBPF	flyback booster processing facility
FCR	fault containment region
FCR	flight control room
FCT	flight controller trainer
FDIR	fault detection, isolation, and recovery
FEU	flight equivalent unit
FRF	flight readiness firing
F.S.	factor of safety
FSS	fixed service structure
FTE	full–time equivalent
GAP	general avionics processor
GEO	geosyncronous orbit
GN&C	Guidance Navigation and Control
GPC	general purpose computer

Acronyms (continued)

GPS	global positioning system
GSE	ground support equipment
GTS	GN&C test station
HGDS	hazardous gas detection system
HLLV	heavy-lift launch vehicle
HW/SW	hardware/software
ICD	interface control document
IFMU	integrated flight management unit
IGES	initial graphics exchange standard
INS	inertial navigation system
IOC	initial operational capability
JSC	Johnson Space Center
KATS	Kennedy avionics test set
KSC	Kennedy Space Center
L/D	lift-to-drag ratio
LCC	Launch Control Center
LCC	life cycle cost
LEO	low Earth orbit
LFBB	liquid flyback booster
LPS	launch processing system
LRB	liquid rocket booster
LTS	LFBB test station
MCC	Mission Control Center
MDM	multiplexer/demultiplexer
MECO	main engine cut-off
MLG	main landing gear
MLP	Mobile Launch Platform
MPD	manufacturing/operations process difficulty
MPS	main propulsion system
MPSR	multi-purpose support room
MSFC	Marshall Space Flight Center
NASCOM-DB	NASA cost model data base
NEC	National Electric Code
NEOM	nominal-end-of-mission
NGP	National Grid Project
NLG	nose landing gear
NPSP	net positive suction pressure
Nz	normal acceleration
OI	operational instrumentation
OMDP	operations and maintenance down period
PASS	primary avionics system software
PCMMU	pulse code modulation master unit
PER	personnel resource status
QUADPAN	Quadrilateral Element Panel Method

Acronyms (concluded)

RCS	reaction control system
RPSF	Receiving, Processing, and Storage Facility
RSLS	redundant set launch sequencer
RSRM	redesigned solid rocket motor
RSS	rotating service structure
RTLS	return-to-launch-site
SAIL	Shuttle Avionics Integration Laboratory
SCA	shuttle carrier aircraft
SCOM	Shuttle Crew Operations Manual
SLF	Shuttle Landing Facility
SLOC	source lines of code
SMTF	Shuttle Mission Training Facility
SOT	state of technology
SSME	Space Shuttle Main Engine
SSTO	single stage to orbit
STDN	spaceflight tracking and data network
T&V	test and verification
T/W	thrust-to-weight
TABI	tailored advanced blanket insulation
TAL	trans-oceanic abort landing
TDRSS	tracking and data relay satellite system
TEST	test resource status
T0	liftoff
TPS	thermal protection system
TSFC	thrust specific fuel consumption
TSM	tail service mast
TSTO	two-stage to orbit
TVC	thrust vector control
UDF	unducted fan
VAB	Vehicle Assembly Building
VHM	vehicle health monitoring
VHMS	vehicle health management system
WBS	work breakdown structure

SECTION 6
OPERATIONS CONCEPT

6.1 Operations Concept

The operations concepts are divided into major components of flight operations and ground operations. The ground operations concepts include all activities required from LFBB wheel stop of one mission to launch of the next mission. It includes post-launch processing, pre-launch processing, launch preparations, and launch. The ground operations are described in section 6.5.

The flight operations concepts provide descriptions for all flight phases from launch to wheel stop. The flight operations concept is further divided into two major areas. Integrated flight covers the flight phase during which the LFBBs are attached to the Orbiter. Post-separation/return flight covers the flight phase from booster separation to wheel stop. These flight operations concepts are described in sections 6.2 and 6.3.

A typical mission scenario is included in section 6.4. The mission profile is presented for ascent and booster flyback. The key events in the mission timeline are presented.

6.2 Integrated Flight

The Orbiter SSMEs and the main engines for each LFBB are started and brought to liftoff thrust. At t = 0 seconds, the Shuttle/LFBB lifts off from the launch pad and command and control transitions to the Mission Control Center (figure 6.2-1). The LFBB launch vehicle configuration operates within present shuttle procedures and operational constraints. There are no additional launch window requirements, launch hold requirements, or launch weather restriction constraints. The LFBB weather restriction constraints for landing are identical to the Shuttle RTLS restrictions. During ascent (until booster separation), the LFBB main propulsion system commands come from the Orbiter GPCs. Booster-critical system parameters are downlinked (separate telemetry per booster) to a ground station for routing to the Mission Control Center for monitoring (to detect changes in systems status and to alert the flight crew). The TDRSS will participate in the data and communication link since the boosters are below the horizon for part of the flyback trajectory. Selected booster data and Orbiter data is made available to the Launch Control Center (LCC) and the LFBB control room by direct routing through NASCOM. By making key LFBB systems status and trajectory data available during ascent, a smoother and more efficient post-separation LFBB CR command and control transition of the LFBBs will occur.

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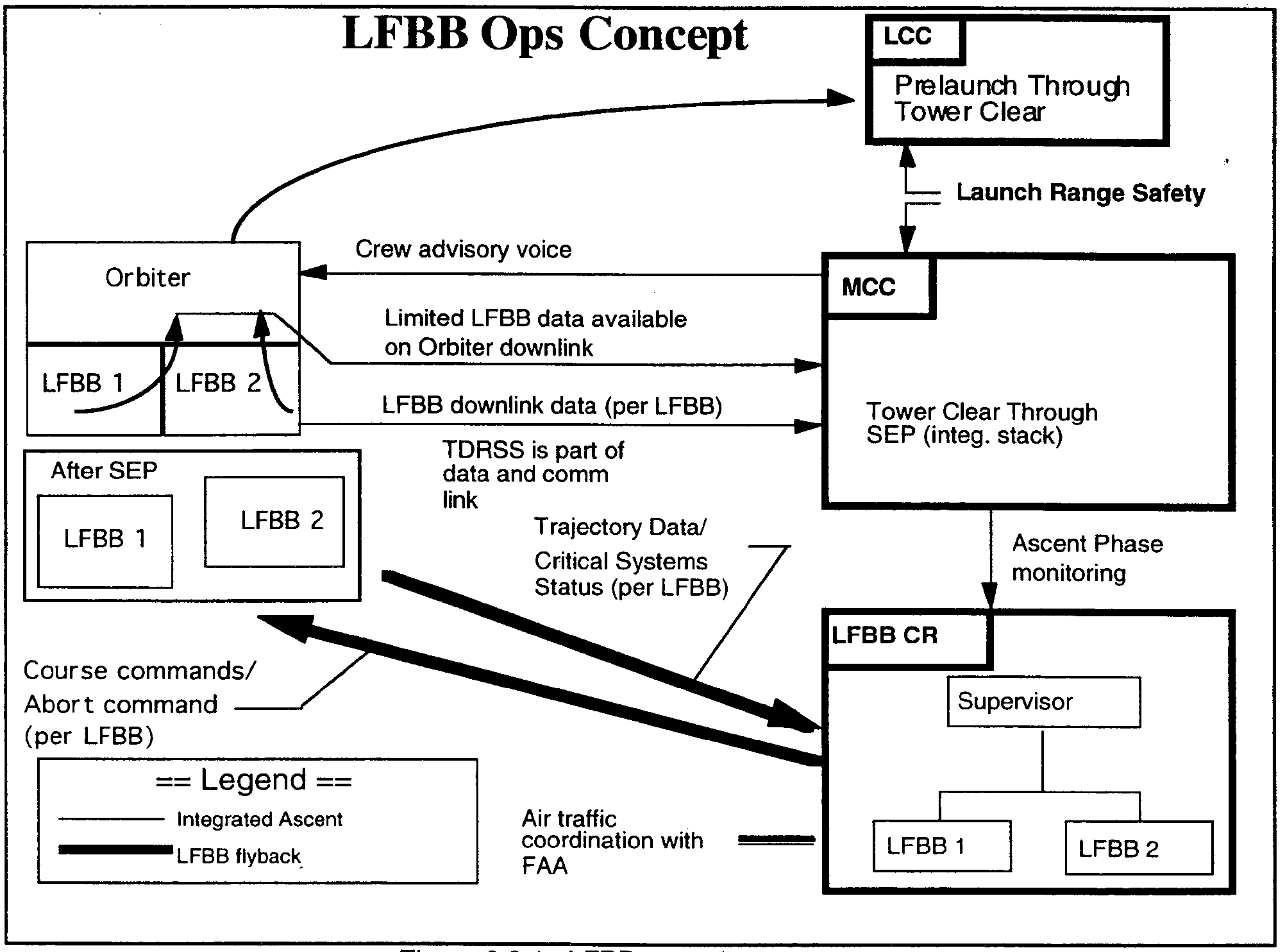


Figure 6.2-1 LFBB operations concept.

6.2.1 Philosophy and Assumptions

- The LFBB onboard Vehicle Health Management capability during flight consists of automated FDIR, selection of specific sensors from multiple/redundant data sources, and sensor data incorporation processing.
- The LFBB provides a control and propulsion health and status data link to the Orbiter.
- The Orbiter provides LFBB control and throttle commands.
- Each LFBB provides its own antenna management.
- Each LFBB provides telemetry for monitoring the status of critical systems.
- An automated separation command will be issued by the Orbiter.
- LFBB telemetry data will be downlinked to the ground through the LFBB telemetry system. There will be a separate data stream for each booster.
- Continuous communications with each LFBB will be available throughout the entire mission.

- There will be no capability for the flight crew or flight controllers to intervene in the LFBB operation during integrated flight. However, information will be enunciated to the flight crew and flight controllers as required for changes in system status and configuration.
- Before separation, the Orbiter provides the state vector and flight attitude data to the LFBB GN&C.
- There will be no communications interference between the boosters, and each booster will be protected from misdirected or intercepted commands.
- The LFBB onboard flight trajectory, runway selection, and other GN&C targeting parameters shall protect for an Orbiter RTLS.
- There will be no additional requirements on launch window, launch hold, or launch weather window constraints for launch.
- KSC has responsibility for the command and control of the integrated vehicle from pre-launch through liftoff (T0).
- JSC has the responsibility for the command and control of the integrated vehicle from T0 to Orbiter booster separation.
- The LFBB control team has responsibility for command and control of each LFBB vehicle from Orbiter separation through landing and wheel stop.
- There will be a capability reserved for minimal ground operator and/or flight crew determination of LFBB system failures during flight.

6.3 LFBB Post-Separation/Return Flight

Following separation from the Shuttle, each booster will execute a series of attitude maneuvers designed to dissipate excess energy and turn the vehicle back toward the landing area. Each LFBB has autonomous GN&C capability, and only limited monitoring of the onboard subsystems is required by the ground. Both the left and right LFBBs have a loiter point and holding pattern included in their design. The location of the holding pattern (25 nmi from landing site) was selected to ensure that a booster with a failed engine could not reach land. Upon reaching the loiter point, each booster can either be instructed to continue to the landing site or enter the holding pattern (see figure 6.3-1). The only flight modes that can be entered from the holding pattern are the landing mode or the abort mode. The abort mode is used for safe disposal of the LFBB in the event a landing at the prime or alternate landing areas is not possible, or a failure of critical booster systems occurs. During an abort, the booster engine thrust and aero-surfaces can be commanded to abort settings or the booster can be redirected to an abort ditch site as performance, flight rules, and/or operational constraints permit. During the landing mode, the booster is commanded from the holding pattern to the desired landing area, which is selected based on the status of the trajectory, approach corridor, critical subsystems, and ground base conditions. For nominal flight, one booster is commanded to the primary landing area (currently runway 15 at the Shuttle Landing Facility [SLF]) while the other maintains the holding pattern. After successful landing, rollout, and taxi of the first booster, the second booster is commanded to the same landing area. For a contingency flight, each booster has the capability to be commanded to an alternate landing site (currently runway 31 at the KSC skid strip, figure 6.3-2).

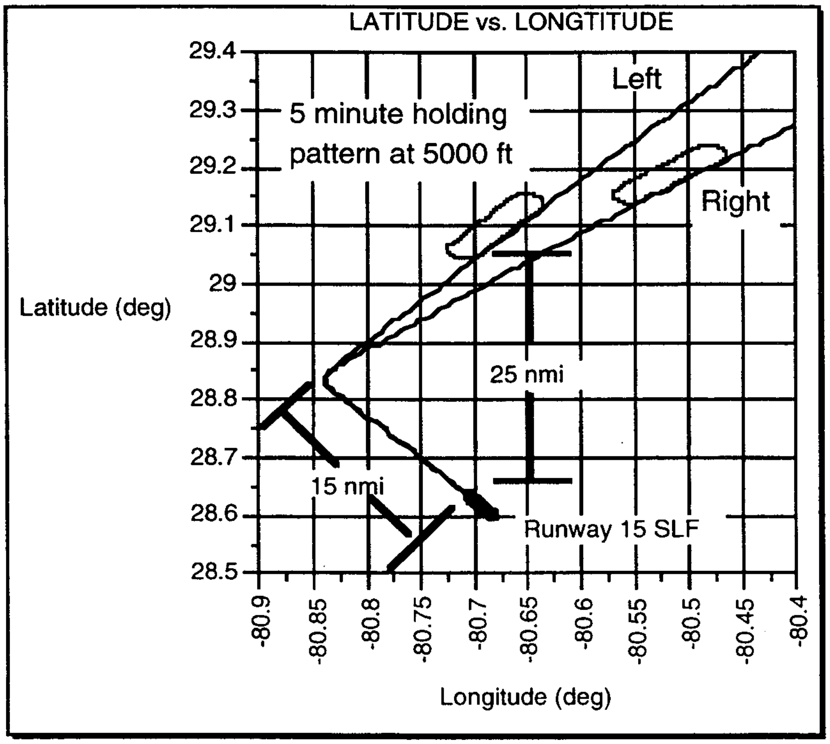


Figure 6.3-1 LFBB approach to KSC SLF runway 15.

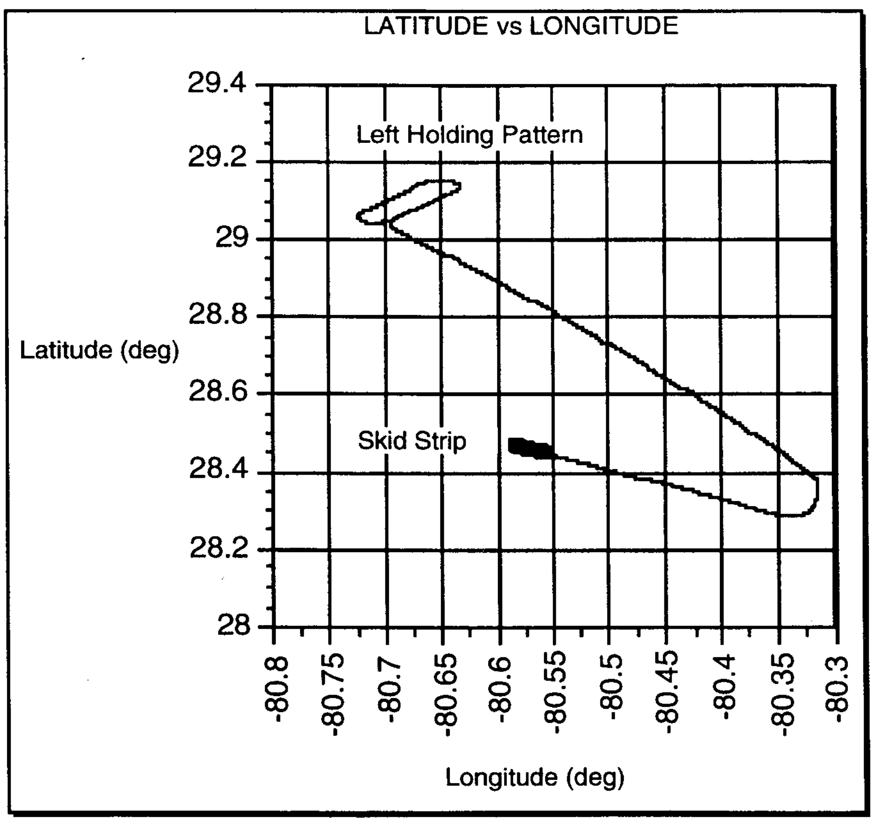


Figure 6.3-2 LFBB approach to CCAFS skid strip runway 31.

6.3.1 Philosophy and Assumptions

- Each LFBB is managed separately by the LFBB CR.
- FAA air traffic control will ensure priority air space for both boosters.
- The flight dynamics command and control will be exclusively onboard functions.
- The LFBB will be capable of autonomous onboard flight without ground communication to enable re-establishment of communications. In the event communications cannot be established within time limits, the LFBB will maintain capability for safely aborting the return at all times.
- The LFBB flight abort will be by water impact and not by a vehicle self-destruct system.
- The LFBB has the *capability* to execute a pre-stored post separation through loiter flight sequence without ground intervention. The LFBB also has the *capability* to receive changes to runway selection or enter an abort mode.
- The LFBB will require permission to transition out of loiter mode into the landing mode. If permission is not granted or if communication is lost, the LFBB will enter a default abort mode.
- Each LFBB will have 30 minutes of loiter capability.
- Each LFBB will transmit its trajectory data and critical systems status data to the LFBB CR.
- All LFBB system management will be performed through onboard FDIR.
- Each LFBB uses GPS for navigation during flyback.

6.3.2 Flight Modes

The LFBB post-separation mission sequence is divided into five flight modes (post-sep, cruise, loiter, landing, and abort). Each flight mode controls a defined phase of the booster mission and has a defined set of mission events, flight control parameters, system commands and target commands and parameters.

Figure 6.2.2-1 shows the five LFBB mission modes and how they are operationally sequenced. The first three modes (post-sep, cruise, and loiter) are all executed automatically without the assistance of ground command or control. The landing mode can only be initiated by ground command. The abort mode can be entered at any time by either ground command or by the onboard system sensing a system failure or malfunction.

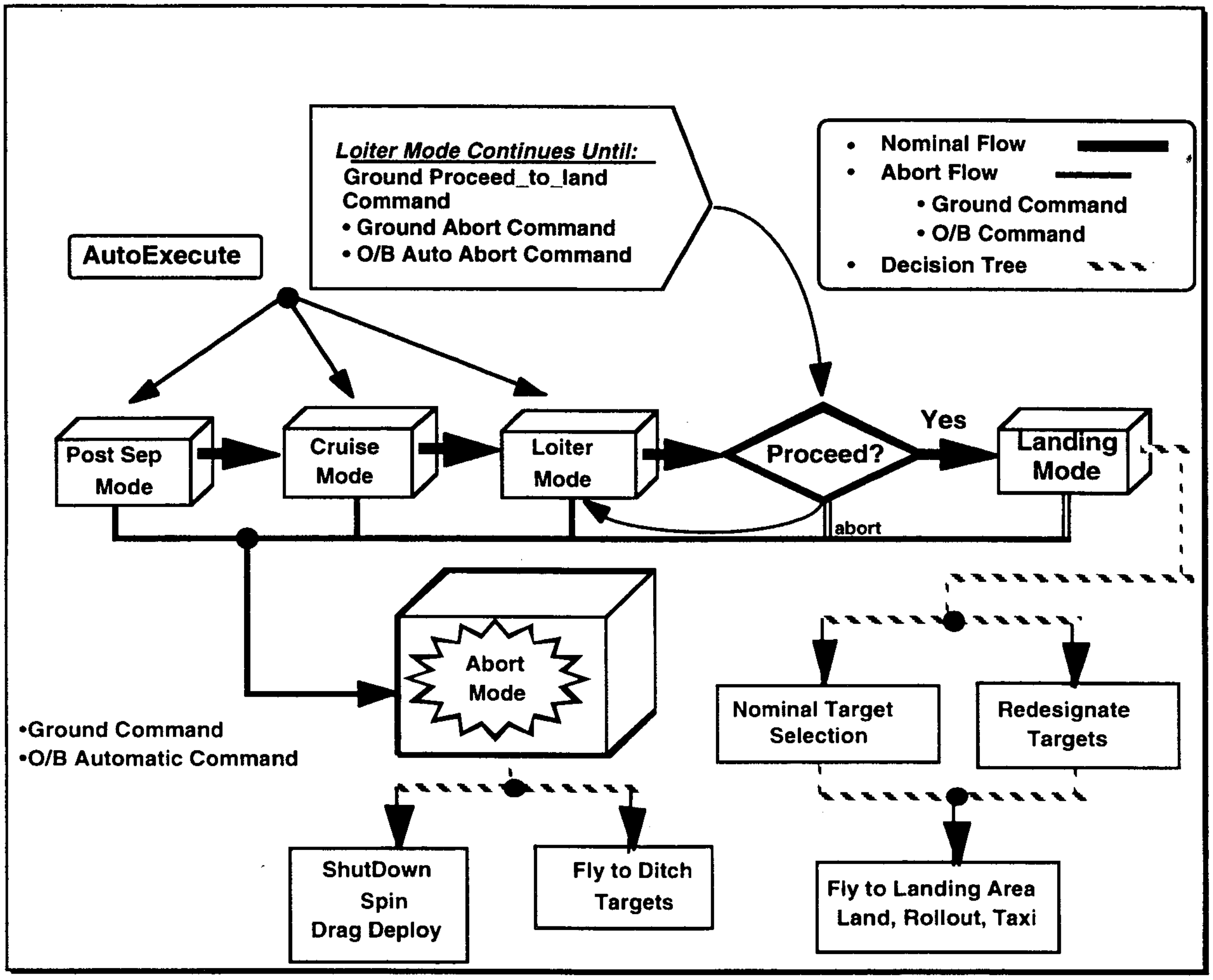


Figure 6.3.2-1 Onboard command and control concept.

A. Post-Sep mode includes all of the mission events from Orbiter separation to air-breathing engine ignition. The Post-sep mode continues for about nine minutes after separation and includes any events required to prepare the vehicle for reentry and gliding flight. This mode also controls the energy dissipation, load relief, and plane change phases of the entry. This includes events for wing deploy, maneuver to entry attitude, load relief, altitude oscillation control, and plane change maneuvers. The vehicle will fly autonomously. The vehicle can exit this mode automatically at a mode transition, by an onboard abort command, or by a ground abort command.

B. Cruise mode includes all of the mission events from preparation for air-breathing ignition to loiter initiation and has a duration of about one hour. This includes events to eject engine inlet covers, ignite engines, achieve cruise altitude, and fly a desired descent glide slope to loiter mode transition. The vehicle will fly autonomously in this mode. The vehicle can exit this mode automatically at a mode transition, by an onboard abort command, or by a ground abort command.

C. Loiter mode includes all of the mission events from loiter mode initiation to the ground proceed command and includes a set of maneuvers required to maintain the holding pattern and altitude. The loiter mode will be automatically entered when the vehicle reaches the loiter mode transition point unless the ground commands an immediate transition to the landing mode. The loiter mission mode places the vehicle in a constant altitude holding pattern for up to 30 minutes. The only automated exit from the Loiter mode is an abort failure mode initiation (e.g., onboard system failure, low fuel, etc.). This ensures that no booster will approach the landing area unless the ground has approved the status of vehicle systems and verified that the selected runway is clear. The vehicle will fly autonomously in this mode. The vehicle can exit this mode only by a ground command to mode transition, by an onboard abort command, or by a ground abort command.

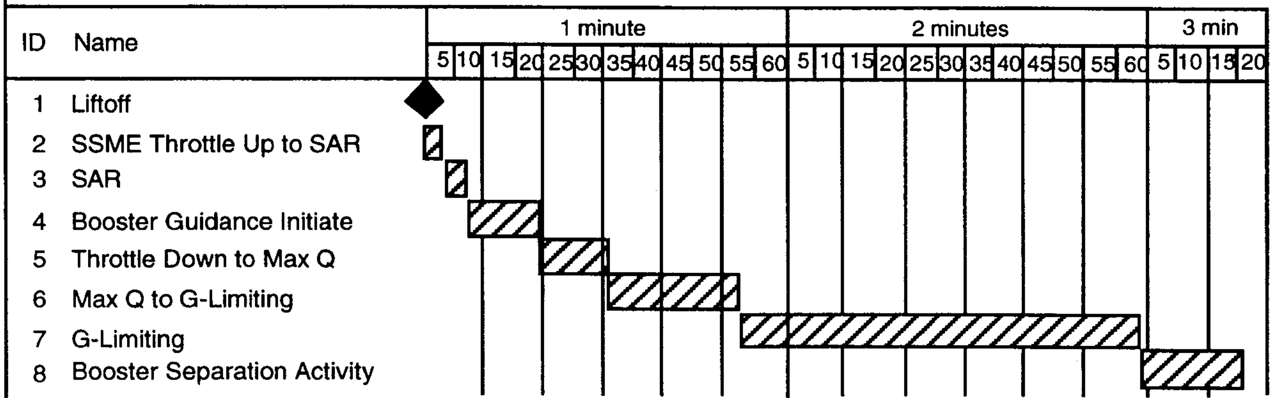
D. Landing mode includes all of the mission events from the ground proceed command to wheel stop. This includes mission events such as maneuvering to runway alignment, final approach, landing gear deployment, flare, land, deployment of braking system, rollout, and taxi. The landing mission mode begins following a ground command to the booster to proceed to the desired landing area. If no command is received the booster will continue to loiter until an abort condition is reached (low fuel, etc.). After receiving the proceed command, the booster will fly to a point 15 miles from the landing site, execute a bank maneuver for runway alignment, execute final approach, flair, land, rollout, and taxi to a desired location. The ground can permit the vehicle to target and attain the nominal landing site selection or redesignate to an alternate landing site. If landing occurs at runway 31 at the KSC skid strip, some arresting devices may be required. The vehicle can exit this mode only by an onboard or ground abort command. Note, the first booster to touch down must maneuver to a location to safe the runway for landing of the second booster. The second LFBB will land at the same runway.

E. Abort mode includes all mission events following either a ground or onboard FDIR abort command. The abort mode can be entered from any flight mode by either a ground command or automatically in the event of an onboard system failure or out-of-tolerance condition. Two abort modes are currently planned. In the first mode, the vehicle will target and fly to a preprogrammed or uplinked set of ditch targets. This might occur if engine and GN&C performance is nominal and the ground desires to ditch the booster at a precise location. In the second mode, the booster engine, control surfaces, or drag deploy devices can be commanded to abort settings. This might occur for off-nominal engine or GN&C performance where precise targeting and/or maneuvering to ditch targets may not be feasible. For example, booster systems could be commanded to a configuration that minimizes the time to water impact.

6.4 Operational Mission Timelines

Figure 6.4-1 provides the timeline for the integrated vehicle ascent. The integrated flight segment lasts 2 minutes 16 seconds, at which time the boosters separate from the Orbiter and begin flyback. Figure 6.4-2 shows the duration of key events during the flyback phase. The flyback phase starts at booster separation and continues until wheel stop. The flyback timeline provides a total mission elapsed time from liftoff to touchdown of 1 hour, 17 minutes, 41 seconds for the left booster and 1 hour, 34 minutes, 24 seconds for the right booster. The right booster has a 15-minute holding pattern built into the timeline. During this time, the left booster flies to runway 15 at the SLF, lands, and taxis to a safe location before the right booster is commanded out of the holding pattern and into the landing mode.

LFBB Nominal Ascent Timeline



ID	Event	Mission Time Duration (hh:mm:ss)	Mission Time Elapsed (hh:mm:ss)
1	Liftoff	0:00:00	0:00:00
2	SSME Throttle Up to SAR	0:00:03	0:00:03
3	SAR	0:00:03	0:00:06
4	Booster Guidance Initiate	0:00:12	0:00:18
5	Throttle Down to Max Q	0:00:12	0:00:30
6	Max Q to G-Limtting	0:00:22	0:00:52
7	G-Limiting	0:01:07	0:01:59
8	Booster Separation Activity	0:00:17	0:02:16

Figure 6.4-1 Ascent timeline.

LFBB Mission Time Line (data)

		Left Booster		Right Booster	
	Mode	Duration (hh:mm:ss)	Elapsed (start time) (hh:mm:ss)	Duration (hh:mm:ss)	Elapsed (start time) (hh:mm:ss)
Liftoff	0	--	0:00:00	--	0:00:00
Ascent	0	0:02:16	0:00:00	0:02:16	0:00:00
Booster Separation	1	--	0:02:16	--	0:02:16
Climb to Maximum Altitude	1	0:01:15	0:02:16	0:01:15	0:02:16
Maximum Altitude	1	--	0:03:31	--	0:03:31
Glide to Re-entry	1	0:01:42	0:03:31	0:01:42	0:03:31
Load Relief	1	0:00:43	0:05:13	0:00:43	0:05:13
Linear Energy	1	0:00:31	0:05:56	0:00:31	0:05:56
Glide and Plane Change	1	0:00:43	0:06:27	0:00:43	0:06:27
Maximum Down Range	1	--	0:07:10	--	0:07:10
Glide and Plane Change	1	0:01:30	0:07:10	0:02:00	0:07:10
Glide Bank Zero	1	0:02:26	0:08:40	0:01:50	0:09:10
Air Breathing Engine Ignition	2	--	0:11:06	--	0:11:00
Descend to Constant Altitude	2	0:31:32	0:11:06	0:31:32	0:11:00
Constant Altitude	2	0:22:27	0:42:38	0:21:02	0:42:32
Descent on Glide Slope	2	0:03:38	1:05:05	0:04:00	1:03:34
Loiter Decision Point	3	--	1:08:43	0:15:00	1:07:34
Descent on Glide Slope	4	0:04:07	1:08:43	0:06:54	1:22:34
Bank Maneuver for Runway Alignment	4	0:01:00	1:12:50	0:01:00	1:29:28
Final Approach	4	0:03:51	1:13:50	0:03:56	1:30:28
Touchdown	4	--	1:17:41	--	1:34:24
The left booster touchdowns 00:16:43 before the right booster.				Without Loiter	1:19:24

Figure 6.4-2 LFBB mission timeline.

6.5 Ground Operations Processing and Timelines

The flows and timelines presented in this section were developed with the understanding that key drivers of the design of the LFBB are operability, maintainability, and the reduction of Shuttle recurring costs. The KSC LFBB Study Team developed an operational plan that is considered by KSC management to be optimistic, but doable. However, this plan requires a mandatory management commitment to design for the stated design drivers and for the design centers to adhere to the guidelines provided to them by the KSC LFBB Study Team for operational efficiency. If management does not make this commitment, or the design of the LFBB is not consistent with these guidelines, it will result in a reevaluation of the flows, timelines, and associated facility and operational costs.

The launch site flow of the LFBBs through their processing facilities is detailed in figure 6.5–1. The following paragraphs describe the processing activities in each of the major facilities.

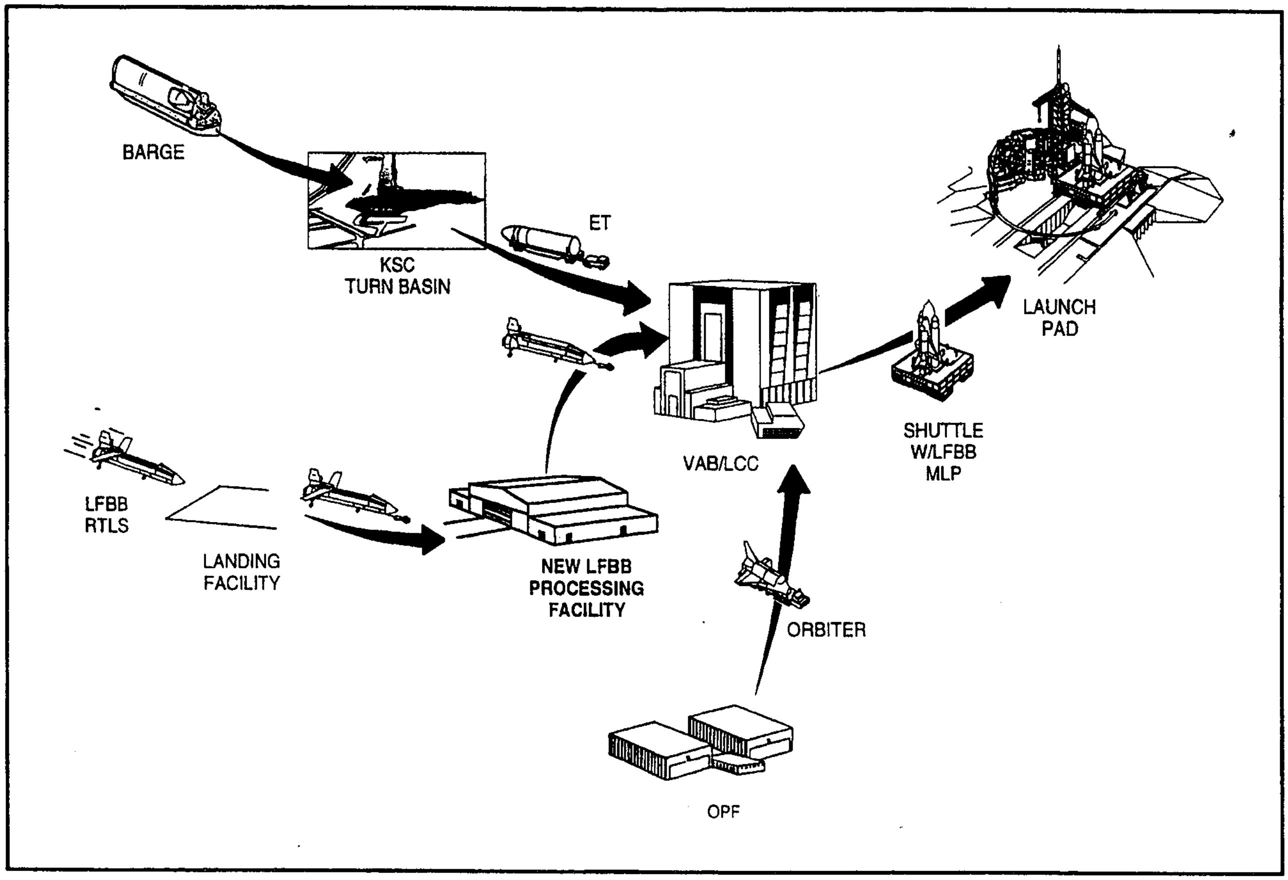


Figure 6.5-1 Launch site flow of LFBBs.

6.5.1 Landing Operations

Both LFBBs will land at the SLF from the north after separation from the external tank/Shuttle. Control of the landing operations after separation will be performed by KSC personnel located in the LCC. Each LFBB will be monitored and controlled by a dedicated LFBB control team with overall integration provided by an LFBB flight director. LFBB critical systems functionality, trajectory, and flight path weather will be monitored post–separation to determine which of a limited set of commands will be sent to the LFBBs. These commands include flight path commands (selecting prestored way points) for landing at KSC SLF 15 or the Cape Canaveral Air Force Station (CCAFS) skid strip, loiter commands (30–minute loiter capability), and abort commands (directing the LFBB to fly to prestored ditching coordinates). If communications are lost between the LFBBs and the LCC during return, the LFBB will automatically fly to a prestored way point over the ocean until communications are reestablished. The LFBB control team training will be provided by a KSC LFBB test set (Minisail), which will also be used to supplement ground software and procedure development.

Both LFBBs will autonomously fly back and land at the SLF. The first LFBB will land and taxi onto the tow way at the south end of the runway. About 15 minutes later, the second LFBB will land in the same manner from the north and also taxi off the runway. Landing teams will then proceed to each LFBB and will begin the runway operations. These operations will include safing the range safety system, purging and drying the LFBB oxygen tank, and ensuring all systems are shut down and safe for movement to the flyback booster processing facility (FBPF). Before LFBB systems are powered down, postflight anomaly troubleshooting can be performed. Landing operation timelines are based on the assumption no toxic residuals, such as hypergols, are on board that require special handling or ground support equipment

(GSE). Once safing operations are completed, a tow vehicle will be attached to each LFBB and they will be towed on their landing gears to the FBPF.

In the case of an Orbiter RTLS, the LFBBs will be commanded to land at the CCAFS skid strip approximately 15 minutes apart. After normal runway/safing operations, one LFBB will be placed on its transporter and moved to the FBPF at KSC. After removal of the LFBB from its transporter, the transporter will return to the skid strip to repeat the process with the second LFBB.

6.5.2 LFBB Processing Facility Operations

Each LFBB will be towed into the FBPF and positioned over floor lifts. The LFBB will be lifted and placed on jack stands under the vehicle. This will provide access to landing gear systems for turnaround operations. Portable workstands will be positioned around each LFBB for access to the air-breathing engine, main engine areas, and the TPS. Cables will be connected for health management and for test and checkout equipment. Access doors in the engine heat shield will be opened to gain access for engine turnaround operations. Other access doors will be opened as required to hook up GSE or perform required turnaround operations.

Processing operations for the left and right LFBBs will be offset by approximately 1 week to optimize the work crew utilization. Moving back and forth between the two LFBBs, one processing crew will progress through the required processing activities for the two LFBBs.

The LFBBs will be powered up for the start of the system test and checkout to determine the operational status and readiness for the next flight. Postflight inspections will be performed on the engine systems, and a fuel flush will be performed on the RD–180 engines to eliminate carbon buildup and coking. Spent hypergol start cartridges will be removed, fuel residuals will be drained from each engine, and electrical and pneumatic systems associated with the booster engines will be checked and verified for the next flight. Disposable combustion chamber throat plugs will be installed. The RD–180 engines will be removed and replaced every 10 flights during operations and maintenance down periods (OMDPs). It is assumed that no heat shields will be removed except for engine removal and replacement and no turbopump torquing will be required during normal engine turnaround operations.

Main propulsion system (MPS) operations will include electrical/mechanical checks on LO_2 and fuel system valves. Also, a low–pressure LO_2 tank pressure decay check will be performed. MPS functionals and required testing per operational maintenance requirements specifications will be performed.

In parallel with the above tasks, LFBB structures will be inspected for flight damage, control surfaces will be tested, and wings will be stowed for launch. A protective shroud will be installed over the folded wings and secured for flight. Tires, brakes, and bearings will be inspected and removed and replaced as required. Landing struts will be inspected, and leak checks and landing gear functionals will be performed. Avionic system tests will also be performed in parallel with engine and MPS verification. A standalone launch processing system (LPS) test set, in conjunction with the VHMS, will be used to verify all avionics systems are functional and ready for flight.

Also, the ABE will be inspected for leaks, and preflight checks and maintenance will be performed to certify the ABE is ready for flight. The ABE will be removed and returned to the vendor during the OMDP.

The LFBB thermal protection system will be inspected for damage after each flight and repair work and waterproofing will be performed as required. It is assumed that TPS work can be performed in parallel with LFBB critical path operations.

The EMAs and associated electrical systems will be checked and verified ready for flight. Flight batteries will either be recharged in place or previous-flight batteries will be replaced with new ones.

After all subsystem testing is completed, a flight readiness/all systems test will be performed. This end–to–end test will certify all systems are ready for flight. Next, the area will be cleared for installation of the forward and aft booster separation motors, which are used to move the LFBB away from the ET during separation. New hypergol cartridges will be installed in each engine.

Final mechanical closeout operations will be performed specifically in the aft area in preparation for the move to the VAB for mating to the MLP. Tire pressures will be checked, landing gears will be retracted, thermal barriers around the landing gear doors will be installed, and the remaining closeout operations will be performed. The LFBB transporter will be positioned under the LFBB and secured for moving to the VAB in a ready–to–mate configuration.

After departure from the FBPF and before entry into the VAB, the LFBB will be moved to a test area north of the VAB. During the first four flows, an ABE start/run test will be performed. Upon completion, the LFBB will be moved through the north VAB door for assembly operations.

6.5.3 VAB Operations

Before moving the LFBBs to the VAB, the MLP will be positioned in VAB Integration Bay 1, and turnaround activities from its previous mission will be performed. The holddown posts will be refurbished and prepared for LFBB mating. The LFBB will enter the VAB through the north door into the transfer aisle.

The lifting fixture will be attached, and the two VAB cranes will lift the LFBB off the transporter and into a vertical position. The aft crane hook will be disconnected, and the LFBB will be hoisted up and into Bay 1 where it will be lowered and mated to the MLP. Next, it will be mechanically and electrically mated to the holddown posts, the T–0 umbilical, and the new booster tail service masts through which fueling and electrical command/control interfaces exist between the ground and vehicle. Leak checks between the mechanical interfaces, specifically the fuel system, will be performed. After both LFBBs are mated to the MLP, they will be aligned for mating with the ET. The ET, which has been processed in VAB Bay 2, will be moved across the transfer aisle and mated to the LFBBs. Necessary mechanical and electrical tasks involved in the mate will be performed. It is assumed the LFBB/ET interfaces will be designed for easy mate, and no matched drilling will be required for closeout. Also, it is assumed that composite fairings will be used to reduce closeout time, and TPS closeout requirements will be reduced.

The remaining activities, from Orbiter mating to transfer to the launch pad, are similar in task and timeline to the current Shuttle processing operations.

6.5.4 Pad and Flight Operations

LFBB launch pad operations will be performed in parallel with current integrated Shuttle pad operations. Command and control of LFBB activities in the VAB and launch pad will be through LPS consoles in either Firing Room 1 or 3 located in the LCC.

Unique LFBB pad operations will include RP–1 and JP–4 loading, which will be performed after Shuttle hypergol loading and before the start of the launch countdown. A flight readiness firing (FRF) will be required and performed during the first flow of each new LFBB to verify end–to–end system integrity.

During countdown, the LO_2 tank onboard the two LFBBs will be loaded after ET loading to minimize icing and gaseous oxygen overboard dumping. The LFBB propellants will be loaded through new TSMs. At launch, the Orbiter Space Shuttle main engine (SSME) ignition and LFBB engine ignition will commence before T0. After verification that all engines are running at 90% thrust, the holddown mechanism will be commanded to release the Shuttle for flight. At tower clearance, control of flight will be handed over to Mission Control in Houston. After LFBB separation, control of LFBB descent and landing operations will be controlled by KSC personnel located in the LCC.

6.5.5 LFBB Processing Timelines

Task sequencing and duration for LFBB mature operations are depicted in figure 6.5.5-1 These timelines are based on the assumptions listed on the timeline chart and can only be achieved by a mandatory program management requirement to design the LFBB for operability. The timelines were developed with limited knowledge of system design and capability, especially for the RD–180 engine, MPS, and TPS turnaround activities and are, therefore, considered preliminary, optimistic, and a "design–to" goal. The overall Shuttle flow is shown in figure 6.5.5-2.

Changes to the stated assumptions given herein could have an impact to the assessments provided in this report. For example, if the assumption to use GOX/RP–1 for RCS propellants were changed to NMH/NTO propellants (hypergols), there would be a significant change to the safety requirements as well as an impact to the timelines, facilities/GSE, manpower, and cost. Although this analysis indicates only a 1–day impact to the success–oriented overall processing schedule for the LFBB, additional GSE and manpower would be required in all areas where the LFBBs are processed. SLF operations upon return of the LFBBs would be constrained by the need to ensure that no toxic vapors are present before Safety would allow post–landing tasks to begin. Also, additional GSE and manpower would be required to support hypergol safing/deservicing operations, which are similar to the Orbiter but occur twice as often for each launch, as well as contingency tasks in the FBPF should there be a leak/spill during processing. If the RCS is an integral part of the booster and not a removable pod that could be serviced offline, any nonstandard tasks, such as unscheduled maintenance, a leak, or any other problem with that system, would result in a serial impact to the processing timelines. This impact could manifest itself in a number of ways depending on the magnitude of the problem. The least of these impacts would be overtime to work the problem on third shift and/or over weekends.

Operations at the launch pad would be impacted by a requirement for LFBB hypergol loading, which is anticipated to be serial to other Orbiter hypergol operations. All of these things will add to the cost and efficiency of operations for the LFBB at the launch site.

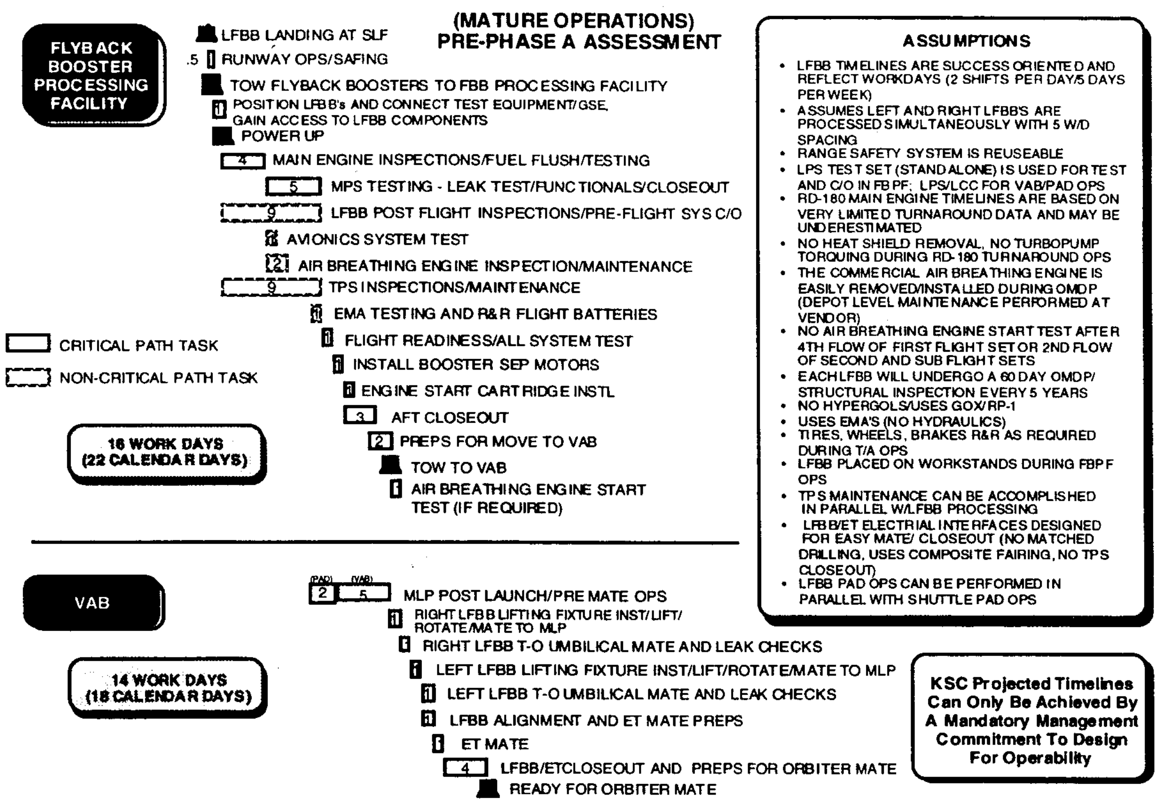


Figure 6.5.5-1 LFBB processing operations (mature operations).

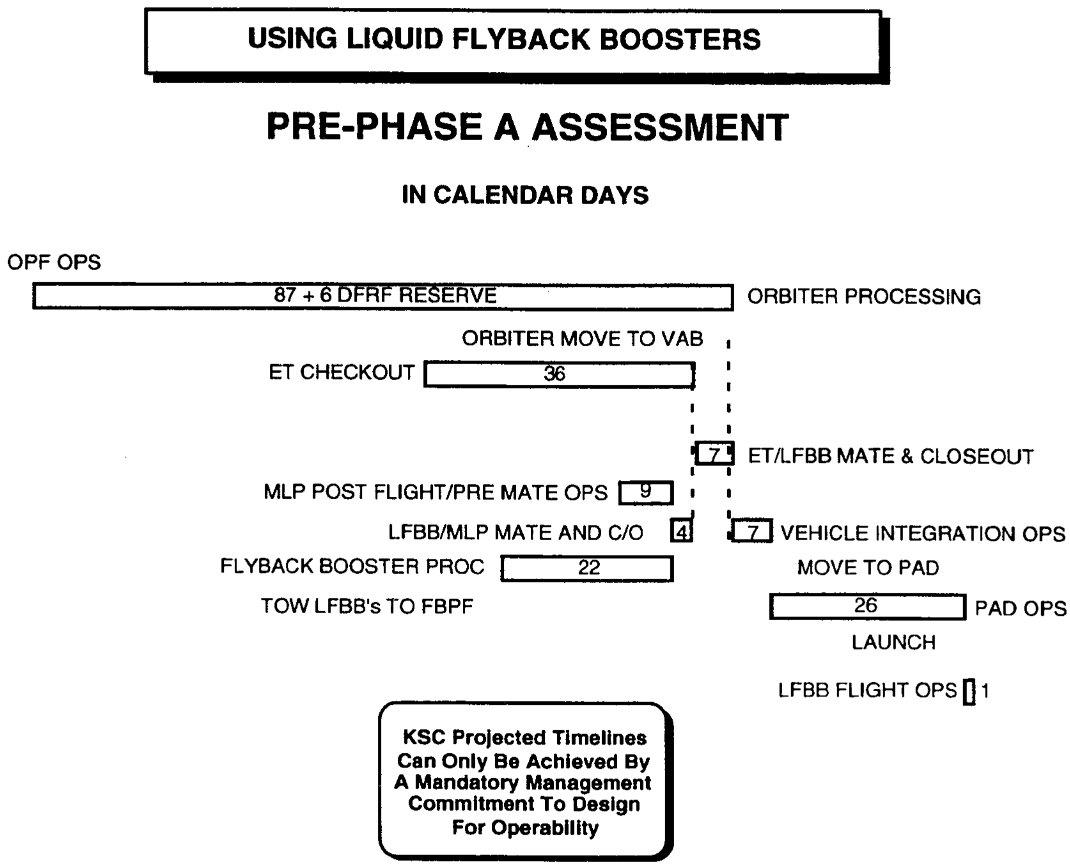


Figure 6.5.5-2 Space Shuttle processing flow (mature operations).

The operational cost difference would be about $4.5M per year and a manpower increase of about 52 full–time equivalent (FTE) people. This increase would be the result of more facility operations and maintenance for the hypergol system, additional SCAPE suit purchase and maintenance, and additional and more complex GSE to operate and maintain. The facility impacts for the inclusion of hypergols are covered under subsection 7.1.7.

6.5.6 LFBB Transition Planning

The LFBB transition plan is depicted in figure 6.5.6-1 The figure depicts the timeframe for facility modifications, KSC delivery date milestones for LFBB flight sets, and transition plan for phasing out the RSRM's and phasing in the LFBBs, while maintaining the Shuttle flight rate as close to eight flights per year as possible. Constraints and limitations during the transition plan are also listed on a per–year basis.

To achieve the first launch using a set of LFBBs in 2003, facility modifications must begin in 2000. Since each Shuttle/RSRM MLP is capable of supporting approximately 3.5 launches per year, MLP–1 will be removed from service in the first quarter of 2000, after supporting at least one Shuttle/RSRM launch due to the requirement to achieve eight flights that year. MLP–1 would be out of service for approximately three years undergoing major modifications. During this period, the Shuttle launch rate would be reduced to seven flights per year due to the utilization constraint of only two MLPs.

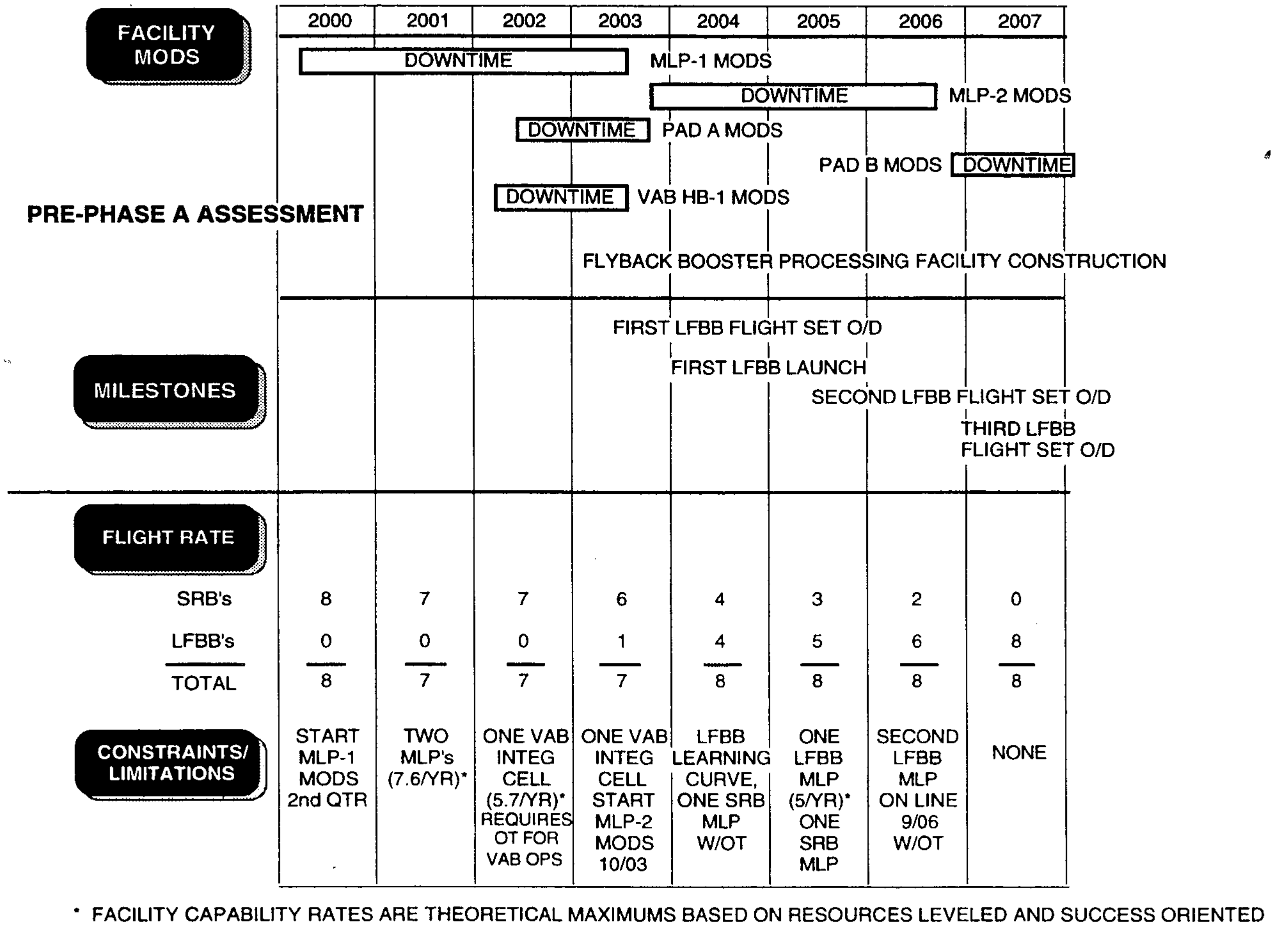


Figure 6.5.6-1 LFBB transition planning.

In the second quarter of 2002, VAB high bay 1 and launch pad A will be removed from service for a 1-year modification period to support LFBB processing. During 2002 and 2003, RSRM processing will be further constrained by the use of only one VAB integration cell. Working overtime and achieving at least one launch using VAB high bay 1 will allow us to achieve seven flights in 2002.

The first LFBB flight set will be delivered to KSC in late March 2003 and will undergo an initial 4.5–month processing flow. Construction of the FBPF will be completed, validated, and ready for use before the first-flight-element delivery. MLP–1 modifications will be completed by June 2003, and launch pad A modifications will be completed by July 2003 to support the first LFBB flow. The first LFBB launch will occur in September 2003. During 2003, RSRM flights will be limited to six flights due to the use of only one RSRM VAB integration cell. Soon after MLP–1 is operational, MLP–2 will be removed from service to undergo its 3–year modification period starting approximately September 2003.

During 2004, LFBB processing will benefit from learning experience and therefore can achieve four flights during the year. Achieving four Shuttle/RSRM flights in 2004 to maintain the required eight flights per year may require some overtime to process the RSRMs due to the availability of only one Shuttle/RSRM MLP during this period.

In 2005, the Shuttle/LFBB flight rate would increase to five, which is the maximum with one LFBB–configured MLP. The remaining three shuttle launches would be using the RSRMs.

Once the second LFBB MLP is operational in August 2006, facilities will be available to support eight LFBB launches per year and, therefore, RSRM operation will end after two Shuttle/RSRM flights in that year. To provide flexibility and ensure facility readiness to support Shuttle processing contingencies, launch pad B modifications will begin at the end of 2006 and last one year without impact to the launch rate.

The length of the transition period is paced by the time required to convert the two Shuttle MLPs to the LFBB configuration. The 3-year-per-MLP assessment is based on the experience of converting the MLPs from a Saturn V/Apollo configuration to the current Shuttle/RSRM configuration. The schedule is further based on cost–effective planning that could be shortened with the allocation of additional resources.

SECTION 7
FACILITY IMPACTS

7.1 KSC Facilities

The facility impacts presented in this section were developed with the understanding that key drivers of this program are operability, maintainability, and the reduction of Shuttle recurring costs. With that in mind, the KSC LFBB Study Team developed these facility impacts to enhance operational efficiency, while striving to be cost effective by utilizing existing facilities, systems, and equipment to the maximum extent possible. The facility impacts reflect an LFBB that has been designed to be consistent with the guidelines for operational efficiency. If the design of the LFBB is not consistent with these guidelines, it will result in a reevaluation of these impacts and the associated costs.

These impacts reflect the best attempt to provide for operational efficiency in processing the LFBB. To accomplish this requires a new facility for processing the LFBB. The use and modification of existing facilities for processing the LFBB have been considered, but each of these options presents constraints to the operational efficiency. These options can be further examined in greater detail as the study proceeds to the next step.

As noted, existing KSC facilities, systems, and equipment will be used to the maximum extent possible during launch site processing. However, to process the new LFBB elements, some modifications to these existing facilities will be necessary. These modifications are described in the following paragraphs. Once the LFBB is operational, the following facilities will be phased out:

- Hanger AF, the RSRM Retrieval and Disassembly Facility
- RSRM Receiving, Processing, and Storage Facility (RPSF)
- MSFC Assembly and Refurbishment Facility (ARF)
- Mobile Launcher Platform 3 (MLP–3)
- RSRM Parachute Facility

Facility modification design will be accomplished by a series of fixed–price contracts with architect and engineering firms. System and equipment designs will be performed by the existing on–base support contractors. Facility construction will be accomplished through several competitive price construction contracts. Systems and equipment fabrication or installation will be performed by a series of fixed–price fabrication contracts. Facility, system, and equipment activation, test and checkout, and validation will be performed by the existing on–base operations and maintenance support contractors. See figure 7.1–1 for the facility development schedule.

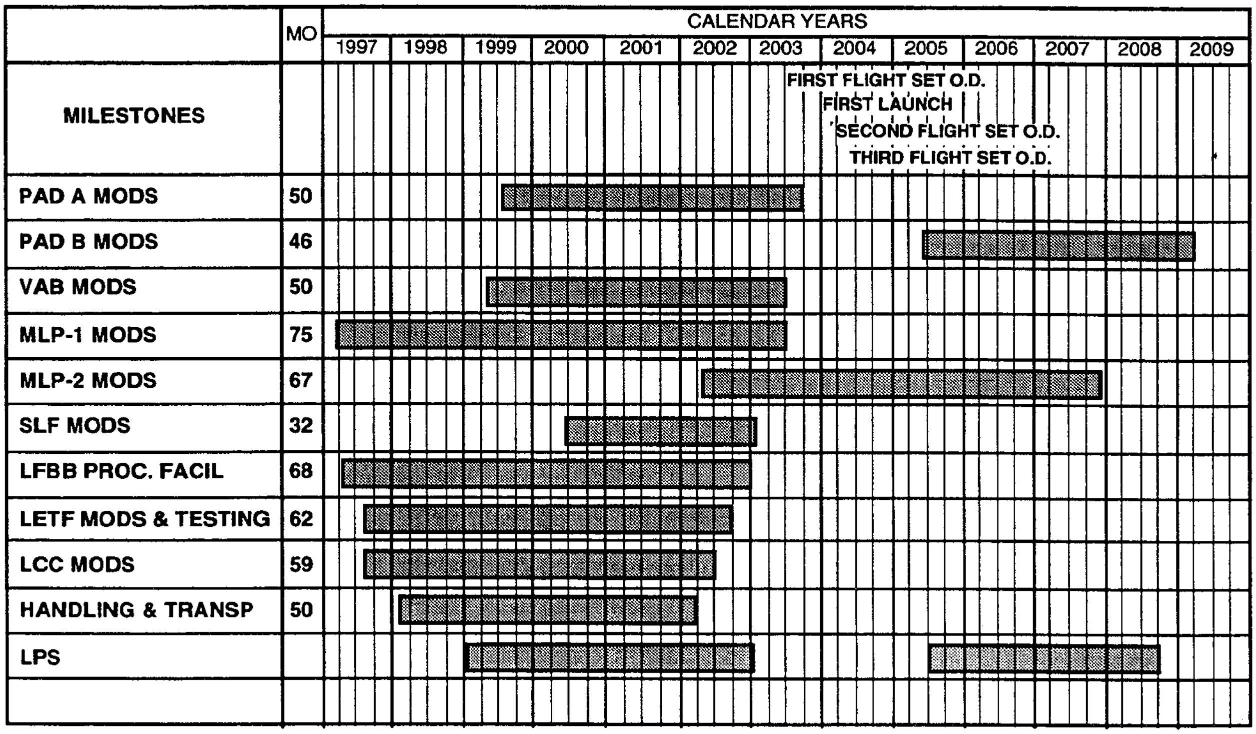


Figure 7.1-1 LFBB facilities schedule.

7.1.1 Launch Pad

Launch complex 39, pads A and B, will be modified for the LFBB. A new servicing system capability for RP–1 and JP–4 will be installed to load LFBB propellants. Booster access will be provided to the forward skirt and intertank hatches from the pad rotating service structure; no access will be provided to the booster TPS at the launch pad. The existing Orbiter weather protection system must be modified to eliminate structural interferences with the LFBB.

The main flame deflector and the side flame deflectors located adjacent to the flame trench will require extensive modifications to accommodate the eight engine exhaust nozzles located on each LFBB. RD–180 engine changeout capability is also planned for the launch pad.

Extensive modifications to the ET hydrogen vent umbilical will be required due to interference between the umbilical system and the LFBB during liftoff. Solutions to the problem may include relocating the umbilical on the ET and/or a complete redesign of the umbilical retract system. Oxygen venting from the LFBB has been assumed to require no umbilical since the gaseous oxygen will be vented to the atmosphere. See figure 7.1.1-1 for the concept of the LFBB at the launch pad.

7.1.2 Mobile Launcher Platform

The existing MLP–1 and MLP–2 will be modified for the LFBBs. MLP–3 will remain in the Shuttle/RSRM configuration. The modified MLP will provide access to the booster boattail and the booster engines. RD–180 engine changeout capability will be provided as a part of the MLP. Four holddown mechanisms will support each booster. The concept for the new holddown mechanisms is similar to that presently used for the RSRMs.

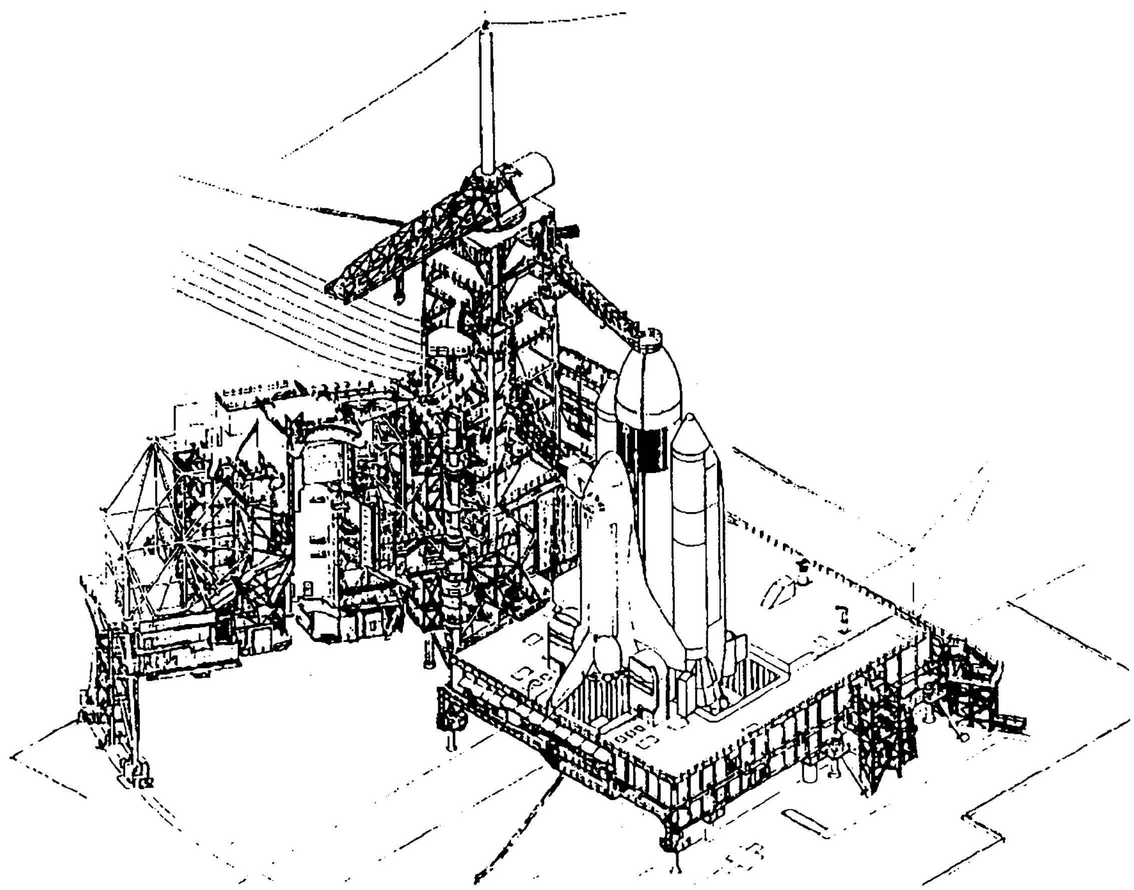


Figure 7.1.1-1 Launch pad with the LFBB.

New fuel and oxidizer TSMs will be required for each LFBB (see figure 7.1.2-1). The LO_2, RP–1, and JP–4 servicing lines will be located within the TSMs. Extensive modifications will be required for the propellant loading system on board the MLP to load LO_2, RP–1, and JP–4. New fill–and–drain lines, skids, and mechanical/electrical control panels will be added to the MLP to control booster propellant loading. Several booster MPS panels will be added for booster engine purge and valve actuation. Extensive LPS changes will be required to support these new servicing systems.

In order to support the TSM and holddown mechanisms, the MLP girder structure must be modified in approximately the same way it was for the Shuttle. Major demolition and reconstruction of the girders will require extensive removal and replacement of the existing systems and equipment, in addition to new system and equipment installation.

7.1.3 Vehicle Assembly Building

One existing VAB high bay will be modified for the LFBBs. The other high bay will be retained as an emergency rollback location. Platforms B, D, and E will be modified to accommodate the larger LFBB diameter and the wing shroud. These modifications will provide booster access for mating to the MLP and to the ET. Access will be provided to the forward skirt, the intertank hatch, and the boattail hatch. Access to the TPS will be limited. Access for booster–to–Orbiter cabling will be provided. The existing Orbiter and ET access requirements will be maintained.

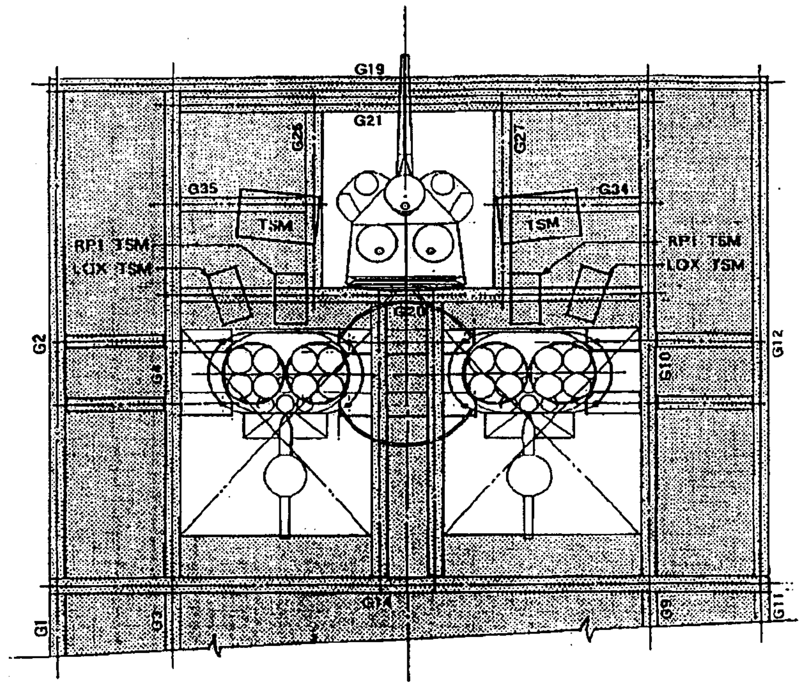


Figure 7.1.2-1 Mobile launcher platform deck.

7.1.4 Flyback Booster Processing Facility

The FBPF will be a new facility with the capability to horizontally process two flight sets of boosters (four boosters total). The facility will accommodate the transportation of the LFBB on its landing gear with the wings deployed. A three–point jacking and support system will be supplied. The facility will provide 100% access to the booster TPS and will support the capability to remove and replace both the RD-180 and air-breathing engines. The facility will be RP–1 and JP–4 residual compatible. Complete MPS fluid line and tank pressurization, leak checks, and validation testing systems will be available.

The booster wing shroud will be installed within the facility. Major booster maintenance activities [similar to the Orbiter maintenance down period (OMDP)] may be performed in the FBPF. Complete powerup and avionics system checkout, testing, and validation will be performed using a new LPS standalone checkout set. The facility will also accommodate transporter movement of the LFBB to the VAB.

7.1.5 Launch Control Center

To support the LFBB during prelaunch, launch, and flyback phases, an additional control room and software development set will be established at Launch Complex 39 within the existing facilities. The control room will contain the additional necessary data processing hardware, workstations, and software to support all Shuttle/LFBB requirements for the stacked configuration through to the landing of each element. The software development set will be used to develop the flight and ground support software applications, simulation software, and software configuration control. LFBB flight equivalent avionics hardware will be installed into the Kennedy avionics test set (KATS) in support of this set. Additional modifications will be required to the existing data networks and video switcher to integrate the software development set and the LFBB control room into the overall LPS.

7.1.6 Landing Site

The SLF and CCAFS skid strip will be used for LFBB landing operations. The SLF is the primary landing site for the LFBB; the skid strip is used only for a return–to–launch–site abort. The SLF will be modified by the addition of a GPS ground station. The skid strip roadway system will be modified to permit the movement of the LFBB on its transporter from the runway to the FBPF via the beach road.

7.1.7 Impact of a Hypergol Reaction Control System on KSC Facilities

As stated in section 7.1, the facility impacts presented in this section are based upon a vehicle designed with operability as the key driver and, therefore, assume that the RCS for the LFBB is nonhypergolic. Since hypergolic fuel systems pose a serious threat to personnel safety, operations involving the checkout and maintenance of hypergol systems are costly, time-consuming, and prohibitive to parallel operations in the same facility. Ground support equipment (GSE) and systems designed for hypergol use are costly to procure and maintain due to strict compatibility and safety requirements. For these reasons, the use of hypergols for the LFBB RCS will have significant impacts to KSC facilities.

If a hypergolic RCS were selected for the LFBB, then hypergol loading would be performed at the launch pad in the same timeframe as the Orbiter hypergols. LFBB RCS servicing would be done using new portable servicing units placed on the deck of the MLP. Modifications to the existing hypergol fuel and oxidizer systems would be necessary to connect the portable units to the manifolds currently used to load the Orbiter RCS.

Modifications to the MLP would not be required since the hypergols would be loaded with portable servicing equipment. Some provisions for power and communication links to the onboard RCS would be provided as a part of the LFBB TSM design. Additional modifications to the VAB high bay would not be required because the RCS would be closed out and static while in the VAB.

Due to hypergol deservicing and RCS maintenance requirements, the FBPF would be a hazardous facility with all power and communications electrical requirements in accordance with Class 1, Division 2, of the National Electric Code (NEC). GSE would be required to deservice the LFBB should any residuals need to be drained before working on the RCS. The FBPF would require significant modifications to meet safety requirements associated with hypergol operations. Systems required to mitigate the hazards associated with hypergols would include a hazardous gas detection system (HGDS), an emergency ventilation and toxic air handling system, firex washdown in conjunction with floor trenches and a sump system, hypergol scrubbers and containment tanks, and emergency eyewash and safety showers. Although a normal LFBB turnaround would not require RCS deservicing, component failure or system malfunction may require disassembly of the RCS in a manner similar to that done during OMDP. This would require that the LFBB work cells be isolated from the rest of the facility for containment purposes. Further assessment is required to develop a thorough understanding of how the hazardous operations associated with hypergols would affect the processing flow of the LFBB, which would in turn impact the facility design.

Post–landing deservicing operations would require additional time to safe each LFBB following touchdown. Hypergol detection and safing equipment would be required at the SLF (existing Shuttle equipment) and simultaneously at the skid strip (new equipment required) for contingency landing operations. The boosters would be safed one at a time at the landing site and then transported to the FBPF for servicing.

The facility cost impact for accommodating a hypergol RCS based on the current understanding of the LFBB configuration is estimated to be $39.5M.

7.2 JSC Facilities

The JSC Mission Operations Facility impacts are addressed from different strategic objectives. The mandatory objective is for the facilities at JSC to continue to fulfill their roles and assigned responsibilities as the operator of the integrated Orbiter/Booster vehicle during ascent. In addition, the opportunity was taken to assess different potential implementation options, such as sharing common modifications across all JSC facilities and synergy between the added LFBB facilities and modified Mission Operations facilities. An attempt was made to define the requirements for the operational facilities to support the LFBB ascent and flyback phases (simulation and command and control concept) for costing support and to provide data for implementation of options that may be considered

7.2.1 General Philosophy and Assumptions

7.2.1.1 Flight Systems

7.2.1.1.1 Integrated Vehicle Flight System (integrated ascent)

a. LFBB onboard vehicle health management capability during flight consists of automated FDIR, selection of specific sensors from multiple/redundant data sources, and sensor data incorporation processing.
b. The LFBB provides a control and propulsion health and status data link to the Orbiter.
c. The Orbiter provides LFBB control and throttle commands.
d. Each LFBB provides its own antenna management.
e. Each LFBB provides telemetry for monitoring the status of critical systems.
f. An automated separation command will be issued by the Orbiter.
g. LFBB telemetry data will be downlinked to the ground through the LFBB telemetry system. There will be a separate data stream for each booster.
h. Continuous communications with each LFBB will be available throughout the mission.
i. There will be no capability for the flight crew or flight controllers to intervene in the LFBB operation during integrated flight. However, information will be enunciated to the flight crew and flight controllers as required for changes in system status and configuration.
j. Before separation, the Orbiter provides the state vector and flight attitude data to the LFBB GN&C.
k. There will be no communications interference between the vehicles, and each vehicle will be protected from misdirected or intercepted commands.

7.2.1.1.2 LFBB Flight System (post-separation and -return)

a. Before the point where the LFBB transitions from entry vehicle operations to airplane operations, all LFBB systems and flight dynamics command and control functions will be exclusively onboard functions.
b. Following successful transition into an airplane flight regime, the LFBB will be capable of autonomous onboard flight without ground communication for a limited time to allow for re-establishment of communications. In the event that communications cannot be established within time limits, the LFBB will at all times maintain capability for safely aborting the return.
c. At no time during the entry phase will the LFBB rely on successful transition to airplane operations for achieving a safe abort location.
d. The LFBB flight abort will be by surface impact (planned crash/ditch) termination and not by a vehicle destruct system.
e. The debris model to be considered for range safety will be based on natural vehicle breakup analysis and not detonation analysis.
f. The LFBB onboard GN&C operations concept is as shown in figure 6.3.2-1.
g. The LFBB has the *capability* to execute a pre-stored and pre-selected flight sequence (post separation through wheel stop) without ground intervention. The LFBB also has the *capability* to receive changes to the flight sequence, course, or flight control data from the ground.
h. The LFBB will require permission to transition to the landing mode in the flight sequence; if permission is not granted, the LFBB will enter an onboard default (loiter or abort) mode.
i. Each LFBB will transmit its trajectory data and critical systems status data to the LFBB control room for command and control.
j. All LFBB system management will be performed through onboard FDIR.

k. The LFBB onboard GN&C commands and parameters loaded preflight for the flyback phase shall protect for a concurrent Orbiter RTLS, LFBB loss-of-communication condition.
l. Unless commanded ground intervention is invoked (based on the LFBB telemetry), each booster will independently execute its onboard flight sequence without uplink from the LFBB controllers.
m. The commanding of each LFBB consists of redesignating from pre-stored trajectory way points and selecting the preferred rather than default sequences, modifying the loiter in the pre-stored flight sequence, or issuing a command to execute the automated abort sequence.

7.2.1.2 Mission Control

a. KSC has responsibility for the command and control of the integrated vehicle from prelaunch through T0.
b. JSC has responsibility for the command and control of the integrated vehicle from T0 to Orbiter booster separation.
c. The LFBB control team has responsibility for command and control of each LFBB vehicle from Orbiter separation through landing and wheel stop.
d. ETR range safety has responsibility for range safety and issuing destruct commands during ascent.
e. There will be a capability reserved for minimal ground operator and/or flight crew determination of LFBB system failures during ascent.
f. The assumed top-level command and control mission architecture functional interfaces during the integrated ascent and the LFBB flyback phases are depicted in figures 7.2.1.2-1 and 7.2.1.2-2.

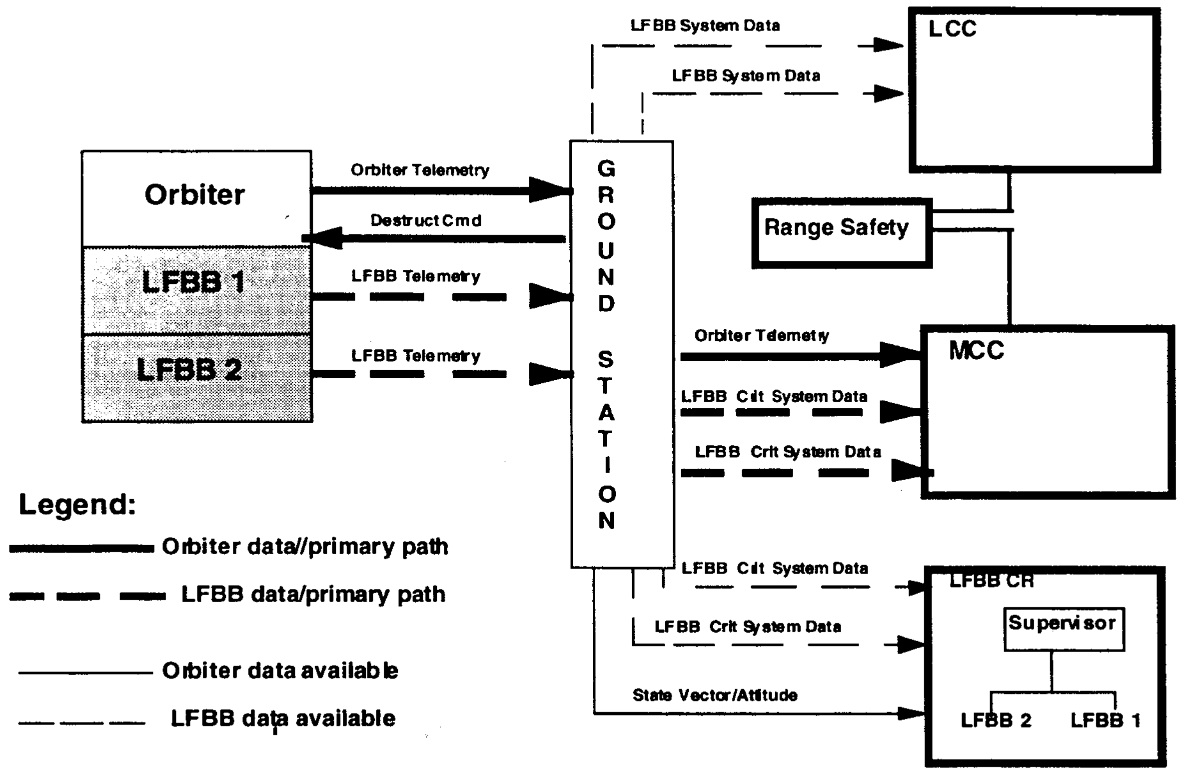


Figure 7.2.1.2-1 Integrated ascent command and control architecture requirements and interfaces.

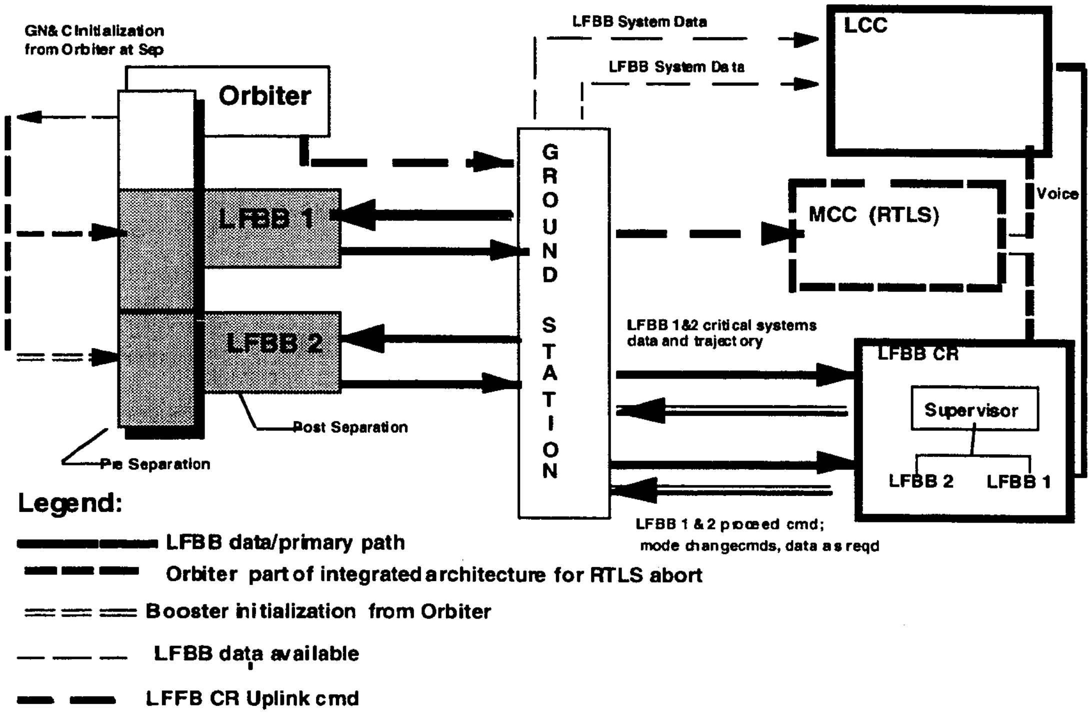


Figure 7.2.1.2-2 LFBB flyback command and control architecture requirements and interfaces.

7.2.1.3 Training

a. There will be no crew station hardware modifications required in the Shuttle Mission Training Facility (SMTF). Specifically, no panel changes, switch additions, etc., will be made to the SMTF crew station to support LFBB.
b. Training has no requirement for joint simulations between the LFBB CR and the Shuttle MCC. In other words, there is no training requirement to provide the capability to run simulations with the SMTF, MCC, and LFBB CR together where data from the LFBB simulator is transferred real time into the SMTF to affect ascent performance.
c. The SMTF will only be used to simulate integrated flight. The LFBB simulator will have the capability to simulate both integrated flight and LFBB flyback.
d. The LFBB simulator will interface directly to the LFBB CR. Training has no requirement for the LFBB simulator to send data to the MCC or SMTF. LFBB data flow to the MCC will be provided by the SMTF.

7.2.2 User Operations Concept and Support Requirements

The assumptions contained in Section 7.2.1 form one source of requirements for assessing the impact on facilities; a second source of facility requirements are derived from the facility user. The user needs, operational concept, and requirements are derived from the assumptions in section 7.2.1 and by the services they are obligated to provide to their customers.

7.2.2.1 Control Teams

7.2.2.1.1 MCC Booster Control Team Concept. While providing capability consistent with the assumption in section 7.2.1.2(e), the reference approach minimizes the number of new positions and the total number of positions required to support the integrated Orbiter/LFBB flight. Since the LFBB is a significantly different and more complex system than the RSRMs it replaces, one-for-one substitution of booster system responsibilities for RSRMs among the current flight control team cannot be made.

Therefore, the overall strategy is to distribute the added booster flight control room (FCR) functions, imposed by the LFBB, to as many of the existing FCR positions as possible, to confine additional support to a multi-purpose support room (MPSR) position, and to minimize the number of new MPSR positions required. The conceptual integrated ascent flight control team structure is shown in Table 7.2.2.1.1-1 below. This chart also contrasts the differences with the existing flight control team structure. One additional MPSR position is required with this scenario. Should this strategy subsequently prove to be unwise, fallback options do exist that would add an additional MPSR position and/or an FCR position.

Table 7.2.2.1.1-1 Conceptual Integrated Ascent Flight Control Team Structure

POSITION	CURRENT RSRM SYSTEM RESPONSIBILITIES	PROPOSED LFBB SYSTEM RESPONSIBILITIES
BOOSTER (FCR)	SSMEs, RSRMs, MPS, & ET	SSME's, ~~RSRMs~~ *(LFBBs)*, MPS, & ET
Main Engine (MPSR)	SSMEs	
MPS (MPSR)	MPS, RSRMs, & ET	MPS, ~~RSRMs~~, & ET
LFBB Engine (MPSR)	-----------------------	{*LFBB MPS (including engine controllers and possibly DMS)* }
GN&C (FCR)	SSME & RSRM thrust vector control (TVC), Orbiter GN&C Functions	SSME & ~~RSRM~~ (*LFBBs*) TVC, Orbiter GN&C Functions
EGIL (FCR)	(Orbiter EDP&C)	Orbiter (*& LFBB)* EDP&C
PROP (FCR)	(Orbiter OMS/RCS)	Orbiter OMS/RCS (*& LFBB RCS*) (if required for safety)

The above concept will require increasing the current cadre of Booster flight controllers from 11 to 13 people. This is predicated on the assumption that the system operation will indeed permit minimal ground monitoring and intervention and that the booster propulsion system operational complexity, hence flight controller tasks, is analogous to that of a booster equipped with two RD-170 engines. The anticipated MCC workstation requirements to support the integrated vehicle command and control function is for the Booster position to have three monitors driven from one workstation. One of these monitors will be used for LFBB engine/MPS information instead of the plots and history tab information currently planned. The LFBB Engine MPSR position will be manned from the RMS MPSR console. Workstations will have to process all three telemetry streams coming from the front end processor.

7.2.2.1.2 LFBB Control Team Concept. The LFBB Control Team will consist of three members: one controller per booster and one control person as the lead for the two controllers. Based on the extent of relevant existing experience that is applicable to the proposed booster flyback concept and dialog with Dryden's drone aircraft operations team, a three-person booster flight control team should be considered an optimistic estimate (the lower limit of the manning boundary). As the vehicle design evolves and as the evaluation and definition of the required LFBB control center functions are extracted, the size of the flight control team may increase, creating somewhat of a ripple effect in cost due to additional control center accommodations, training, etc. Two full teams of flight controllers, for a total of six flight controllers under the current assumed team staffing, will be maintained.

The LFBB flight controllers are the personnel responsible for the command and control of LFBB operations from booster staging to landing. These personnel will perform the command and control functions from an LFBB control room/area. LFBB flight controllers will only be capable of sending limited commands to the LFBBs. These commands will be for the post-entry phase only, and they will consist of commands to LOITER, SELECT ALTERNATE PRELOADED WAYPOINT, ABORT/DITCH. The training concept for the LFBB flyback controllers and the requirements for conducting the training is discussed below: LFBB training should begin about 1.5 years before the first launch.

7.2.2.2 Training

7.2.2.2.1 Integrated Ascent. The training plan for Shuttle flight controllers consists of common training workbooks and computer-based training that will need to be created for LFBB Flight Controllers, a play back trainer to provide "stand-alone" training for operations and systems monitoring, LFBB SMTF models to provide data to Mission Control (MCC) during Shuttle flight controller ascent training, and current level of Shuttle flight controller training hours to train controllers to monitor ascent LFBB data. The training plan for Shuttle flight crews consists of common training materials created for LFBB flight controllers, and to provide the training required to perform the anticipated new contingency abort scenarios. As long as no crew interaction with the LFBB is required, no other training is anticipated.

Because the current Shuttle training resources will be able to assume the additional load of training the Shuttle flight controllers, there should be no Shuttle training costs required to support LFBB ascent simulations. It is assumed there will be no Shuttle flight crew interaction with the LFBBs; consequently, there will be a minimal increase in Shuttle training cost. The costs that would be incurred would be limited to training Shuttle flight crews on the new contingency aborts required for combinations of LFBB engine and/or SSME failures. However, these costs are assumed to be small. There is no crew or flight controller interaction with the LFBB during ascent. Providing the flight crews and/or flight controllers with the capability to reconfigure the LFBBs during ascent would dramatically increase training requirements and associated costs.

7.2.2.2.2 LFBB Flyback. The training concept for the LFBB controllers described in 7.2.2.1.2 and the requirements for conducting the training are discussed below:

Training Workbooks: Two workbooks will be developed for LFBB training. These two workbooks will be an "LFBB SYSTEMS" workbook and an "LFBB OPERATIONS" workbook. The level of complexity of these two workbooks is between the Shuttle Crew Operations Manual (SCOM) and our current workbooks.

Computer-Based Training (CBTs): Three CBTs will be developed for LFBB training. These CBT lessons will be "LFBB SYSTEMS," "LFBB FLIGHT OPERATIONS," and "LFBB CONSOLE OPERATIONS." The LFBB console operations CBT would also serve the purpose of our current Shuttle flight controller trainers (FCTs). This CBT would serve as preparation for the controllers on how to use their flight control consoles and will minimize the time required to bring LFBB controllers to a level of proficiency required to perform training in the LFBB simulator. If JSC were employed to assist in developing the CBT training, the necessary software and hardware resources are currently available.

LFBB Part Task Trainers: LFBB part task trainers will not be required

LFBB Control Team Simulator: LFBB controllers will need one 4-hour LFBB simulation per week during initial training. Initial training will include two months of simulator training. Once certified as a controller, the LFBB controller will need one 4-hour LFBB entry simulation per month to maintain proficiency.

The primary LFBB simulator will be a "stand alone type" trainer. There is no training requirement to have the SMTF or MCC attached to the simulation. This simulator will provide the capability for the flight controller to run a simulation alone or with an instructor.

7.2.3 Flight Design and Dynamics

Updates to the current Shuttle ascent flight techniques, flight rules, and procedures will be required to launch the Shuttle/LFBB vehicle. It is anticipated that the launch environment will change from the current Shuttle/RSRM configuration and thus, so will the operation of the Shuttle/LFBB vehicle. Trajectories and the resulting flight regimes will need to be designed, evaluated, and certified to ensure that the new boosters will not violate the constraints of the Orbiter. Through this analysis, the operational capabilities, constraints, and decision points will be mapped into an updated set of flight rules, flight techniques, and ground/onboard procedures for the integrated flight. These techniques, procedures, and flight rule development support must be performed in concert with the LFBB development to support the first flight; beyond the first LFBB flight, there will be some recurring support for maintenance of these flight products. Based upon the present understanding of the configuration, there has been no change to the current mission-specific support (functions, services, and products) requirements identified; therefore, the resources for mission support are accounted for in the Shuttle operations budget and no unique resources for supporting specific LFBB missions are included.

Flight techniques, flight rules, and procedures similar to above will also need to be developed for the LFBB flyback phase of the mission. In addition to the activity required to support a single vehicle, the effort will also need to be expanded to include operations (Orbiter aborts). Whereas, for the integrated ascent, the effort focused on changes and updates to an existing set of techniques, et al., this activity for the LFBB is an entirely new development. Although each function may impose different specific detailed tasks and costs, it is assumed that the resources will balance out. Hence, the estimated resources for the LFBB flight design development work are the same as for the flight design development work for the new integrated vehicle.

It is noted that there will need to be some development work on the existing planning system (software models, etc.) that will likely be required to support the flight design for the integrated vehicle ascent phase. Cost estimates have not been made since the appropriate level of detail has not been developed. Planning tools will also need to be provided for the LFBB flyback phase. This capability does not presently exist and there are several implementation options available. The existing JSC planning system could be modified to accommodate the design and analysis activity for the LFBB flyback phase and then (a) KSC replicates the system, (b) JSC provides KSC access to this system under a negotiated agreement, or (c) KSC contracts the analysis and technique development work to JSC. A track separate from the above would be to build a new optimized planning system.

7.2.4 Reconfiguration

LFBB flight software is reconfigured by the vendor and is not dependent on the Shuttle flight software reconfiguration process. Having a mixed fleet does not change the number of MMU software loads delivered to the field. Shuttle reconfiguration tool impacts due to this change are minimal. Changes to the I-load process are minimal.

LFBB simulator changes for use by the FEIDs are supplied by Loral and are synergistic with similar models used by the SMTF and SAIL. FEID software cost is included in the total LFBB vehicle software costs.

A new software database tool is required to deliver some type of ASCII file to the MCC, the LFBB Control Center, and to SAIL. This tool will run on an existing mainframe or workstation and no extra computing power or software licensing will be required to support the tool. This tool is estimated at about 60,000 lines of code.

Table 7.2.4-1 identifies the facilities supported by Reconfiguration.

Table 7.2.4-1 Facilities Supported by Reconfiguration

Mission Control Center
LFBB Control Room
Shuttle Mission Training Facility
LFBB Simulator
Shuttle Avionics Integration Laboratory
LFBB Avionics Integration Laboratory

7.2.5 Mission Control Center

The enclosed MOD Mission Control Center description for LFBB operations is built around the current distributed control center architecture that is being installed at JSC (see figure 7.2.5-1). The LFBB control room would be expected to use all of the standard telemetry and command and control functions that are provided in the MCC. The evaluation was made using the assumption that the MILA ground station would be prime for commanding each LFBB with current available resources and the Orbiter would be supported exclusively through the TDRSS. TDRSS currently does not have the resources available to support three vehicles simultaneously using identical links. In addition, primary launch support by Shuttle from T0 by TDRSS is not a baselined operation, although discussions continue on this topic for consideration of closing MILA.

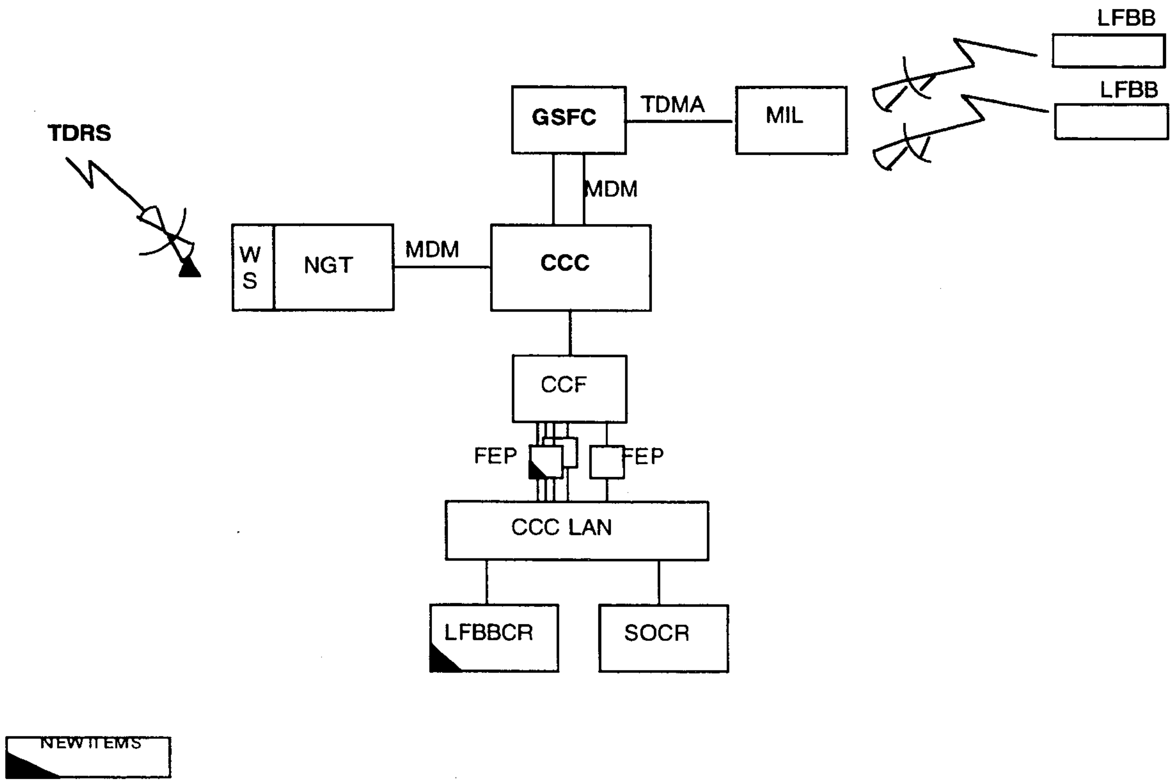


Figure 7.2.5-1 LFBB command and control.

Front-end processing would be provided by the Consolidated Communications Facility (CCF) using two dedicated front-end processors, each processing independent LFBB telemetry streams. The Orbiter will continue to be processed in a separate front-end processor. This configuration will provide system redundancy for dynamic flight for the LFBB. Interfaces to MILA and the TDRSS network for ground-to-ground operations can be provided through existing data and command paths to the MCC. Standard MCC UNIX-based consoles will be provided for LFBB control room operations and training support with the LFBB trainer. Applications will be developed for this commercial computing environment for monitoring and required command functions for return flight operations. Command and Control will be supported through a distributed system that can support shuttle and LFBB operations simultaneously.

7.2.6 Shuttle Mission Training Facility Cost and Design Study for the LFBB

An assessment of the impacts to the SMTF for supporting the LFBB was conducted. The impacts to the SMTF include a conceptual definition of a stand-alone LFBB full mission simulator. The result is a proposed design with alternatives (including synergy approaches) identified.

7.2.6.1 Methodology

The SMTF is a mature facility and, as a result, the study and cost estimates were generated by using a bottoms-up approach. This provided a detailed basis for all acquired hardware and generated software estimates. Factors such as code complexity are implicitly handled in the actual source lines of code (SLOCs) reported. Hardware costs and proposed platforms are based upon equipment already in the facility or scheduled to be installed in the facility.

SLOC counts and equipment specified and costed were based on known facility cost data and were not parametric estimates. The key to the actual SLOC count is the specific assumptions and guidelines given in the sections that follow. It was intended that the structure given in this initial cost estimate and concept definition be such that a rework of the assumptions and, consequently, SLOC and cost, would be simple and depend only on the refinement of the technical assumptions and the programmatic directives.

7.2.6.2 Scope

Due to the overall LFBB activity and product schedule, this study had to be conducted concurrently with the development of the program requirements and vehicle configuration. This meant that a stable set of requirements and configuration data, generally required as input to initiate this activity, was unavailable. Since the data available at the time the study was conducted was insufficient to support the definition of a baseline in enough detail to accurately conduct a bottoms-up architecture and cost proposal, assumptions were made where and when required. These assumptions expanded the available data and established a pseudo-baseline against which the proposed requirements and programmatic needs could be structured. Any issues discovered during the effort were documented with an appropriate assumption. In each key section and for each level of detail, the assumptions used have been stated.

Trade study approaches to the options identified are based on the understanding of the facility as an operational unit and previous experience in similar programs. The results of the trade studies are included here as options, although not all are considered suitable for implementation. The synergy approach included has two levels of proposed synergism. The first is the inclusion of the LFBB simulation into the SMTF. This approach limits the synergy to the development of capabilities required at JSC in the area of training. The second level of synergy identifies the need to conduct a broader level of testing, integration, and verification, specifically across facilities at JSC and potentially across the agency. This level of synergy proposed to develop a single simulation product that would support, with minimum changes and integration, a number of facilities that would be tasked with the independent verification and validation task. These facilities include the SES, SAIL, and SMTF.

7.2.6.3 Derived Programmatic Implementation Guidelines and Recommendations

The development of a programmatic implementation strategy for facilities will be required. There is opportunity to address minimizing known duplication of non-recurring costs while addressing the training needs of the SMTF; consequently, this is the motivation that underlies the proposal for a single set of models with avionics hooks that can support multiple facilities. This is reflected in the following assumptions. In addition, the minimization of the recurring costs was considered a driver in the development of all of the concept options in the proposed plan. Note that a system engineering cost comparison of the synergy approach vs the independent facility costs was not performed due to time constraints.

Given that the approach selected uses flight equivalent avionics boxes and avoids functional flight code (thereby minimizing recurring costs), the cost summaries are based on end-to-end verification requirements. The significance of this is that the training requirements will be adequately covered by a single system engineered design. Training costs therefore are not, per se, a driver for the synergy case. The synergy concept as well as the non-synergy configuration used in the costing model are estimates made, as noted without a specified programmatic baseline defined or a specification documented. Instead, assumptions were used to define an equivalent baseline concept.

7.2.6.4 Trainer Requirements

The trainer requirements fall into two broad categories. The first, and the simplest, is that of the SMTF requirements needed to perform crew training. This is ascent only and would adequately support the MCC during integrated training runs. The training requirements did not identify end-to-end testing and verification testing and as such were not included in the present resource estimates; likewise the customer did not indicate a connectivity to the optional LFBB trainer simulation. The second category is that of the requirements that are driven by the (optional) LFBB simulator. In the absence of any synergy approaches, this would be stand alone, with no connectivity to the SMTF. The concept of a synergy and a merging of facilities is discussed in the Trade Study Options Investigated section.

7.2.6.5 General Operational Assumptions

In addition to the vehicle and ground support assumptions noted previously that define how the trainers (SMTF and LFBB) will be used to support the Shuttle, the following describe the assumptions that are independent of the implementation concept:

a. There is no requirement to have joint simulations between the LFBB control room and the Shuttle MCC.
b. The LFBB control room will driven by the LFBB simulator. Integrated simulations between the MCC and the LFBB control room will not be required.
c. The SMTF at JSC will be able to support LFBB data flow to the MCC for flight controller training.
d. The SMTF software must be modified to provide LFBB data to the MCC and SMTF instructor station. The LFBB parameters supplied by the SMTF shall be the same parameters provided by the real LFBB during integrated ascent.
e. The SMTF's LFBB model will also need to support an instructor interface for malfunction insertion on the LFBB. The SMTF instructor will have the capability to fail LFBB engines and to degrade the performance of the LFBB engines.

7.2.6.6 SMTF Simulation Requirements, Assumptions and Implications (ascent phase only)

The SMTF's LFBB simulation will provide crew training for pre-launch through LFBB separation, including launch processing system simulation. The SMTF will provide LFBB training capabilities for the first-stage ascent flight profile. The SMTF's LFBB simulation modeling will also include engine models, command/telemetry communication, interfaces to the Orbiter, LFBB dynamics and aerodynamics, onboard systems, propulsion systems, and Orbiter interfaces. The SMTF's LFBB simulation functions and measurements will be capable of generating malfunction scenarios and profiles as required.
The SMTF will provide an independent telemetry capability to the MCC as defined by program requirements. There will be no SMTF crew station hardware modifications required. SMTF will support dual baseline model and reconfiguration for mixed fleet (RSRM/LFBB) operation for at least four years from LFBB initial launch. In addition, models are of sufficient complexity to provide validation in SMTF and SAIL (single system trainers, if required). Integration test and verification was costed for the SMTF and LFBB simulator only.

For the SMTF, it is necessary to develop a functional simulator of the LFBB onboard computer or utilize flight equivalent unit (FEU) avionics boxes for the flight computers.

In the area of the host computer, the SMTFER host/IOS upgrade will be installed before this installation. The SSVTF GSDE ADA software development environment will be used for LFBB development. Interface between LFBB simulator and the NSS is not impacted by the size of down-linked telemetry, because it is a function of the MCC FEP capabilities.

The following SMTF host models are impacted: LFBB onboard VHM-to-GPC interface; Shuttle GN&C models (accelerometers, IMU, rate gyro's); Shuttle aero data tables; vehicle dynamics (mass prop, EOM); motion control (on MB); mechanical systems; LPS modifications (or LPS-like support system model for

LFBB system); network simulation system; C-band tracking; two separate MILA S-band data streams independent of Orbiter downlink (or TDRSS or GPS link).

The off-line software impacts to the SMTF include: reconfiguration (mass prop, I-loads, flight software deltas) and GSDE (development environment). Note, SMTF visual databases do not require increased KSC landing site fidelity, since there is no live closed circuit TV video from the LFBB.

7.2.6.7 LFBB Simulation Requirements, Assumptions, and Implications (full mission)

The SMTF/LFBB model will also require an instructor interface to input malfunctions for the LFBB. The SMTF/LFBB instructor will have the capability to fail LFBB engines and to degrade the performance of the LFBB engines. The LFBB simulator shall have the capability to simulate ascent, entry, cruise, and landing. The simulator will be used to train the LFBB control room flight controller in

- Procedure development (i.e., malfunction)
- Procedure verification
- End-to-end verification testing

The LFBB simulator will have the capability to run two real-time, six-degree-of-freedom simulations for the LFBB. This simulator will send data to the LFBB control room to provide LFBB controller training. The parameters supplied by the simulator should be the same parameters provided by the real LFBB during ascent, entry, cruise, and landing. The LFBB model will also provide data to a separate console that will allow a trainer to interface with the model. The trainer will have the capability to input malfunctions into the LFBB MPS, RCS, C&T system, electrical power and distribution system, and the GN&C system.

The attributes of the LFBB simulator computer host hardware are as follows: one session computer (RTSC class A); one instructor operator station (SSVTF copy); one onboard VHM computer; and LAN connectivity to these elements.

For non-model software, the LFBB simulator requires the following off-line software capability: reconfiguration functionality and session host interface to LFBB onboard VHM computer. LFBB simulator applications software model functionality consists of the following:

engine model
fuel slosh model
thrust vector control model
GN&C model
Orbiter interface model
nose wheel steering model
communications system model
ground contact dynamics model
electrical power and distribution system model
air-breathing engine (fidelity driven by malfunctions) model
environment and atmosphere (aero tables) models
LFBB vehicle dynamics model (mass prop, fuel dump)
propellant model
engine controller model
RCS (Shuttle separation) model
EMA model
thermal (heaters) model
post-separation malfunctions model
mechanical systems (wing deploy) model
landing gear (weight on wheels, brakes) model
TDRSS and GPS communication interfaces

Specifically not required by the LFBB simulation are body bending and CCTV (for video).

7.2.6.8 Options and Configurations Modeled

There were two optional configurations investigated with associated costs. The first option considered the use of functional flight software against FEU avionics boxes where there was considerable complexity that must be modeled. Based on the code estimates available for the LFBB FSW, it appears that the proper approach would be to use FEUs for the avionics and thereby avoid costly (in both time and cost) impacts caused by LFBB FSW development slippage or continued evolution. The actual break point is dependent upon the cost of the FEUs as well as the size, complexity and stability of the FSW code. Only very preliminary estimates were available. The estimate of $5.0 M for the avionics containing approximately 200k SLOC for the ascent portion required for just the SMTF showed the correctness of the FEU approach. The concept is shown in figure 7.2.6.8-1.

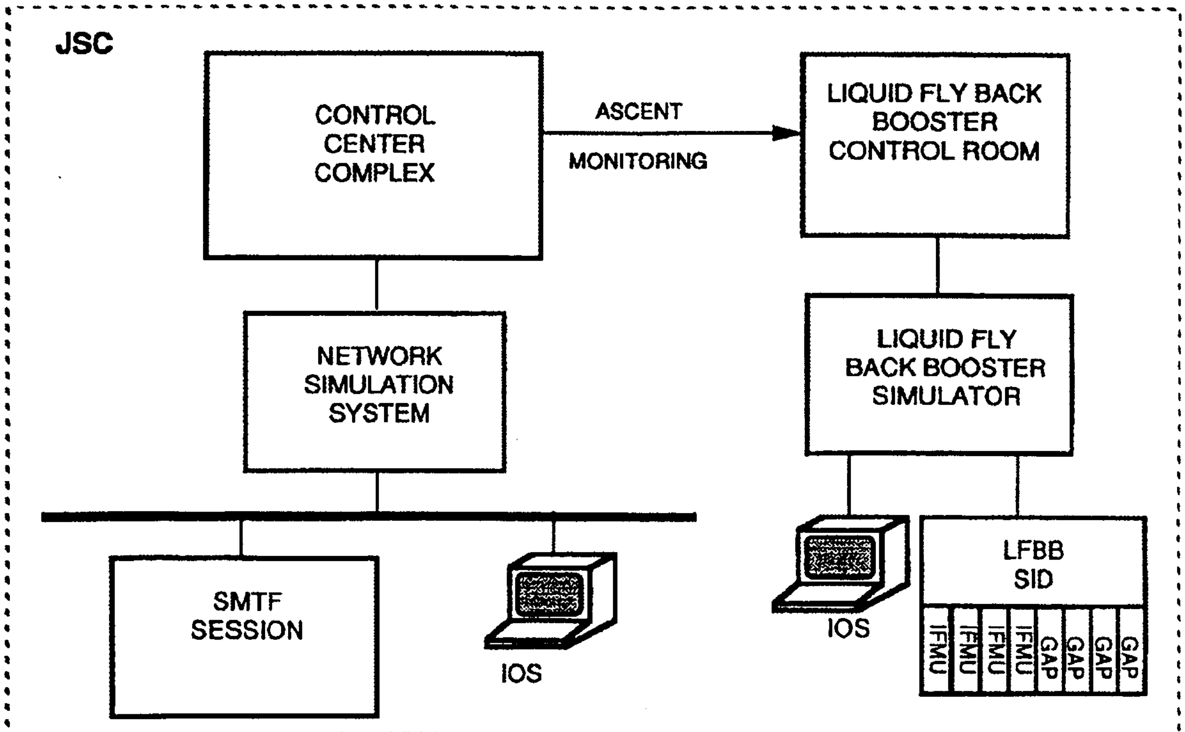


Figure 7.2.6.8-1 LFBB training concept.

The LFBB full mission scenario is even more convincingly in favor of the FEU approach. The amount of onboard software within the four GAPs and the four IFMUs that needs to be simulated for training drives the training approach. This is driven by ground controller and crew displays along with malfunctions, which specify training fidelity. The size of the GPC and GAP/IFMU coupling may dictate a functional equivalent GAP/IFMU hardware solution for sufficiently large code body size. This approach has a high front-end cost, but very low recurring cost (no additional cost for sustaining functional flight software). If the size of the GPC and GAP/IFMU coupling is very small and the FSW is stable (i.e., little change traffic), then a functional flight software solution could be considered. However, sustaining the LFBB functional flight software over the life of the program would be costly due to training requirements instability. This is in addition to the concern for independent verification and validation costs. The cost data is given in the summary table. This concept is also shown in figure 7.2.6.8-1.

The second principle trade study that was performed was the integration of the LFBB full mission simulator into the SMTF as a synergized concept. The rationale was that the models for aerodynamics, environment, navigation, etc., all exist in the SMTF, and if the FEU approach were taken, the synergy of one simulator with one set of FEUs avoids expenses required by separate facilities and the associated recurring costs. Since the option would dedicate an SMTF-based computer string to the stand alone nature of the LFBB simulator, the availability of the string was determined. From a facility loading perspective, there appears to be no limitation on this approach. This necessitates a ground rule that the LFBB simulation is based at JSC. Again, these results are given in summary level in the data tables. This concept is illustrated in figure 7.2.6.8-2. It should be noted that, unlike figure 7.2.6.8-1, this architecture must be at JSC in the SMTF. Location is not optional.

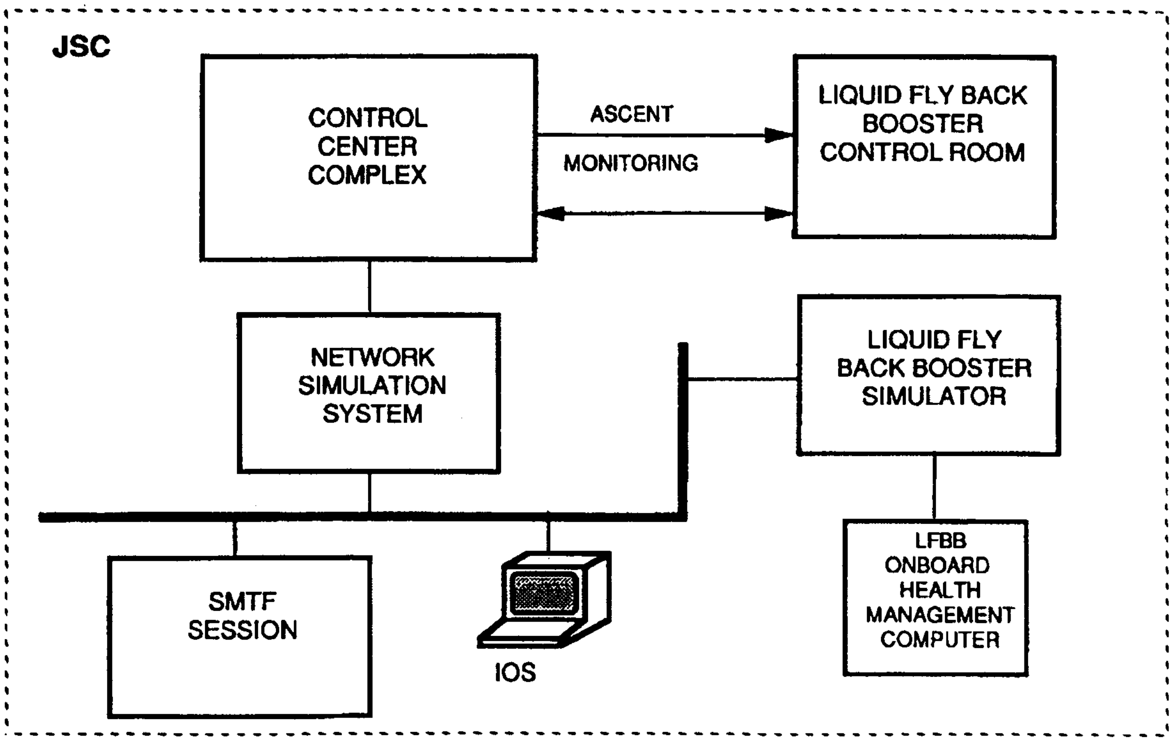


Figure 7.2.6.8-2 LFBB training synergy concept.

In both these trade studies, it was assumed that the application models and the host computer architecture were sufficiently robust, sophisticated, and well documented to enable relatively easy portability to other facilities. There is no cost breakdown associated with the differentiation between the "minimal" set of models and the proposed set. This was not attempted because the experience and history of the SMTF indicates that the front end economies of highly tailored requirements and designs are overcome by the independent test and verification, end-to-end testing, and reconfiguration needs.

7.2.6.9 Schedule

The schedule is given in figure 7.2.6.9-1. The assumptions made for Authority To Proceed (ATP) through first launch have been supplied by available documentation. The additional assumptions made on the schedule pertain to the historically based need for multiple FSW drops and the T-12 months between RFT and first launch. It should be also noted, the same schedule applies to the synergy and non-synergy case. This is reflective of the fact that the LFBB would be developed in incremental drops and the SMTF would also be incrementally developed, but ostensibly ahead of the LFBB as the SMTF today is a functioning facility. The maintenance and sustaining engineering tasks apply only to the LFBB, as the SMTF M&O and SE are in place.

LFBB SIMULATION DEVELOPMENT SCHEDULE

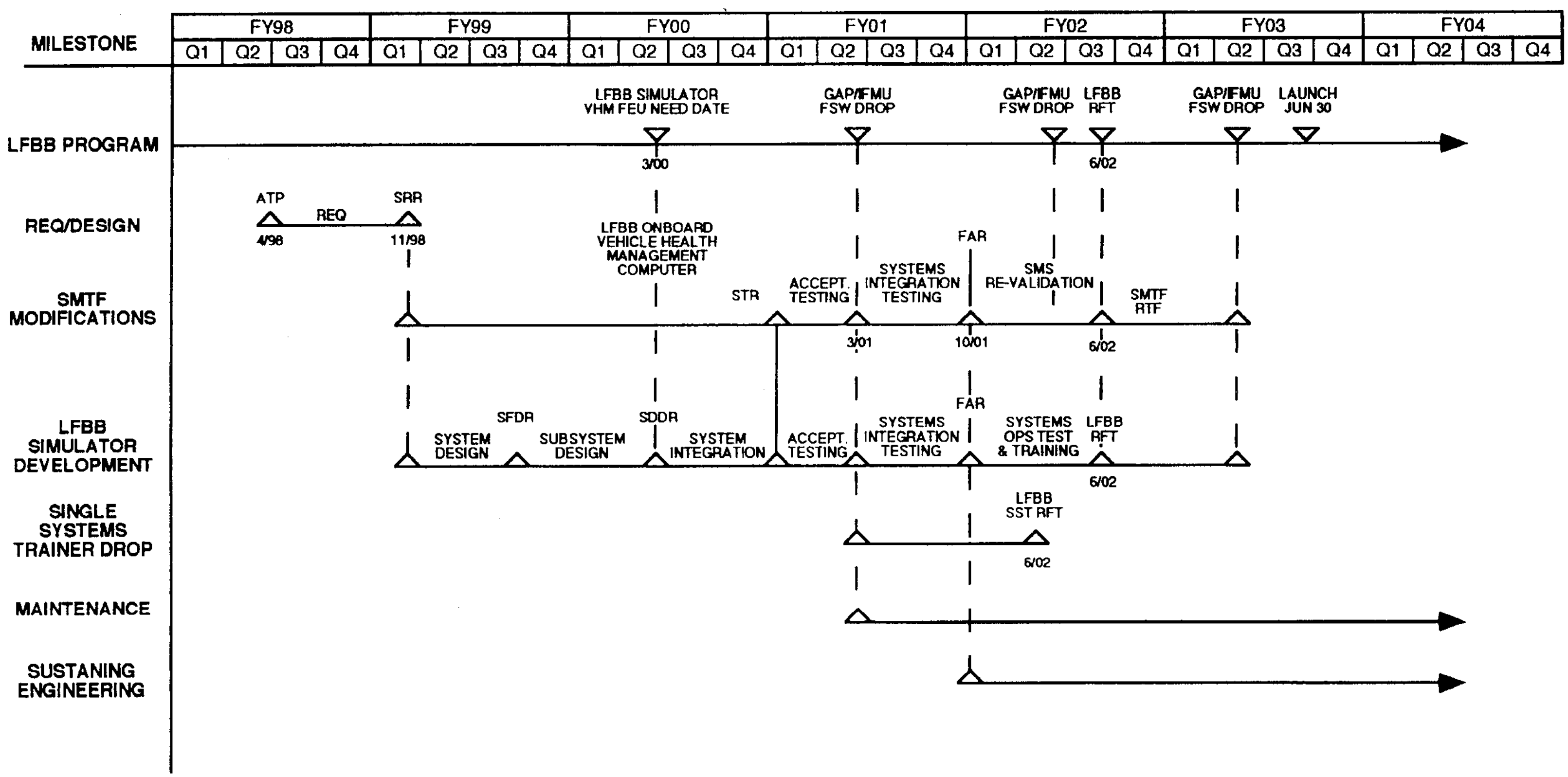


Figure 7.2.6.9-1 LFBB simulation development schedule.

7.3 MSFC Facilities

The MSFC facilities required to support the LFBB program are limited to testing facilities at this time. All facilities will require some modifications. It is assumed that LFBB hardware will be built by contractors and delivered to MSFC for testing except for wind tunnel models. The MSFC model shop and wind tunnel facilities will be required.

The MSFC structural test facility, building 4619, will be required for subcomponent structural testing (i.e., tanks, intertank, thrust structure, etc.). A dynamic test facility will be required to test the complete booster stack. This test series might be coupled with the propulsion test if a protoflight unit is used for propulsion tests and the test is performed at MSFC.

A large propulsion test stand capable of captive firing the complete LFBB along with the required non-firing flow tests is available. A single engine test stand is not required assuming the individual engines have been acceptance test fired before delivery to MSFC.

A medium-sized assembly building is needed to perform final assembly of the LFBB into a propulsion test article. This assumes that the subcomponents will be shipped disassembled due to size.

SECTION 8
SPACE SHUTTLE IMPACTS

8.1 Orbiter Impacts

8.1.1 Orbiter Hardware Impacts

Orbiter hardware changes are limited to the addition of EIUs for the LFBBs. Eight engine interface units are required to support the four RD-180 engines on each booster. These units would be located in the Orbiter avionics bays along with power and data connections.

8.1.2 Orbiter Flight Software Impacts

The impacts to the Shuttle FSW due to LFBBs has been assessed by the avionics team. Three areas of concern were studied: transport lag between the GPC and the rocket engine for issuing opposing engine shutdown commands in the event of a engine failure, I/O handling capacity, and FSW change size estimation

Assuming the booster rocket EIU I/O requirements are similar to the SSME controller, a preliminary study reveals a potential I/O handling problem with the current Orbiter data processing system. There is not sufficient time margin to acquire the four EIU's worth of data, for the LFBB's, and preserve sufficient margin for special processing, such as a one bus I/O error. This concern should be revisited when the I/O requirements of the booster engine are better defined

8.1.2.1 Primary Avionics System Software

Our initial primary avionics system software (PASS) assessment of replacing existing shuttle RSRMs with LFBBs developed the following data.

This study was performed with engine configuration of two RD-170 engines on each LFBB. Four RD-180 engines were later selected. With the RD-180 engine configuration, the I/O handling between the GPC and booster EIU will be reduced. Further analysis will be required in the next phase of study.

8.1.2.1.1 Assumptions

- Two boosters per stack, each propelled by two liquid-fueled engines
- LFBBs will produce same nominal launch trajectory as the current RSRMs (thrust profile, gimbal capability, etc.)
- Configuration requires balanced operational booster engines (e.g. 2-2 [two operational engines on the left booster and two operational engines on the right booster], 1-1, 0-0)
- Provide differential throttling/gimbaling between boosters
- Enforce slaved throttling/gimbaling across the engines of a single booster
- Post-separation requirements not considered (i.e. dumps, repositioning, flyback, etc.)
- Architecture will consist of one SSME-type EIU, for each LFBB engine, with identical I/O (fig. 8.1.2.1.1-1)

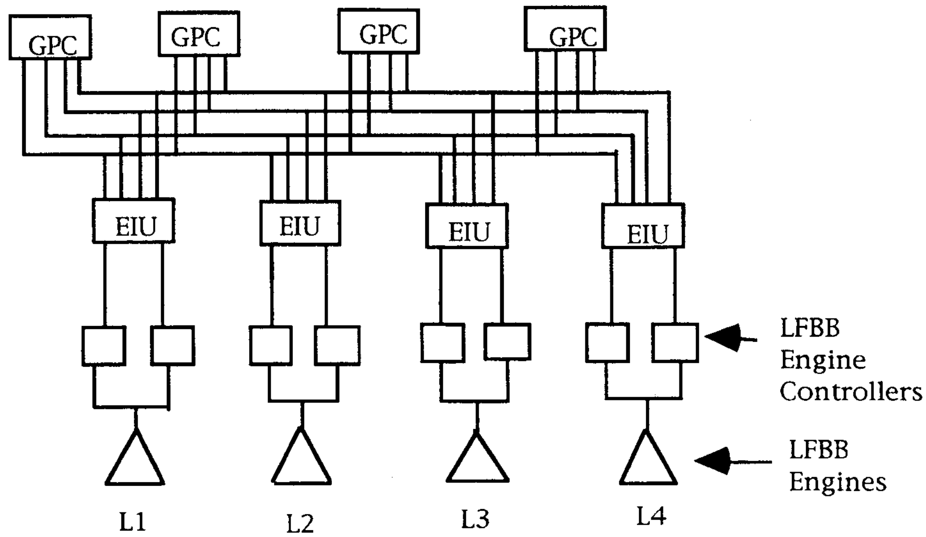


Figure 8.1.2.1.1-1 Primary avionics system software architecture.

8.1.2.1.2 Transport Lag. Transport lag, for issuing opposing engine shutdown commands in the event of an LFBB engine failure, was studied using the shuttle SSMEs as the model. PASS is capable of issuing a shutdown command in 20-60 milliseconds, depending on when the GPC polls occurs. However, current software requirements prohibit the software from acting upon a failure notification of an SSME for a count of 3 minor cycles (120 milliseconds). This was implemented to avoid taking action on a "transient" engine failure indication. It is assumed that similar precautions would be taken for the LFBB engines. Therefore, under the current implementation the time to issue a shutdown command is 120-160 milliseconds.

8.1.2.1.3 I/O Handling and Capacity. Most of the current RSRM I/O (i.e., RSRM acquisition, RSRM rate gyro pitch and yaw inputs, RSRM rock and tilt gimbal commands, and separation commands) will be maintained with the possible exception of RSRM chamber pressure inputs, which may require burning a new PROM for the MDM. Additional I/O for SSME-like EIUs require:

32 words input/EIU on MFE = 128 total
6 words input/EIU on HFE = 24 total
1 word output/EIU on HFE = 4 total

Preliminary analysis indicates that MFE I/O margin exists to accommodate additional words. *Based upon the current implementation of the HFE EIU I/O, there is not sufficient time margin to acquire the four EIUs worth of data for the LFBBs and preserve sufficient margin for special processing, such as a one-bus I/O error.*

8.1.2.1.4 Abort Mode Processing SLOC Estimate. It is probable that all methods of abort targeting will be affected by the addition of throttling the LFBBs. A conservative estimate would assume a 50% alteration in the existing core abort targeting software, which is currently 2000 SLOCs total. Therefore, it is estimated that 1000 SLOCs of abort software would be affected by this change.

8.1.2.1.5 Overall SLOC Estimate. The following is the estimated number of SLOCs that would be affected by this change.

redundant set launch sequencer (RSLS)		100
SOP/OPS		600
flight control TVC/SOP		300
throttling (guidance)		50
switches/displays		50
SSW I/O		150
abort targeting		1000
	Total	2250

8.1.2.2 Back-Up Flight Software (BFS)

Impacts to BFS are estimated to be equal to PASS with approximately 2250 SLOC changes.

8.2 ET Impacts

There will probably have to be modifications made to the external tank. These are due to the changes in loads and the attachment geometry changes between the ET and the LFBB. The extent of the changes are beyond the scope of this study, but preliminary analyses have identified the regions to be analyzed during follow-on studies. Impacts were identified by considering areas where the factor of safety (F.S.) was less than 1.55. ET structural impacts encompass all of the attach fitting locations to both the Orbiter and the LFBBs. Also, internal structural modifications to the kick ring located at station 2058 must be analyzed. Table 8.2-1 lists the ET areas of concern. We assume that the impacts occur in the time ranges where thrust and inertia are the dominant drivers (e.g., liftoff and maximum dynamic pressure). The structural impacts are highly dependent on the ignition and liftoff loads. The liftoff loads are highly dependent upon the hold-down/release mechanism.

The ET TPS will have to be addressed due to the increase of the ascent aerodynamic heating. The potential impact should be limited to an increase in the thickness of the spray-on foam insulation. Any increases in ET system weights reduce the payload nearly pound for pound.

Table 8.2-1 Potential ET Structural Locations Requiring Modification

- Aft ET/RSRM strut fittings	
*- Upper/diagonal (P8/P10) shear pin and fitting	L.O. and Hi-Q F.S. = 1.43
*- Lower (P9) strut fitting	L.O. and Hi-Q F.S. = 1.44
- Aft ET/Orbiter struts	
- Vertical struts and fittings (P3)	Hi-Q F.S. = 1.46
- Thrust struts (P5)	Hi-Q F.S. = 1.48
- Diagonal strut fittings (P7)	Hi-Q F.S. = 1.44
-2058 ring frame	
- frame at ET/Orbiter diagonal strut	L.O. F.S. = 1.44
- Outer chord at vertical strut	L.O. F.S. = 1.43
- Frame at lower RSRM strut fitting	L.O. F.S. = 1.44
- Forward LH2 barrel panel	L.O. F.S. = 1.51
- LH2 Frame at station 1871	L.O. F.S. = 1.53
- LO2 tank Ogive panel	L.O. F.S. = 1.52
*- Frame at upper/diagonal interface (likely)	

NOTE: SLWT will be designed to provide some additional capability in low margin locations.

(*significant impacts expected)

SECTION 9
SAFETY, RELIABILITY, AND RISK ANALYSES

For this phase of the study, safety, reliability, and risk analyses were limited to the LFBB, its development, construction, and performance. Section 9.1 defines six categories used to identify and quantify factors arising from development and construction activities that may cause unforeseen schedule delays or cost increases. Higher scores indicate a greater probability of event occurrence at a greater severity.

Section 9.2 discusses vehicle reliability from launch to return. From launch through separation, safety is described as a function of the probability of successful operation sufficient to achieve aborts. A summary of this study is included in section 9.3, which includes all conclusions and issues that will need special attention in future work.

9.1 Development and Construction Risk Assessment

This section assesses common risk sources stemming from development and construction activities for the LFBB system and its major subsystems. The risk categories and the method for quantifying their probability and severity are described in the following section. At this stage of LFBB development these risk categories and their measurements are inherently qualitative. The described scoring method is useful for comparison and for identifying potential trouble areas.

The risk assessment scores for the system and its subsystems follows the description of risk categories and their measurement. The given ratings are chosen to best describe the system or subsystem as a whole. Where portions of a system or subsystem differ from the given rating, it will be noted. Conclusions based on this analysis are included in Section 9.3.

9.1.1 Risk Categories

The first two described risk categories deal with technical development risk. The probability of a failure increases with an item's newness and with the degree that it is different from existing hardware or technology. "State of Technology" (SOT) measures the extent "state of the art" must be advanced to meet project requirements. "Design Engineering Difficulty" (DED) measures the degree to which the requirement differs from that of previous developments. It is a measure of the reusability of existing designs.

The next two categories measure the difficulty involved in manufacturing a piece of hardware or carrying out a process. "Manufacturing/Operations Process Difficulty" (MPD) measures the amount of change and the development required to adapt existing methods or processes to complete a new task. "Production Equipment Status" (EQI) measures the availability of equipment and facilities, and the amount of modifications required.

"Personnel Resource Status" (PER) measures the experience and training of personnel, as related to a task or product. "Test Resource Status" (TEST) is very similar to a combination of the manufacturing measurements. It measures the state of development for required testing procedures, and the availability of testing facilities.

For each risk category, six levels have been defined to provide a rough measure for the probability and severity of occurrence. At the lowest level, "0," there is practically no credible probability that unforeseen events will occur. Everything required for a piece of hardware or a task is available or within experience. This does not mean there is no risk; it means that risks are well understood. In levels "1" through "5," the probability of an unforeseen event, or other problems, occurring increases. Increasing levels of technology or equipment must be developed, personnel trained, or facilities and procedures modified. These risk categories and measurement criteria were adapted for this application from Reference 15.

9.1.1.1 *State of Technology*

SOT measures the extent that existing science must be advanced to meet hardware, software or task requirements. The more that technology must be developed to meet requirements, the greater the risk of unforeseen delays, costs or other problems.

Risk Levels: SOT
0: The technology is in common use. It is deployed in similar equipment or has been used in similar software. This is also appropriate if SOT is not applicable.
1: The technology has been used in applications that have passed qualification tests.
2: Critical functions and characteristics of the required technology have been tested and proven in existing qualified applications. Not all aspects of the technology are proven.
3: The technology exists and has been lab-tested. Prototype applications are being developed or tested.
4: The technological theory exists, has been lab-tested, and is accepted. It has never been put into practical use and no prototype applications have been developed.
5: Research is ongoing. The required technology is not proven or accepted.

9.1.1.2 *Design Engineering Difficulty*

DED measures the extent that existing hardware or software meets project requirements. More design or development increases the chances that cost or schedule will be impacted beyond what is expected.

Risk Levels: DED
0: The subsystem or hardware piece is off-the-shelf and qualified for similar applications as is; no modifications are required.
1: The item is off-the-shelf but has not been qualified. No modifications are required and the item exists.
2: The item is off-the-shelf but requires some minor redesign and subsequent qualification.
3: The item requires a new design that uses established technology.
4: The item will require a major engineering development effort that advances technology.
5: No hardware exists and a major technological breakthrough will be required.

9.1.1.3 *Manufacturing Process Difficulty*

MPD measures the extent that processes necessary to manufacture a designed item or complete a designated task must be designed or developed. If new hardware differs a great deal from existing hardware, there is a greater likelihood that the methodology will need to be revised during the task.

Risk Levels: MPD
0: The process either exists and requires no modification, or there is no associated process.
1: An integrated process exists, but requires minor modification.
2: The required processes exist, but must be integrated to produce the required item or complete the task.
3: The required processes exist. Some require further development and they must be integrated.
4: Processes are within the state of the art, but have not yet been developed.
5: The required process is beyond the existing state of manufacturing technology.

9.1.1.4 *Production Equipment Status*

EQI measures the availability of facilities and equipment that are necessary to carry out a manufacturing process or task, and the extent they must be modified.

Risk Levels: EQI
0: Production equipment and facilities are available and require no additions or modifications.
1: Facilities and equipment are available. Some minor modifications or purchases are required.
2: The facility is available and may require minor modifications. Major retooling or equipment purchases are required.

3: The facility is available and may require minor to moderate modifications. New production equipment must be developed and constructed.
4: An existing facility is available, but requires major modifications. New production equipment must be developed and constructed.
5: No facility is available and production equipment does not exist.

9.1.1.5 Personnel Resource Status

PER measures the level of knowledge and experience personnel have in dealing with the given task or hardware. Risk level relates to the organization's experience in the subject item or task due to its newness or the organization's experience with it.

Risk Levels: PER
0: The involved personnel are trained and experienced in the equipment, processes, and disciplines required for the subject item or task.
1: Personnel are trained and experienced in similar items or tasks.
2: Personnel have been trained in similar items or tasks, but have little experience.
3: The personnel lack experience and training. An experienced training staff is available.
4: The process, equipment or discipline is new. No training or experience is possible, i.e., learn as you go.
5: The processes, equipment, and disciplines are in the research stage.

9.1.1.6 Test Resource Status

TEST measures the extent that testing facilities are not available, must be modified, and that testing procedures must be defined. It is similar to a combination of EQI and MPD as applied to equipment or process testing.

Risk Levels: TEST
0: Procedures are defined and in use, and facilities are readily available, or testing is not applicable.
1: Procedures are defined, but facilities have limited availability.
2: The procedures are defined and facilities require modification.
3: Defined procedures require development and refinement. Testing facilities require modifications.
4: Procedures are not fully defined. Facilities need to be designed and constructed.
5: No test procedures have been defined. Testing facilities may not exist.

9.1.2 Risk Measurements

9.1.2.1 Vehicle Development and Construction[1]

SOT: 0[2], **DED:** 3[3], **MPD:** 3, **EQI:** 2[4], **PER:** 1, **TEST:** 2-3

1. Normally, the highest rating of any subsystem is rolled up into higher order subsystems and the system itself. For this report at this level, subsystems will be considered as off-the-shelf with no risk; risk aspects and ratings are for the complete vehicle development and assembly.
2. All major aspects of the launch vehicle (launch, ascent, separation, reentry, flyback) have been used separately in proven systems; the exception is wing deployment. In-flight wing deployment has been used only for much smaller wings in missiles.
3. Similar to SOT, wing deployment may drive aspects of DED higher.
4. It is not verified that a facility is available. The similarity of this vehicle in size and design to existing supports the assumption that a facility will be available.

9.1.2.1.1 Structures

SOT: 1-3[1], **DED:** 3-4[2], **MPD:** 2, **EQI:** 2, **PER:** 1, **TEST:** 3

1. If Al-Li is used, SOT = 3; SOT = 1 if Al is used.
2. The majority of the vehicle utilizes established technology. Development of swing-out wings will require some engineering development.

9.1.2.1.2 TPS/Insulation (System)

SOT: 3[1], **DED:** 3[2], **MPD:** 3, **EQI:** 2, **PER:** 2, **TEST:** 2

1. Driven by insulation requirements and the final choice of insulation. Reusability is an issue.
2. Even assuming a new insulation system, system design is not expected to be unique.

9.1.2.1.3 Ascent Propulsion

SOT: 0, **DED:** 3[1], **MPD:** 3, **EQI:** 2, **PER:** 1, **TEST:** 2

1. The majority of proposed system elements are existing and off-the-shelf. However, the system as a whole is unique and certain elements will require further development (tanks, RD-180 engines).

9.1.2.1.4 RCS Propulsion

SOT: 2[1], **DED:** 3[1], **MPD:** 2, **EQI:** 1, **PER:** 1, **TEST:** 1

1. This assumes a GO2/RP-1 system.

9.1.2.1.5 Separation Propulsion[1]

SOT: 0, **DED:** 2, **MPD:** 1, **EQI:** 1, **PER:** 0-1, **TEST:** 1

1. Based on a system adapted from RSRMs.

9.1.2.1.6 Air-Breathing Propulsion

SOT: 0-1[1], **DED:** 2, **MPD:** 1, **EQI:** 1, **PER:** 0, **TEST:** 1

1. The technology is in common use in similar equipment during operation. Environments experienced until operation are new. Cold start may require technology development.

9.1.2.1.7 Power Systems[1]

SOT: 0, **DED:** 3, **MPD:** 1, **EQI:** 1, **PER:** 0, **TEST:** 1

1. Limited to power storage and distribution. Excludes controls and switching.

9.1.2.1.8 Control Actuation

SOT: 3[1], **DED:** 4, **MPD:** 3, **EQI:** 2, **PER:** 1, **TEST:** 3

1. This assumes EMAs.

9.1.2.1.9 Integrated Avionics

SOT: 0, **DED:** 3, **MPD:** 2, **EQI:** 1, **PER:** 1, **TEST:** 3

9.1.2.1.10 Thermal Control

SOT: 0, **DED:** 3, **MPD:** 1, **EQI:** 1, **PER:** 1, **TEST:** 3

9.2 Safety and Reliability

9.2.1 Launch Through Separation

This section discusses the operational reliability of a future LFBB system and compares it to the current RSRM. Operational reliability will be defined in terms of the probability for successful LFBB system operation sufficient to achieve PTM, ATO, TAL, or RTLS. These will be evaluated for the alternative designs of two RD-170 engines per booster, three RD-180 engines per booster, and four RD-180 engines per booster.

Reliabilities determined for the LFBB refer to the probability that the LFBB system (two boosters) will operate sufficiently well that PTM, ATO, TAL, or RTLS could be achieved. Reliabilities of other Shuttle systems (Orbiter, ET) or probabilities of an abort success are not included or considered.

The individual engine reliability for the RD-170 engine is published at 0.998 per flight (95% confidence)[16]. This is based on flight and test data. Although the RD-180 has not been fully developed and has not been tested as a system, its reliability will also be assumed to be 0.998 per flight. The RD-180 utilizes components used in the RD-170 and in other existing NPO Energomash engines, and is essentially half of an RD-170. Also, 0.998 is in the range of historical reliabilities for U.S. engines using RP-1 fuel. For instance, the reliability for the F-1 engine is documented at 99.85%[17].

The RD-170 and RD-180 engines include several systems normally considered external from U.S. engines; these include the gimbal system and associated hydraulic pumps. Having these systems included in the engine reliability results in a significant difference in the way propulsion system reliability is determined. Historically, roughly half of U.S. vehicle failures attributed to propulsion systems are not caused by the engines. Excluding tanks and fuel lines, U.S. propulsion subsystems that failed in flight are included in the RD-170 or RD-180 engine systems. A review of the extensive failure listing included in reference 18 found no modern (post-1970) propulsive failures in subsystems that would not be included in these engines. For the RD-170 and RD-180 engines, therefore, the engine system reliability is essentially synonymous with the propulsion system reliability.

For each engine case, two sets of reliability numbers will be presented. In the first set (high-end), reliability data (excluding engines) is based on the assumption that design flaws that caused failures are fixed. These failures are not included in estimating the system reliability. The second set (low-end) includes all historical failures regardless of cause. Both sets of numbers assume a mature, fully tested system. For the reference RSRM, high mean reliability, excluding the single failure, is 99.2%[19]. The RSRM historical mean (1/60) is 98.3%[19]. Since the reliability of the RD series engines are assumed fixed at 99.8%, the difference between "high" and "low" is produced by the expected reliability of non-propulsion stage level systems.

For the "high" value, 99.9% reliability per booster is used for non-propulsive stage level systems. Reference 20 projected a range of values 99.9% to 99.6% (99.8% listed mean) for future expendable systems. This value included no guidance and assumed design failures were fixed. A review of failures listed in Reference18 found the majority of this failure type were from flight (attitude) control followed by stage or fairing separation then electrical systems. Of ten failures (1970 to 1988), two were found to possibly be applicable for an LFBB during ascent. The Saturn series most closely resembles the LFBB and it had no failures of this type. The LFBB would be part of a manned system also having no failures of this kind. Considering these factors, the 99.9% was considered the most appropriate.

For the stage level "low" value, 99.4%[20] is used. This is a straight historical average that includes design and process failures. It is not adjusted to exclude failures that are not applicable to the proposed LFBB. It should also be noted that both the high and low stage level reliability values are applied to each of the two boosters. Overall reliability for the two-booster system results from the product of the individual booster reliabilities. Strap-on boosters are often considered a single stage and termed a half stage. A good argument could be made for applying the stage level reliability to the booster system reliability. If this argument were used, the listed high and low LFBB reliabilities would be increased by a factor of 1/0.999 and 1/0.994, respectively.

9.2.1.1 Case 1: Two RD-170s per Booster

In this design alternative, each of the two boosters is propelled by two RD-170 engines. Given the RD-170's performance, there are times during ascent when a booster engine could fail and the Orbiter still might achieve a nominal mission or an abort (see 2.2.3). Figure 9.2.1.1-1 illustrates top-level failure modes for this booster option. A stage-level catastrophic failure at any time during the booster ascent is assumed to result in a catastrophic Orbiter failure. An engine failure of any kind before an event minimum time (X) precludes that event. After time X, any engine catastrophic failure or two benign engine failures on the same booster is considered catastrophic.

With a 5-second hold-down baselined, a uniform failure distribution is assumed from launch to separation.

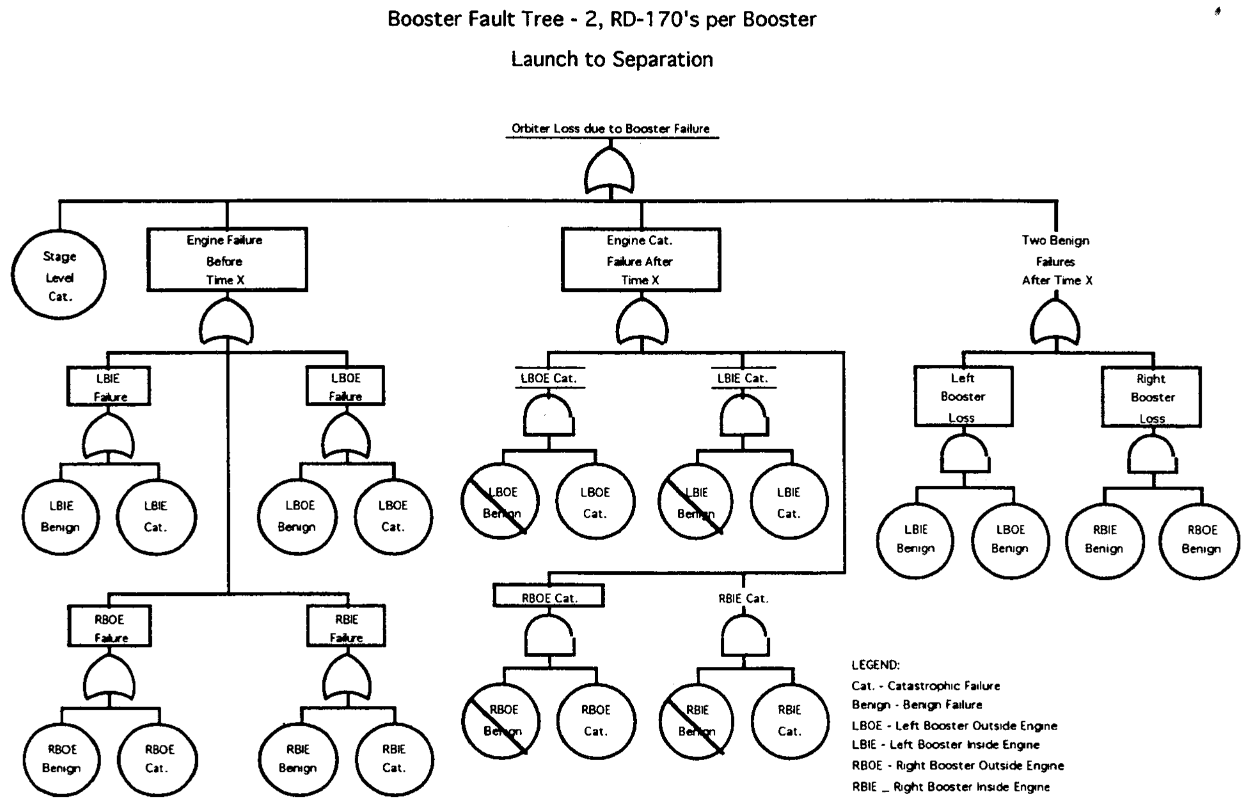


Figure 9.2.1.1-1 Booster fault tree - two RD-170s per booster.

Using additive and linear approximations, the booster fault tree was translated into the following formulation:

$$SLC+4(X/T)(EF)+4(1-X/T)(1-EB)(EC)+2(1-X/T)(EB)^2 \quad \text{(eq. 9.2.1.1-1)}$$

SLC	=	probability of stage level catastrophic failure
X	=	earliest possibility of successful event
T	=	time from lift-off to separation
EF	=	probability of an individual engine failure
EB	=	probability of a benign engine failure (1-CCF)(EF)
CCF	=	catastrophic correlation factor
EC	=	probability of a catastrophic engine failure (CCF)(EF)

The catastrophic correlation factor (CCF) is the portion of failures that propagate beyond the failed engine. These are assumed to result in a catastrophic vehicle failure. The CCF is significant when an engine-out capability exists. For the two RD-170 per booster case, a single engine per booster could be lost at various times in flight, and aborts or nominal mission could still be achieved (fig. 9.2.1.1-2). The CCF information is not available for the RD-170s. To provide a loose reference frame, a survey of SSME flight and test stand data[18] found that 17% of uncontrolled failures propagate beyond the engine. On the test stand 50% of failures resulted in a controlled shutdown. An independent survey[21] estimated a mean of 50% of SSME crit-1 failures are protectable by a health monitoring system. If this data were applicable to RD-170s, its CCF would be 8.5%. Note that the RD-170s have a health monitoring system.

Figure 9.2.1.1-2 plots the expected "high-end" reliability of the LFBB against the CCF for four possible flight outcomes. PTM could be achieved even if both boosters lost an engine at some time greater than 74 seconds into the flight. This line is the probability that no failures occur at less than 74 seconds and that no more than a single benign engine failure per booster would occur after 74 seconds. Similarly, ATO could be achieved at single engine loss after 67 seconds, TAL at 49 seconds, and RTLS at 24 seconds. The RTLS line describes the probability that the LFBB will operate sufficiently well that the Orbiter could achieve RTLS or better (TAL, ATO, PTM). Interpretation for TAL and ATO is similar. The RSRM reliability, using similar assumptions, is listed for reference. RSRM reliability relates to PTM only; no aborts are possible until after RSRM separation.

Figure 9.2.1.1-3 is similar to figure 9.2.1.1-2 except it uses a low-end estimate. RSRM and LFBB non-propulsive reliability are based on historical averages that include failures resulting from design errors. Other assumptions and interpretations are the same as described for figure 9.2.1.1-2.

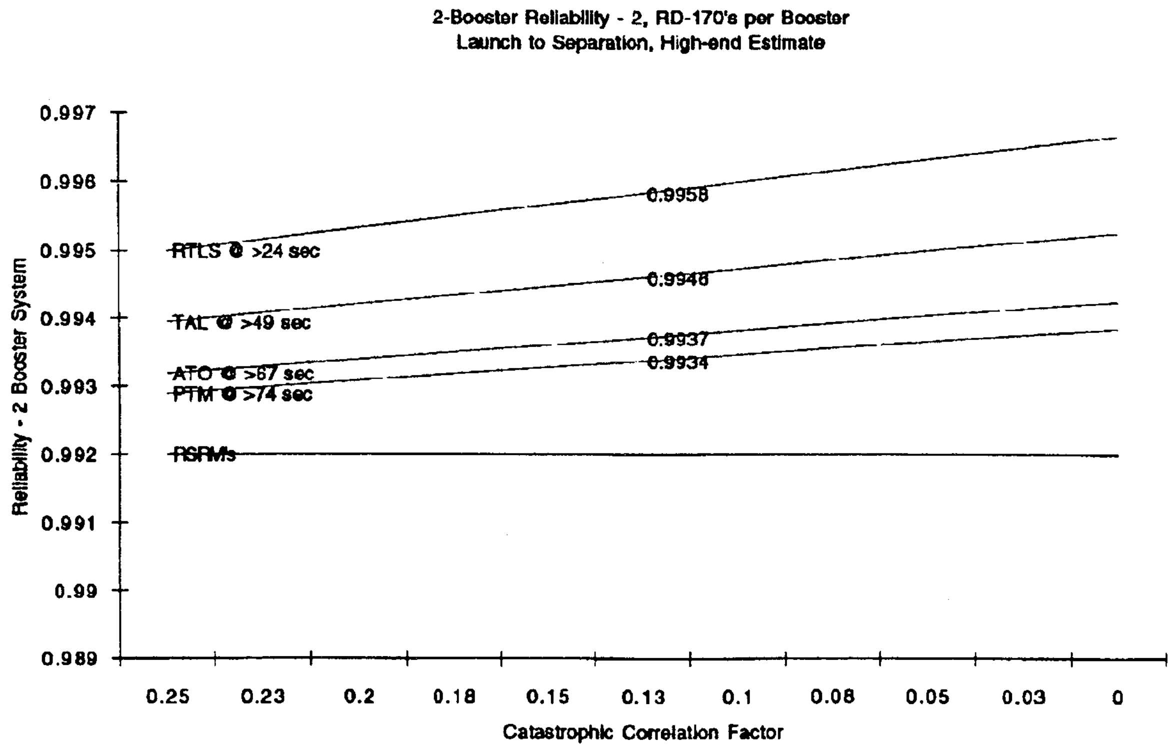


Figure 9.2.1.1-2 Two-booster reliability - two RD-170s per booster launch to separation, high-end estimate.

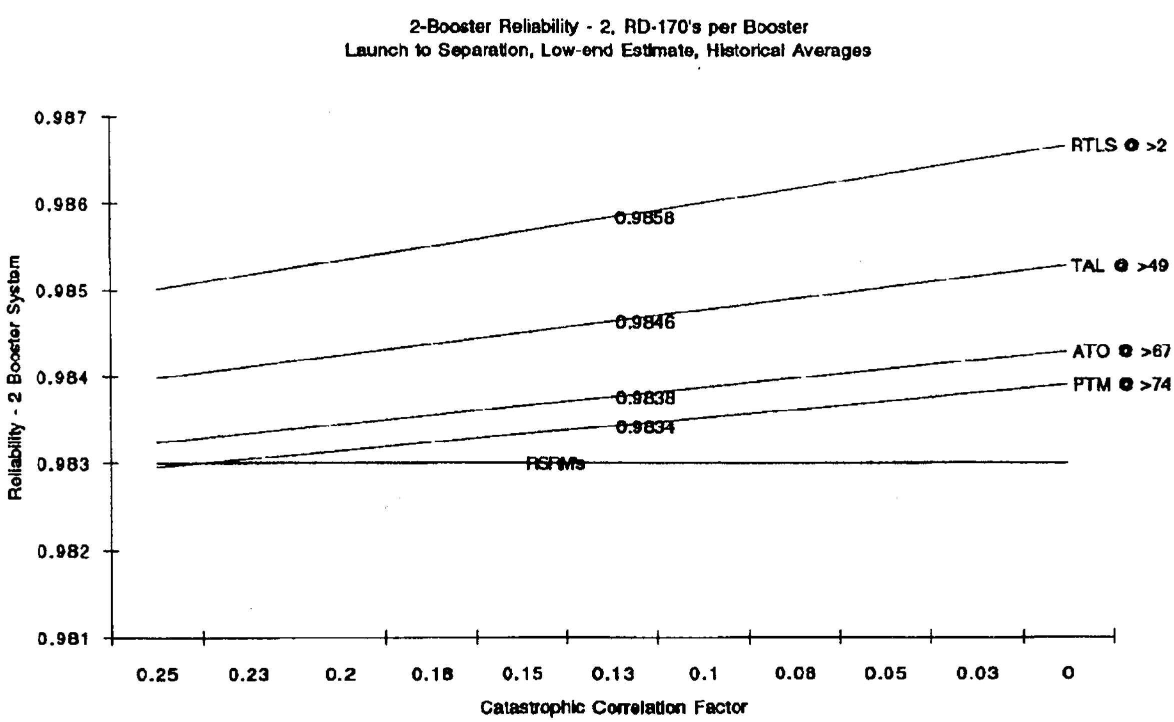


Figure 9.2.1.1-3 Two-booster reliability - two RD-170s per booster launch to separation, low-end estimate.

9.2.1.2 Case 2: Three RD-180s per Booster

In this design alternative, each booster is propelled by three RD-180 engines. Similar to the two RD-170s case, a single booster engine could fail and the Orbiter still might achieve a nominal mission or an abort. Catastrophic failure causes are much the same. Figure 9.2.1.2-1 charts failure modes for this booster option. A stage-level catastrophic failure at any time during the booster ascent results in a catastrophic Orbiter failure. A single engine failure of any kind before an event minimum time (X) precludes that event. After time X, any engine catastrophic failure or two benign engine failures on the same booster is catastrophic.

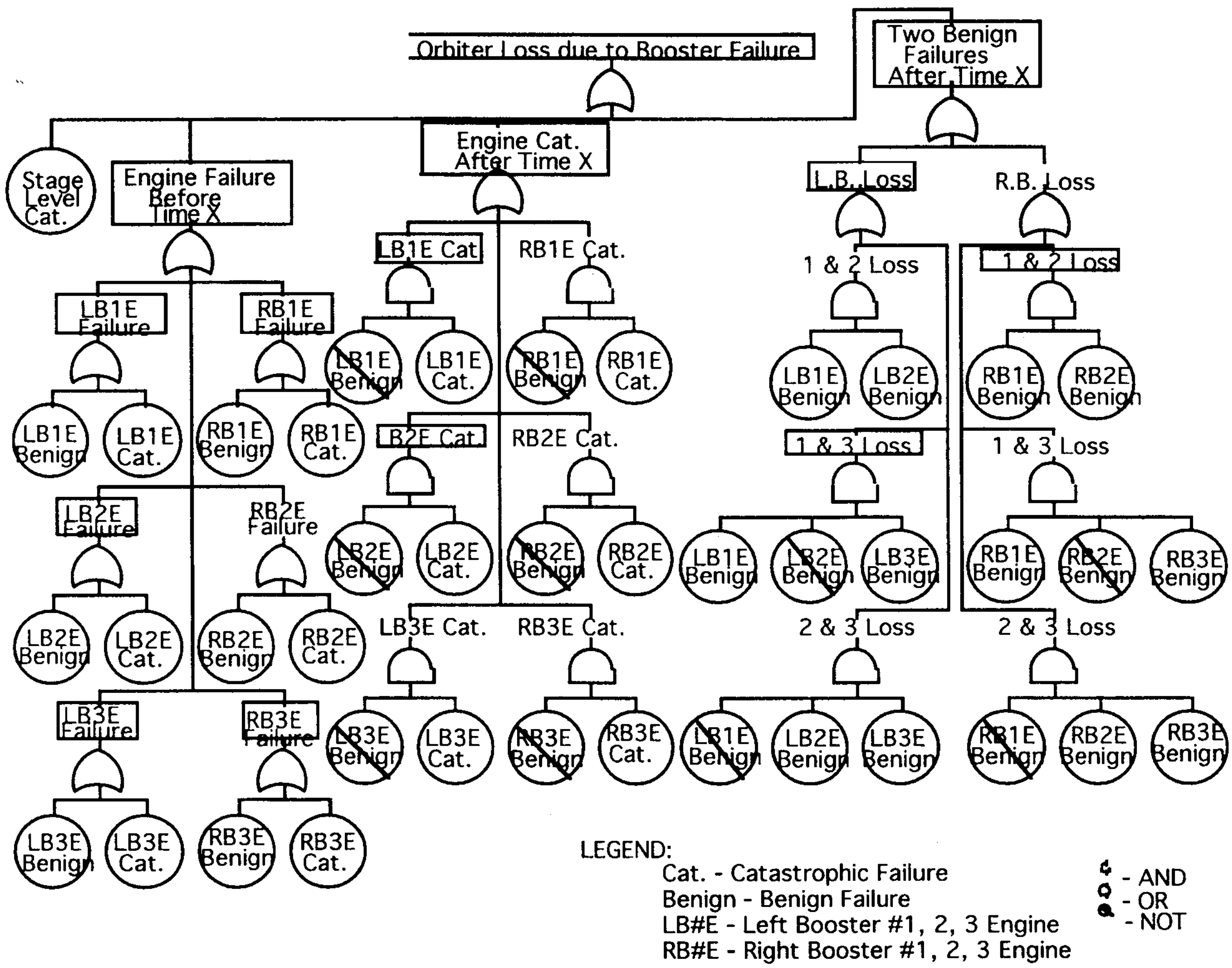


Figure 9.2.1.2-1 Booster fault tree - three RD-180s per booster.

Again a 5-second hold-down is baselined, and a uniform failure distribution is assumed from launch to separation. The booster fault tree was translated into the following formulation using additive and linear approximations:

$$SLC+6(X/T)(EF)+6(1-X/T)(1-EB)(EC)+2[(1-X/T)[1+2(1-EB)](EB)^2] \qquad \text{(eq. 9.2.1.2-1)}$$

Comparing figure 9.2.1.2-1 and equation (9.2.1.2-1) with figure 9.2.1.1-1 and equation (9.2.1.1-1) demonstrates the similarity of failure modes between the two. Using three RD-180s per booster includes all of the failure modes characteristic of two RD- 170s per booster and adds failure modes associated with two additional engines. Figure 9.2.1.2-2 plots the resulting high-end reliability for the four possible flight outcomes using the same single engine-out event times as the RD-170 case. Actual event time may vary due to the reduced performance of three RD-180s as compared to two RD-170s. Interpretations and assumptions are similar to those used for figure 9.2.1.1-2. Plots for the low-end reliability are not included. The three RD-180 engine option is not considered a viable option due to reduced performance (Section 2.2) and reliability as compared to the two RD-170 option.

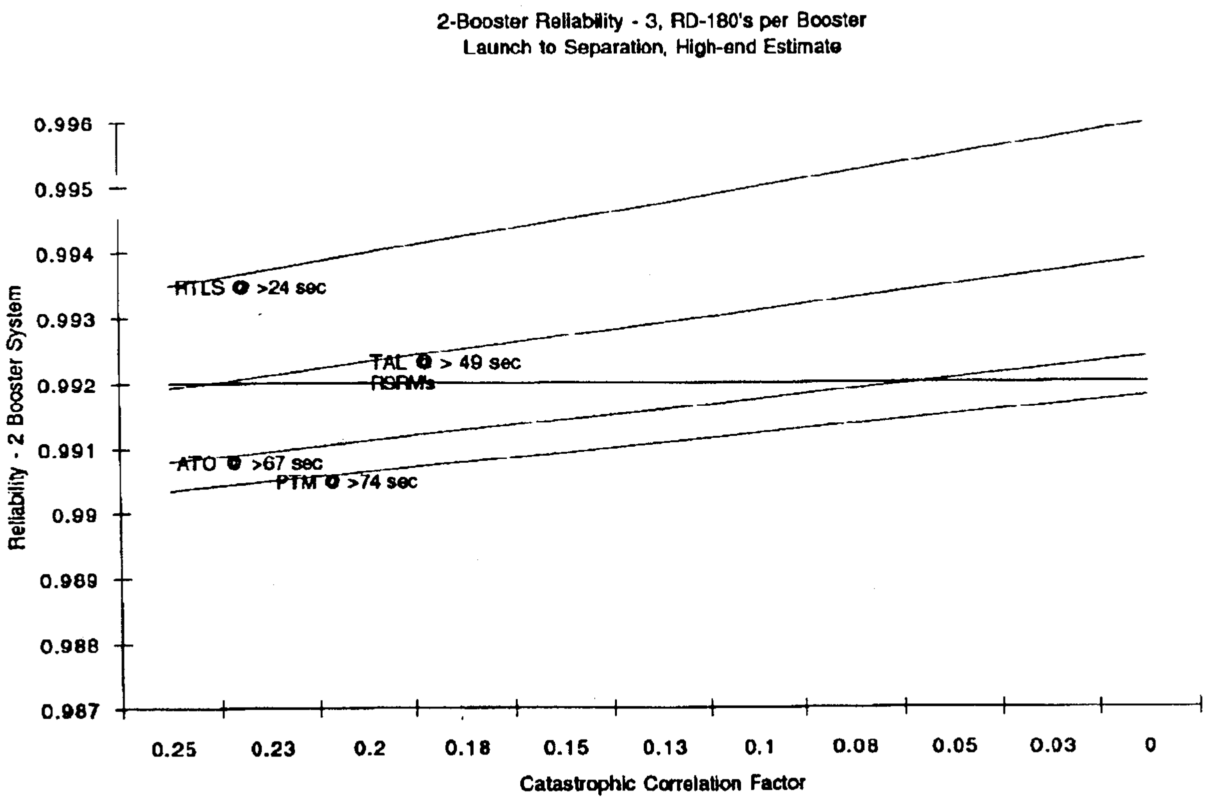


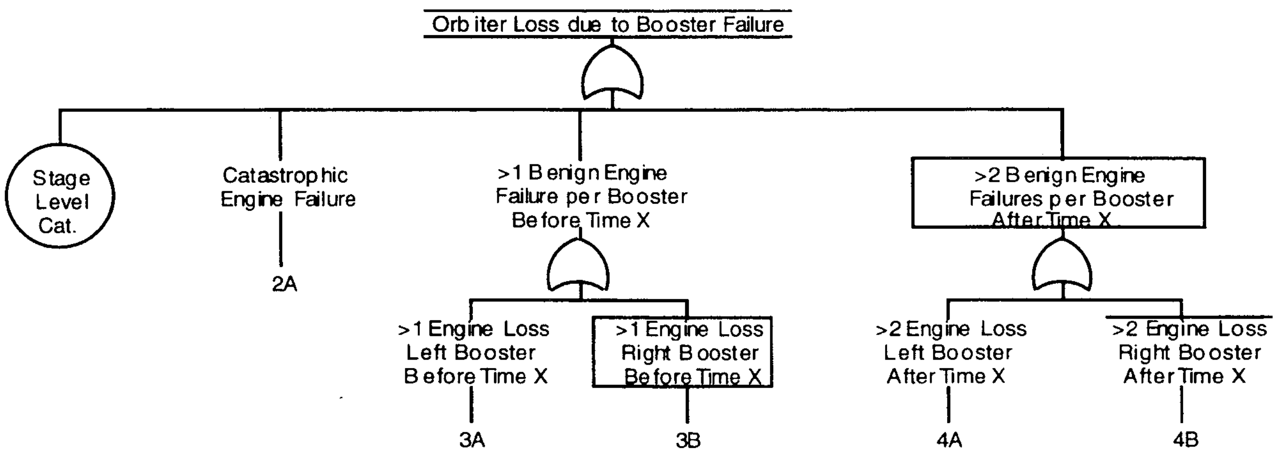
Figure 9.2.1.2-2 Two-booster reliability - three RD-180s per booster launch to separation, high-end estimate.

9.2.1.3 Case 3: Four RD-180s per Booster

In this case, each of the two LFBBs is propelled by four RD-180 engines. Although four RD-180s are equivalent to two RD-170s in thrust performance, they provide abort and reliability capabilities that two RD-170s cannot. A single RD-180 per booster could fail on the pad and the remaining would still provide adequate performance for all aborts; two seconds after launch, PTM could be achieved. Figures 9.2.1.3-1 through 9.2.1.3-4 illustrate the top level failure modes for this booster option. As before, a stage-level catastrophic failure or any engine catastrophic failure at any time during the booster ascent is assumed to result in a catastrophic Orbiter failure. A single benign engine failure per booster from launch does not preclude any abort. For PTM, the T+2 for single engine loss will be assumed equivalent to an off-the-pad capability. Two benign engine failures, on the same booster, before an event minimum time (X) precludes that event. After time X, greater than two benign engine failures on the same booster is considered catastrophic. Times for two engine loss are assumed to correspond to the single engine loss for the RD-170 case. It should be noted, the probability of two benign failures at a reliability of 99.8% are remote. The results of two or greater than two engine-out scenarios do not affect final results at three significant digits.

Booster Fault Tree - 4, RD-180's per Booster

Launch to Separation

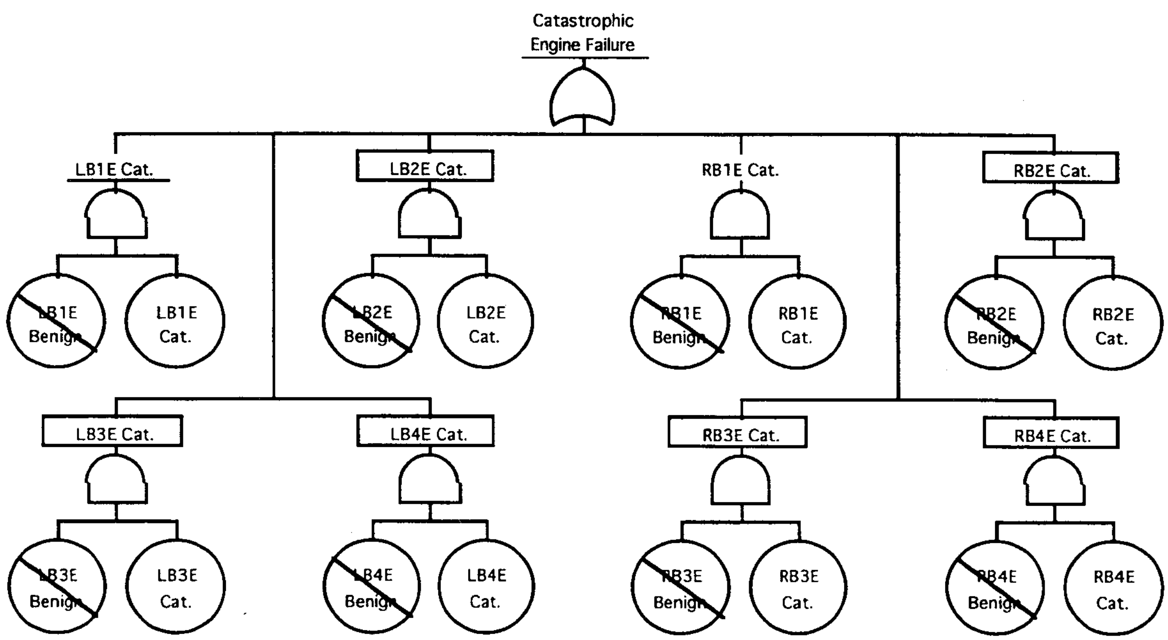


LEGEND:
Cat. - Catastrophic Failure
Benign - Benign Failure
LB#E - Left Booster #1, 2, 3, 4 Engine
RB#E - Right Booster #1, 2, 3, 4 Engine
- AND
- OR
- NOT

Figure 9.2.1.3-1 Booster fault tree - four RD-180s per booster.

Booster Fault Tree - 4, RD-180's per Booster

Launch to Separation



2A

LEGEND:
Cat. - Catastrophic Failure
Benign - Benign Failure
LB#E - Left Booster #1, 2, 3, 4 Engine
RB#E - Right Booster #1, 2, 3, 4 Engine
- AND
- OR
- NOT

Figure 9.2.1.3-2 Booster fault tree - four RD-180s per booster.

Booster Fault Tree - 4, RD-180's per Booster
Launch to Separation

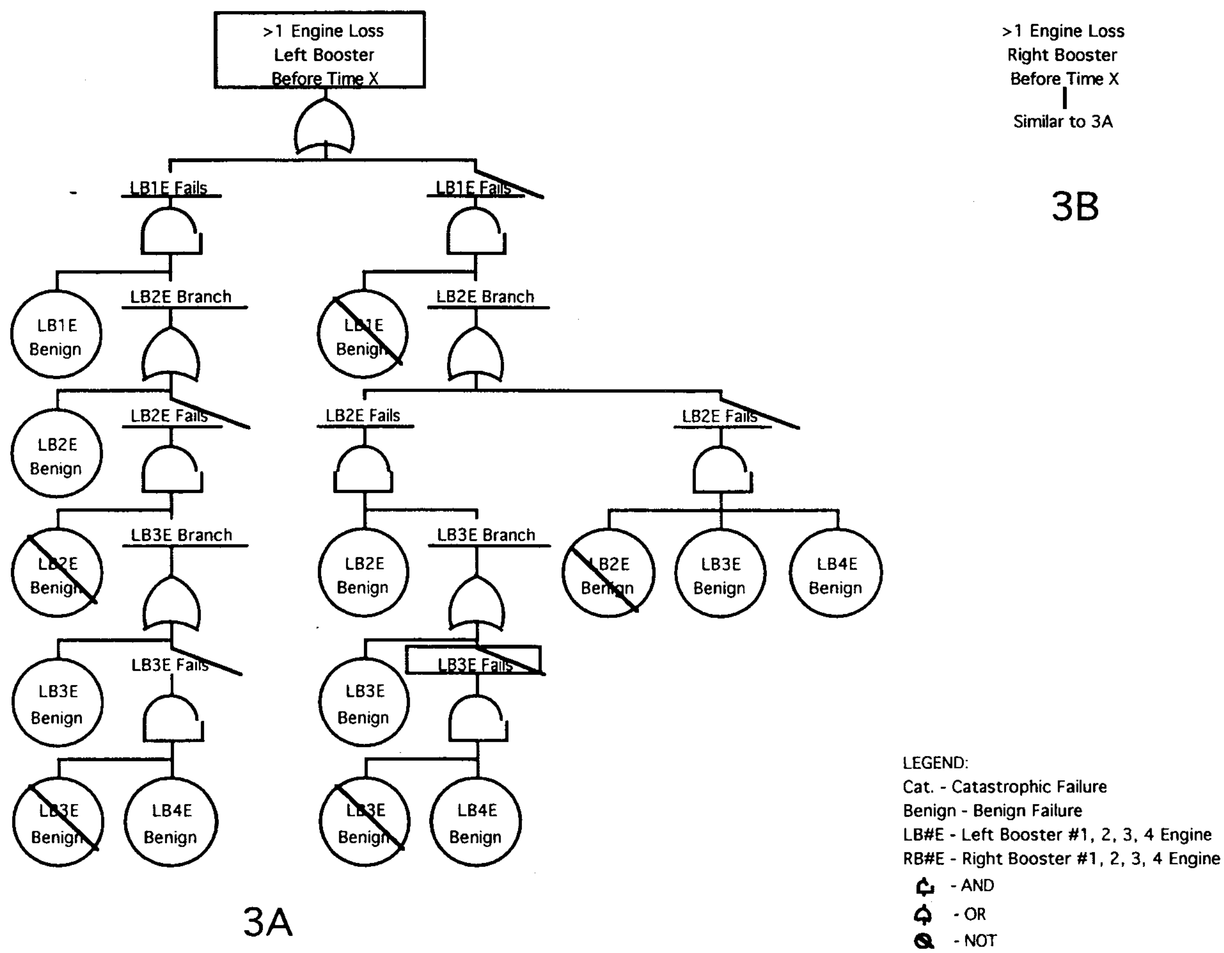


Figure 9.2.1.3-3 Booster fault tree - four RD-180s per booster.

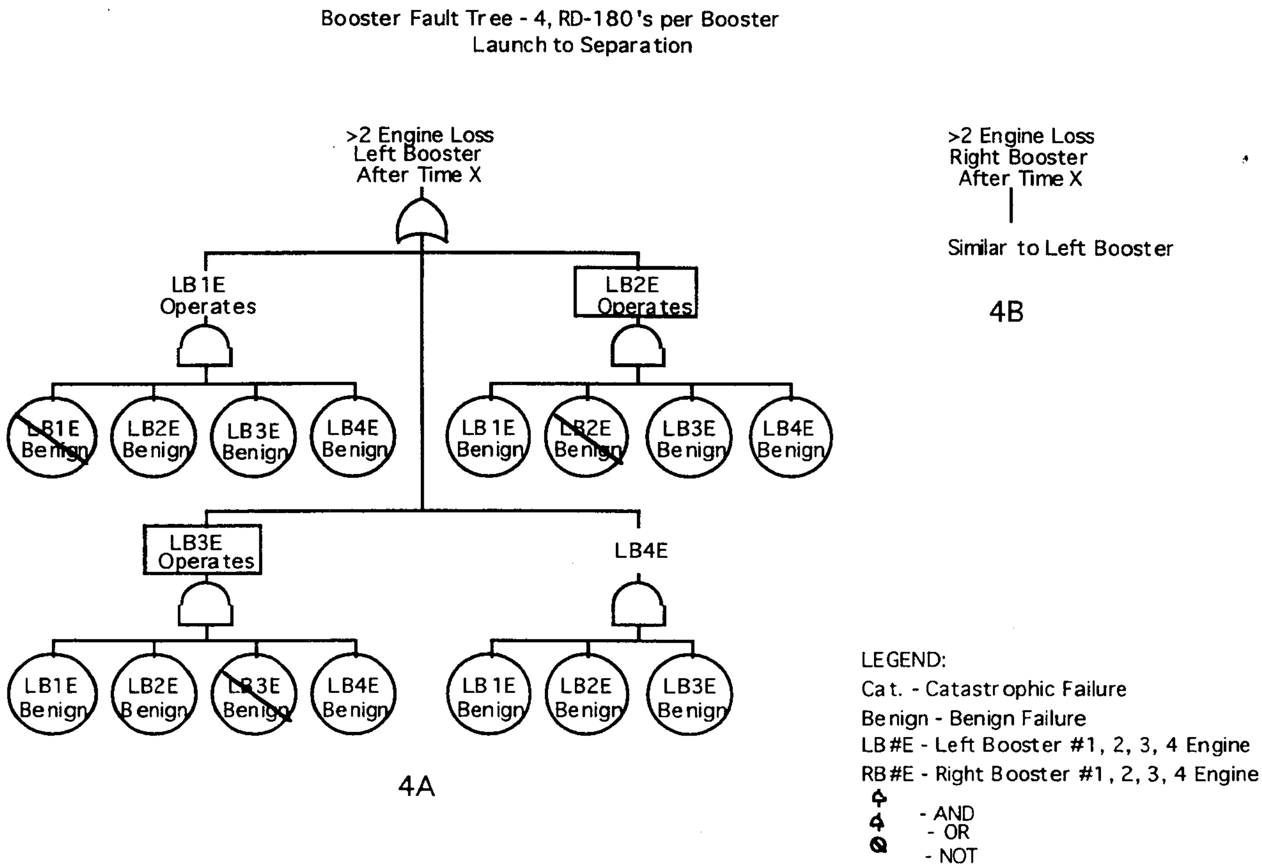


Figure 9.2.1.3-4 Booster fault tree - four RD-180s per booster.

As with the previous cases, a 5-second hold-down is baselined, and a uniform failure distribution is assumed from launch to separation. With additive and linear approximations, the booster fault tree was translated into the following non-simplified formulation:

$$
\begin{aligned}
&SLC+8(1-EB)(EC) \\
&\quad +2(X/T)\{(EB)[(EB)+(1-EB)[(EB)+(1-EB)(EB)]] \\
&\quad +(1-EB)[(1-EB)(EB^{2})+(1-EB)[(EB)+(1-EB)(EB)]]\} \\
&\quad +2(1-X/T)\{[3(1-EB)+1][EB^{3}\}
\end{aligned}
\qquad \text{(eq. 9.2.1.3-1)}
$$

Figure 9.2.1.3-5 plots the expected high-end reliability of the LFBB against the CCF for the four possible flight outcomes. Effectively, PTM, ATO, TAL, and RTLS could all be achieved if both boosters lost an engine at any time during the flight. After 74 seconds two benign engine failures per booster could occur and PTM could still be achieved. However, the probabilities for vehicle loss due to more than a single engine failure is less than the three significant digit resolution of available data. At three significant digits, the probabilities for PTM, ATO, TAL, and RTLS are the same.

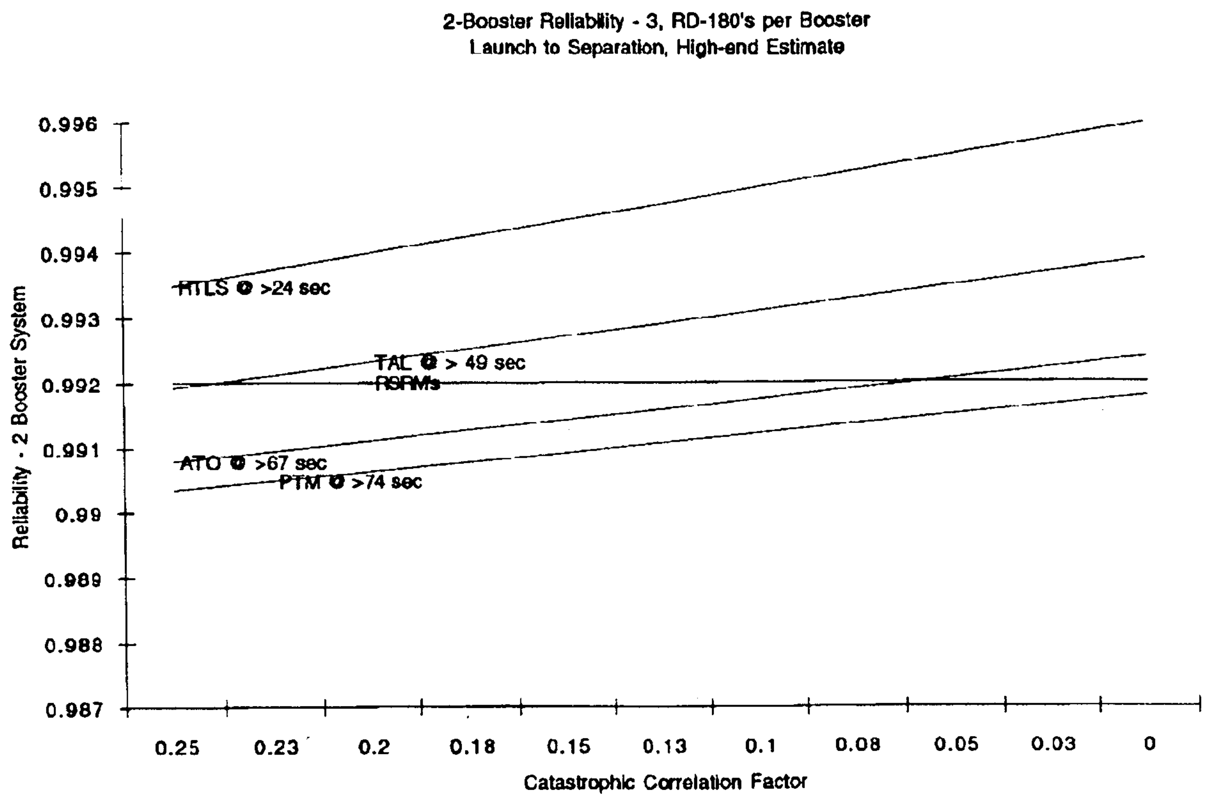


Figure 9.2.1.3-5 Two-booster reliability - three RD-180s per booster launch to separation, high-end estimate.

Figure 9.2.1.3-6 is similar to figure 9.2.1.1-3 illustrating a low-end estimate. RSRM and LFBB non-propulsive reliability is based on historical averages that include failures resulting from design errors. Other assumptions and interpretation is the same as described for figure 9.2.1.3-5.

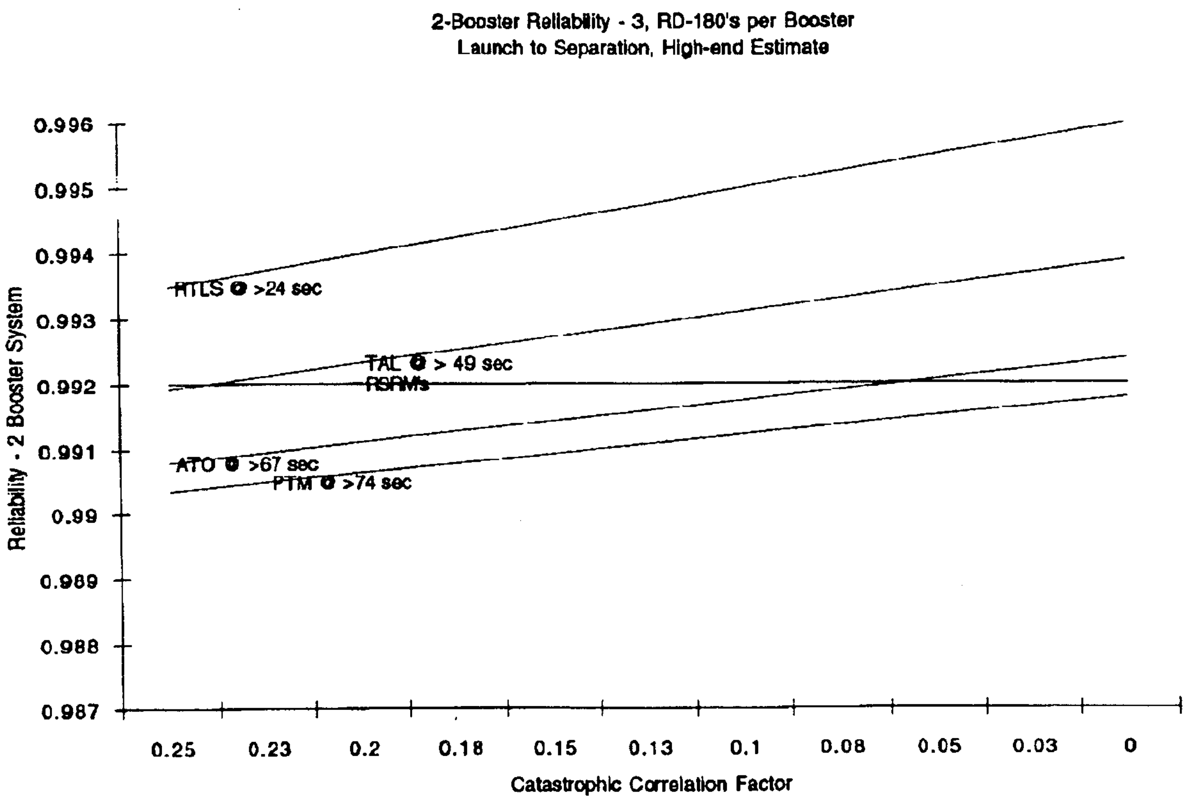


Figure 9.2.1.3-6 Two-booster reliability - three RD-180s per booster launch to separation, low-end estimate.

9.2.2 After Separation Through Recovery

This section reviews the reliability of LFBB systems and operations after separation from the Shuttle stack through landing. After separation, credible failures only affect recovery of the LFBBs. Failure becomes a cost issue only.

Unlike the launch segment, the return segment is relatively unique. The closest historical parallel to this phase of LFBB operation is the Orbiter. The most extensive study of reliability in this area is described in Reference 18. This study noted that little data was available on specific subsystem reliability. The data presented below, from Reference 22, was extracted from military and industrial data for similar subsystems. After separation until aerodynamic control is achieved, attitude control is maintained by RCS propulsion. Over a longer operations period, the Orbiter RCS system has an expected reliability of 0.9997 (based on loss of aft RCS during reentry). The Orbiter reliability for guidance and control through landing is estimated at 0.9997. Flap control is estimated at 0.99997 and elevons at 0.99997.

Deployment of swing-out wings, initially covered by a fairing, has only previously been used in missile systems. A more likely comparison, for wing deployment, is considered to be fairing separation from launch vehicles. Of 1545 expendable launches listed in Reference 17, there were a total of two fairing deployment failures. This results in an expected reliability of 0.999. If this reliability is applied to both the fairing and the wing deployment, the expected reliability for successful wing deployment is 0.998.

The flyback portion of operation can be expected to operate at a reliability comparable to single engine jet aircraft. Reference 23 cites U.S. Navy and USAF experience to predict a failure rate of 11 per 100,000 flight hours for a system with only 10,000 total hours. This translates to an expected reliability of 0.99989 for the LFBB time of air-breathing engine operation (essentially 1.000) assuming that the engine ignites properly. Although this portion of the flight is expected to be the most reliable, it should be noted that dual engine aircraft consistently experience four times fewer mishaps than single engine aircraft. Dual engines would also provide protection against ignition failure.

Including all of the above factors, the expected reliability of the LFBB flyback portion is 0.998 per booster. The fairing jettison and wing deployment dominate.

9.3 Conclusions and Recommendations

9.3.1 Development and Construction

With the exceptions of a reusable cryogenic tank and in-flight wing deployment, existing technology is sufficient to achieve all system requirements. Alternative subsystems that will require technology advancement are being considered or baselined when they offer significant improvement in performance, safety, or operations cost. In all cases the technology exists and has been lab- and prototype-tested. Deployable wings are in use at a smaller scale; this is considered equivalent to prototyping.

All subsystems have designs based on existing developed technology except those related to control actuation and deployable wings. EMAs are baselined for control actuation; their use requires a major engineering development largely due to power demands in switching. In-flight deployable wings of the size estimated are unique. Stress concentrations at the pivot point may require a major engineering development for their design.

The size of the vehicle and its basic configuration (excluding wings) are not unique. As such, manufacturing facilities and equipment are expected to be available. However, the vehicle is new, and many of its subsystems have configurations unique to the vehicle. This will require some manufacturing process development and integration. Some major manufacturing equipment purchases should be expected.

With the exception of insulation, personnel should generally be experienced in similar equipment and processes. Insulation may require application methods unfamiliar to those responsible; this will require some retraining. Testing procedures and facilities will require tailoring to meet the needs of a unique new vehicle. No operation of the LFBB is, in itself, unique.

9.3.2 Safety and Reliability

From launch through separation, the LFBB will offer at least comparable and probably better probability for mission success than the RSRM; this is true for both the two RD-170 per booster and four RD-180 per booster cases. Depending on the portion of engine failures that could be expected to propagate beyond the failed engine, the four RD-180 per booster option would offer significantly greater reliability than the RSRM. If propagation is comparable to the SSME and the health-monitoring system is 50% effective, this LFBB option would be 25% to 50% more reliable.

The LFBB offers the possibility for aborts during the period the RSRM precludes all aborts. These aborts are opened regardless of cause, booster, or Orbiter. The four RD-180 option can lose a single engine per booster on the pad and still achieve all aborts.

The LFBB flyback is the most reliable portion of its operation. LFBB loss during launch is much more likely due to LFBB or Orbiter failure. The fairing ejection, wing deployment, and possibly engine start are expected to be the most critical operations.

9.3.3 Issues and Future Work

The single greatest issue requiring resolution before completing a future phase of design work is the further reliability characterization and verification for the RD-170 engines. Per the Pratt & Whittney representative, Reference 16 contains all of the information currently available. Detailed test stand and flight results will be required for future work. These reports must contain information on failures and their expected propagation. Information will also be required on the engine's various failure modes and probabilities. A related area of study will be determining the protection afforded by single engine-out capability against process failures. Process failures generally result from human error and are highly diverse and random. These failures dominate in mature vehicle failures.

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SECTION 10
TEST AND VERIFICATION

10.1 Introduction

For Pre-Phase A study purposes, the MSFC's NASA Cost Model Data Base (NASCOM-DB) cost estimating process accounts for the costs associated with an LFBB Hardware/Software Test and Verification (T&V) baseline, via certain specific "system wraps" applied to the prime hardware/software (HW/SW) estimates. The findings of this assessment indicate that the LFBB System, at the integrated vehicle level, does not require verification testing deltas beyond that considered within the Shuttle experience-oriented costing baseline. Further, while various LFBB subsystems and technical discipline personnel indicate the need for extensive testing at or below the subsystem levels of hardware, these testing requirements are also considered to be within the T&V costing model envelope.

Given improvements in systems technical analysis (e.g., CFD), methods and databases already developed within the Shuttle program, and the hardware technology readiness levels factored in the LFBB design, the relative confidence that can be placed in an LFBB for the year 2003 is qualitatively reasoned to be:

- well advanced of where the Shuttle program was at the time of STS-1
- not quite as good as the knowledge of the Integrated Shuttle Vehicle at STS-61

In order to increase the LFBB design confidence (i.e., cost-effectively reduce initial flight risks), several T&V recommendations are made, the most noteworthy being the implementation of an LFBB subsonic, horizontal flight test program, using a protoflight unit.

10.2 Test and Verification Purpose

The purpose of the LFBB test and verification program is to establish sufficient confidence in the LFBB, at an acceptable cost and risk, to replace the current RSRMs. To the extent that the Shuttle-configured LFBB will also follow a growth path to other missions, the T&V program serves as a foundation for that capability as well.

10.3 Test and Verification Background

The NASCOM-DB tool was used during the LFBB study for the cost estimating, indexing and accounting process. NASCOM-DB uses a work breakdown structure (WBS) for the new project. Within this WBS, project prime hardware and software are delineated, along with project overhead referred to as "Prime Wraps." The Prime Wraps for the LFBB Project include T&V activity as: "Unit Test Hardware," "Integration, Assembly and Checkout," and "System Test Operations." The T&V-portion Wraps are defined by top-level WBS dictionary definitions for each of these items (see Appendix E). Additionally, the Project WBS shows potential new labs and test facilities under "Program Support." It is possible, then, to cover basic Project T&V (i.e., generic T&V baseline) in the Pre-Phase A timeframe, working from the cost tool definitions and the WBS.

The NASCOM-DB cost estimating methodology uses LFBB hardware weight and SLOC estimates at the subsystem level as the independent variables in mathematical cost estimating relationships. The WBS Prime Wraps are predefined percentages of the Prime HW/SW-subsystem estimated costs, based on U.S. space programs' historical cost data analyzed and preserved within the NASCOM-DB. This includes the Apollo and Shuttle Programs' cost and weight experience. Given a reasonable assumption that the LFBB is a new project not having to execute under "adverse" program conditions or limitations, the T&V-constituent estimates can be calculated at the integrated system level and used as Pre-Phase A foundation values.

The T&V Assessment, covered by this report, started with the above premise that the NASCOM model provides nominal allowances for development, qualification, and acceptance T&V from the lowest component part up through the integrated vehicle level. In other words, NASCOM makes a reasonable "T&V activity envelope" projection using the historical space programs in the database. This assessment attempted to identify those testing requirements that would logically revise (extend or contract) the estimated LFBB T&V envelope.

10.4 Assessment Plan of Action

A three-step approach was followed for this assessment:

A. A defined list of LFBB subsystem and technical discipline personnel were queried through a succession of meetings as to what individual testing would be required to reduce LFBB programmatic risk, i.e., most likely achieve the T&V program purpose.

B. After individual projections from the subsystem and discipline leads were made, these inputs were integrated to ascertain the possibility for testing combinations. Flight demonstration testing was to be considered when justified by the integrated test requirements.

C. Testing requirements were documented. Cost model deltas for additional or reduced testing requirements were made, if necessary, within the overall model T&V estimates.

In order to fit within the overall LFBB study cost estimating process, certain assumptions were made in the T&V assessment approach:

1. The testing requirements and costing adjustments concentrated primarily on the integrated vehicle level of testing. Subsystem-level and below testing requirements are satisfied (costed) in the cost estimating model. However, LFBB subsystem testing could be expanded if the technology readiness or other justifying factors warranted additional testing.
2. Testing objectives and justification took into account the fact that risk to the Shuttle stack must be very low during the ascent phase and is less critical (from a manned flight safety perspective only) after booster separation.
3. Flight demonstration testing should be considered when the flight test provides essential or otherwise unobtainable design confidence, or reflected a net cost benefit over multiple system ground tests.
4. Protoflight testing is the current LFBB Program baseline.
5. The LFBB system is required to achieve RSRM mission success and crew safety levels.

10.5 Assessments

INTEGRATED AVIONICS SUBSYSTEM
The Integrated Avionics Subsystem, encompassing the DMS, GN&C, C&T, Software, and Instrumentation Subsystems, anticipates no extraordinary testing requirements beyond that inherent in the Shuttle Avionics experience. Thus, the LFBB testing requirements are assumed to be covered within the T&V baseline cost model projections. A major Avionics-to-Main Propulsion Subsystems interface test is defined and assumed to be a synergistic part of the Main Propulsion Subsystem testing. (see Appendix F.1)

ELECTRICAL POWER SUBSYSTEM
THE LFBB Electrical Power Subsystem (EPS) anticipates no extraordinary testing requirements beyond baseline T&V, i.e., within previous programs' experiences.

An aspect of EPS/Avionics verification testing—EMA Testing and Certification—warrants special attention. This testing, to certify the integrated aerosurface EMAs and the power supply and distribution systems, is predicated on the reactivation and modification of the government-owned Flight Control Hydraulics Lab at Rockwell Downey. This facility is currently scheduled to be excessed by the end of FY 94. If the LFBB Program continues, the Level II Orbiter Office should be requested to retain this facility in order to hold down EPS T&V costs. (see Appendix F.2)

MAIN PROPULSION SUBSYSTEM

The LFBB Main Propulsion Subsystem will conduct three classes of testing: cold flow tests, terminal drain tests, and full Main Propulsion Subsystem "hot firing" tests. This testing represents a minimum program that is considerably less than either the Saturn or Shuttle experiences. This testing, considered to be within the T&V baseline, has the potential for some synergism with Integrated Avionics interface and Engine/Structure Stability (POGO) testing. (see Appendix F.3)

REACTION CONTROL SUBSYSTEM

The LFBB RCS is considered to be within the T&V baseline. The RCS will be certified using component-level verification methods and subsystem ground hot firing tests. If any proposed LFBB flight test covered the separation and initial return phase with some fidelity, the RCS would benefit from such a test. However, the RCS alone does not provide a significant justification for such a flight test. (see Appendix F.4)

AIR-BREATHING PROPULSION SUBSYSTEM

The LFBB ABE will experience "non-standard" vibration, pressure and temperature environments relative to the flight environment for a commercial transport aircraft. It is expected that substantial development and testing resources will be required to modify an off-the-shelf ABE for the LFBB liftoff, ascent, and reentry environments, with particular concern noted for the bearings and the lubrication system.

Two additional verification tests have been proposed: 1) an airstart functionality test and 2) an installed engine performance flight test. Airstart testing could be performed using an existing aircraft platform such as the Shuttle Carrier Aircraft (SCA) to verify airstart functionality, including inlet fairing deployment, spin-up of the rotating machinery, and engine ignition. Verification of the installed ABE performance, including available thrust and fuel consumption at cruise and loiter conditions, could be performed during the recommended LFBB subsonic full-scale flight demonstration tests.
(see Appendix F.5)

SEPARATION PROPULSION SUBSYSTEM

The LFBB Separation Propulsion Subsystem is considered to be well within the T&V baseline. The Shuttle RSRM separation subsystem is flight-proven, with propulsion motors essentially off-the-shelf. Thus, this subsystem will apply existing technology to the very maximum extent.

THERMAL PROTECTION SYSTEM

The LFBB TPS T&V requirements are within the overall baseline, relating closely to the Shuttle Orbiter TPS certification process and utilizing the Orbiter flight experience/history. Within the T&V envelope, this subsystem provided rationale and justification for aircraft-based flight testing to develop and demonstrate TPS/Insulation Panel concepts using Dryden aircraft facilities. (see Appendix F.6)

STRUCTURES SUBSYSTEM

The LFBB Structures Subsystem T&V development, qualification, and acceptance test requirements generally are within the T&V baseline envelope, assuming the use of common aerospace materials. However, the extent and duration of the test program is dependent on the testing approach—using a dedicated structural test article versus protoflight and component tests. A dedicated structural test article-based testing approach is strongly advocated by the structures subsystem specialists. (see Appendix F.7)

MECHANICAL SYSTEMS

The Mechanical Systems T&V philosophy is to follow the Shuttle experience of using ground testing to verify system function and flight DTOs to verify operational loads. This approach is complicated somewhat by the use of EMAs, with a partial loss of commonality with the Shuttle subsystems models. This point, along with major mechanical systems unique to the LFBB (wing and canard deployment and fairings jettison) will require significant testing below the LFBB Integrated System level. The subsystem cost estimates should, however, cover the projected test requirements. (see Appendix F.8)

LOADS, DYNAMICS, STABILITY
Loads verification is comprised of model verification and predicted loads verification during all LFBB operational ground and flight phases. Within the Dynamics subdiscipline, design and verification are concerned with liftoff, ascent, and early descent acoustics and vibrations. Stability includes the testing for both main engine/structure stability (POGO) (i.e., structure interaction with the booster) and aerodynamics/structure stability (flutter), the structure's interaction with the flight aerodynamic environment. Although extensive, the Loads, Dynamics, and Stability discipline postulates no extraordinary testing requirements, thereby remaining within the Apollo and Shuttle experience base. (see Appendix F.9)

AERODYNAMICS AND AEROTHERMODYNAMICS
The Aerodynamics and Aerothermodynamics technical discipline uses the T&V philosophy that the LFBB is more like an Orbiter than an RSRM configuration. As such, T&V at the integrated vehicle level will need to develop deltas to current technical databases for the ET and the Orbiter and produce new databases for LFBB components. With respect to LFBB reentry, T&V will consider Orbiter testing requirements for the baseline. Implementation of this overall philosophy entails significant wind tunnel testing, along with extensive, but within envelope, integrated launch vehicle, and vehicle reentry testing requirements. (see Appendix F.10)

REENTRY/RETURN PERFORMANCE
The LFBB Reentry/Return Performance discipline does not require any additional testing beyond the subsystems' testing requirements. Instead, the performance predictions will affect the subsystem design. As an example, if wind tunnel testing results in a change to the vehicle aerodynamic model, then the Reentry/Return Performance trajectory may also have to be updated. This change in the aerodynamic model may result in a change to the aerodynamic load and heating predictions, which could affect the vehicle structural and thermal protection system designs.

ASCENT/ABORT PERFORMANCE
Ascent and Abort Performance capability for an Shuttle equipped with LFBBs is the product of subsystem capabilities and limitations. As such, the Ascent/Abort Performance discipline will benefit in part or in whole from each of the subsystem and integrated vehicle tests. Ascent/abort performance will be continuously revisited throughout the T&V program of the LFBB. In effect, the Ascent/Abort discipline will be an analytical test performed to ensure that the integrated Shuttle/LFBB vehicle meets its payload delivery and intact abort requirements. No additional testing is envisioned to complete this work.

LFBB FLIGHT TEST REQUIREMENTS
The T&V assessment consensus on flight testing requirements is as follows:

<u>Full-Scale Horizontal Flight Test</u>
Subsonic, horizontal flight testing using the LFBB protoflight vehicle is an integral part of the verification program. This test phase should continue until the system is certified to operate in the KSC landing environment.

Because of the limited air-breathing engine performance, the LFBB will probably be ground launched using a JATO type of launch assist. It initially should be operated in a test environment (i.e. Edwards/ Dryden) using lakebed and long base concrete runways to define the operational flight envelope.

The horizontal flight tests will be used to verify the following:

- Aerodynamic characteristics
- Flight characteristics
- Flight envelope

- Landing gear and landing loads
- Flight control system

The following adjuncts will also be evaluated during the flight testing:

- Flight procedures
- Flight system monitoring and ground control equipment
- Sensor location and instrumentation
- GSE compatibility
- Personnel training

The scope of the flight testing is similar to the Shuttle Approach & Landing Test (ALT) program and will use the ALT data portion of the cost model for developing the overall flight test cost.

Scale Model Flight Test
Scale model flight testing during early Phase B, while a very desirable mid-step between LFBB wind tunnel testing and the full-scale protoflight flight testing, is not required (i.e., not strongly supported by subsystem or discipline testing requirements). However, the total uses for and, thus, the cost effectiveness of this type of testing in developing the LFBB design, should be reviewed further in Phase A T&V planning.

Subsystem Flight Test
LFBB air-breathing propulsion component test and verification in the actual subsonic flight environment has significant merit. However, there are no conclusions made as to specific approaches in its implementation. This area should be considered in Phase A.

Single Booster Vertical Flight Test
The present design community consensus is that the cost of a vertical booster flight test program cannot be justified for the RSRM-replacement mission alone. This covers the ascent, separation, and supersonic return flight regimes. The finding is predicated on an inability to adequately approximate the Shuttle-stack ascent and separation phase interactions from a stand-alone LFBB flight. Additionally, positions can be taken to diminish concerns about a lack of powered flight testing:

A. Benign, conservative flight environmental limits will be advocated for the initial LFBB-integrated stack flights.

B. Analysis and ground testing should give sufficient confidence that the LFBB mission can be successfully met.

C. The load-relief descent phase maneuvers, although intricate, will be well enough understood that actual flight testing of the involved maneuvers is not essential before the LFBB first flight.

However, if a growth version of the LFBB is developed as a recoverable first stage, specific flight testing relative to that program could apply to the Shuttle/RSRM program as well:

- Launch, ascent and early descent acoustics
- Primary propulsion system test (thrust and stability)
- Flutter
- Thermal loads
- Aero loads
- Air-breathing engine exposure to LFBB flight environment (vibration and acoustic loads, pressures, and temperatures) and verification of inlet fairing deployment, airstart, and cruise performance
- Integrated system testing in a representative flight regime from staging to wheels stop

(Note: This activity would be costed outside the RSRM-replacement program development.)

10.6 Test and Verification Conclusions and Recommendations

The following are the top-level conclusions from having conducted the LFBB T&V assessment:

1. The LFBB System, at the integrated vehicle level, does not require verification testing deltas beyond that contained within the Shuttle experience-oriented costing baseline.

   While various LFBB subsystems and technical disciplines indicate the need for extensive testing at or below the subsystem levels of hardware, these testing requirements are also considered to be within the project T&V envelope.

2. A full-scale flight test program in a subsonic, horizontal flight regime is advocated. The activity would be similar to the Shuttle approach and landing test.

3. Insufficient justification exists for single-LFBB-powered flight testing (ascent, separation, and supersonic return regimes), primarily because of the inability to approximate the Shuttle-stack ascent and separation phase interactions.

4. The costs-to-benefits of both subsonic scale-model flight testing and air-breathing propulsion component flight testing are inconclusive. However, the consensus is that these forms of testing should be further examined in Phase A.

5. Given improvements in systems technical analysis (e.g., CFD), the methods and databases already developed within the Shuttle program, and the technology readiness levels factored in the LFBB design, the relative confidence that can be placed in an LFBB for the year 2003 is qualitatively reasoned to be:

   - not quite as good as the knowledge of the Integrated Shuttle Vehicle at STS-61, but,
   - well advanced of where the Shuttle Program was at the time of STS-1.

   In order to increase the LFBB design confidence (i.e., cost-effectively reduce initial flight risks), specific recommendations from the T&V assessment are:

   A. Implement an LFBB subsonic, horizontal flight test program as part of the integrated vehicle verification process, utilizing the Program's protoflight unit. (refer to LFBB Flight Test Requirements, above)

   B. Incorporate a dedicated structural test article in addition to the protoflight unit test hardware, due to the justifiable cause to test structures beyond protoflight-imposed limits. (refer to Structures Subsystem, above)

SECTION 11
GROWTH PATHS

Given the reference LFBB developed for use with the Shuttle, other uses of the booster to launch payloads were investigated. The objective was to define concepts capable of delivering payloads in the 20 Klb to 40 Klb range, as well as growth paths to a heavy-lift launch vehicle (HLLV) concept.

11.1 Growth Path Options

Three different growth paths were defined for the LFBB and are shown in figure 11.1-1 . The first path involves attaching various upper stages from existing expendable launch vehicles to taking a single LFBB designed for the Shuttle. This path could provide a range of payload capabilities, with minimum investment in the development of upper stages. Although the upper stages are still expended, the cost of launching payloads could be reduced since the first stage (the LFBB) is recovered and reused.

The second growth path also involves attaching upper stages to a single LFBB designed for the Shuttle. However, in this case, newly developed upper stages are used. The new stages can be tailored to provide a specific payload capability and make use of the most recent advances in technology. Again, the upper stages would be expendable, but the LFBB would be recovered and reused.

The end of this growth path involves using one or more LFBBs in conjunction with newly developed core and upper stages to provide a heavy lift capability. A single LFBB could be side-mounted to a new core and upper stage, the core stage being a stretched version of the ET with SSME engines attached at the bottom. Greater performance could be achieved by adding a second LFBB to the stack. Another option is a Saturn V derived launch vehicle in which four LFBBs are attached to a core vehicle that would be similar to the Saturn V vehicle used in the Apollo Program.

The third path for LFBB growth involves using the LFBB as the first stage of a fully reusable TSTOvehicle. This option could serve as a test bed for future technologies, and the eventual development of an SSTO vehicle.

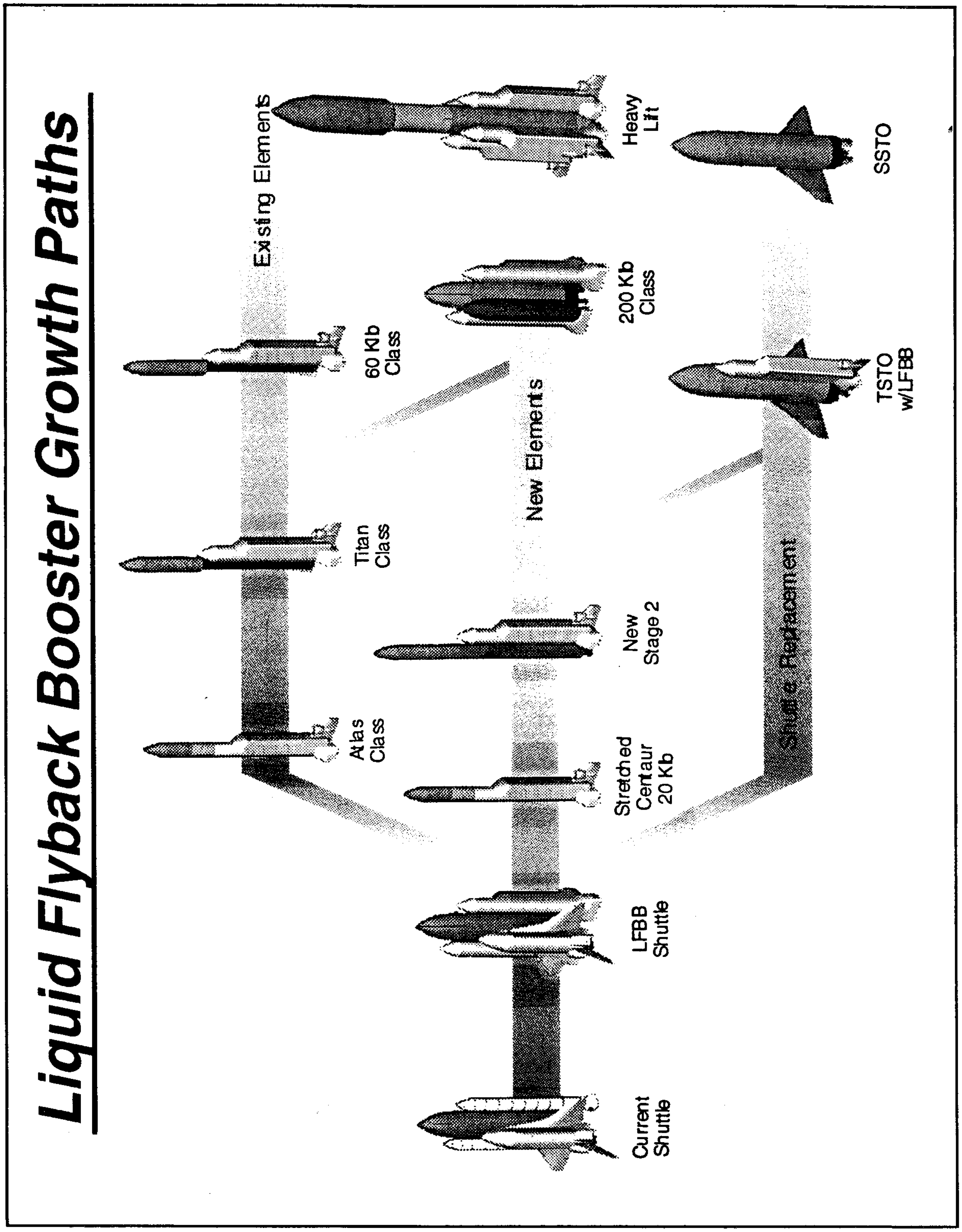

Figure 11.1-1 Growth paths.

11.2 Preliminary Definition and Sizing

Preliminary sizing estimates were completed for the option of using a single LFBB in conjunction with existing upper stages. The upper stages considered included the Centaur and various stages of the Titan IV. The estimated payload delivered as a function of ideal velocity required is shown in figure 11.2-1. A typical ideal delta-V for LEO insertion is 30,000 ft/s. As can be seen, the estimated performance of the LFBB with these upper stages is in the range of 10 Klb to 50 Klb to LEO.

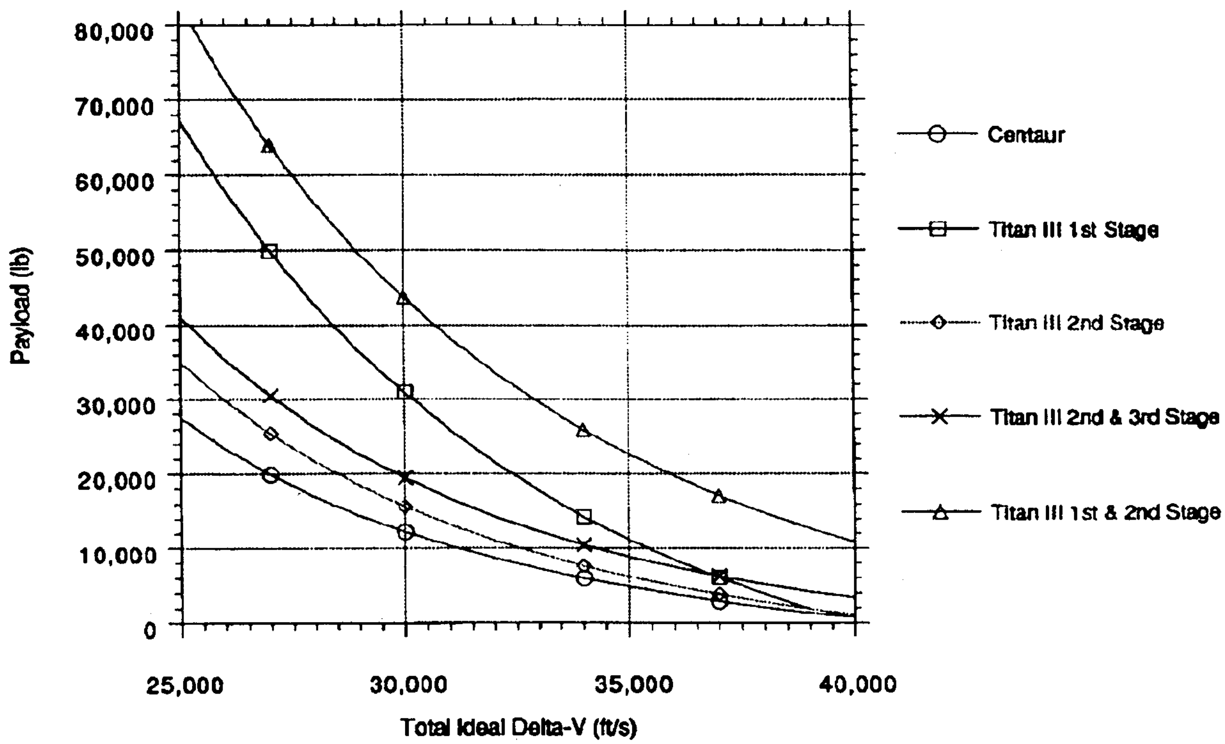

Figure 11.2-1 Estimated payload vs ideal delta-V.

Sizing estimates were also completed for an LFBB with an upper stage sized to maximize payload delivered to LEO. Assuming an ideal delta-V of 30,000 ft/s, the newly developed upper stage would have a propellant mass of 471 Klb, a gross mass of 523 Klb, and deliver 93 Klb of payload.

As the weight of the payload decreases, the LFBB staging velocity, altitude, and range increase. The flyback requirements for the lighter payload classes are, therefore, more demanding than those for the baseline Shuttle mission. Because the LFBB will stage at a higher altitude and velocity, the heating on the vehicle during reentry will be more severe, perhaps requiring a different TPS design than used for the Shuttle mission. Also, because the booster will be farther down range at staging, more air-breathing fuel is required to fly back to the launch site. The LFBB with the Centaur as an upper stage results in the worst case staging conditions. Therefore, this configuration was investigated in further detail to develop ways to avoid the TPS design and flyback range issues.

One way to solve the flyback range problem is to design the LFBB air-breathing propulsion system such that it could use the same RP fuel used for the ascent propulsion. Fuel left in the main RP tank after staging could then be used for the air-breathing engine during the return flight. If this were possible, an appropriate quantity of RP could be off-loaded from the booster such that when staging occurs (at LO_2 depletion), there would be sufficient RP in the tanks to provide air-breathing engine fuel for the return flight to the launch site. A new upper stage could be sized to carry the payload the rest of the way to orbit. Sizing calculations for this case show that 11% of the LO_2 must be off-loaded from the LFBB. After staging, 34 Klb of RP would remain in the tank, which would provide the additional fuel needed for the extended flyback range. An upper stage with a propellant mass of 53 Klb and a gross mass of 68.5 Klb (about 30% larger in gross mass than the Centaur used on the Titan IV) would then be required to deliver a 20-Klb payload to LEO.

An option to solve the flyback range problem and avoid TPS design impacts is to off-load propellant from the LFBB and size an upper stage such that the booster stages at the same velocity it would in the Shuttle case, and the upper stage delivers the 20 Klb to orbit. Sizing calculations showed that the LFBB should be loaded to 50% of its propellant capacity. The upper stage would use a single J-2 engine and would have a propellant mass of 147 Klb and a gross mass of 168 Klb.

A variation of the option just described is to build a scaled-down version of the LFBB that would stage at the same velocity as the Shuttle case, and still deliver 20 Klb to LEO using the upper stage sized from the option above. Sizing calculations show the scaled-down LFBB gross mass to be about 37% of the gross mass of the Shuttle LFBB.

11.3 Trajectory and Performance Analysis

The following assumptions were used in performing ascent performance analyses for the various LFBB growth path options:

Maximum acceleration (1st stage only):	3 g
Maximum dynamic pressure:	900 psf
Lift-off T/W:	$\geq$1.5 but $\leq$2.0
MECO altitude:	100 nmi

Vehicle ascent performance was measured to a 100-nmi circular orbit inclined at 28.5°. The results of the performance analyses are sumarized in table 11.3-1.

Table 11.3-1 Growth Applications Table

	Atlas Class	Titan Class	60 Klbs Class	*90 Klbs Class*	*Shuttle Derived*	Heavy Lift
Stage 2 / Stage 3	"Stretched" Centaur	Titan Stage 1	Titan Stage 1/Centaur	*New Stage required*	*ET derived core*	NLS Core/UpperStage
Gross Mass @ Liftoff	1,450,000	1,780,000	1,860,000	*2,000,000*	*5,000,000*	8,260,000
Thrust @ Liftoff	2,370,000	3,260,000	3,260,000	*3,260,000*	*8,028,000*	14,300,000
T/W @ Liftoff	1.63	1.83	1.75	*1.63*	*1.61*	1.73
Length - ft	199					
Shroud - wt	4,102	8,000	8,000	*14,000*		28,240
diameter	14	17	17	*17*		
length	39	50	50	*86*		
Payload to 100 nm circ. Inclination - 28.5 deg	22,000	41,800	60,200	*90,000*	*200,000*	375,000
Payload to Geosynchronous Inclination - 28.5 deg	5,770	requires kickstage	19,400			117,000(GEO) 149,000 (TLI)

The results from the trajectory analysis verified performance estimates obtained from preliminary sizing estimates. The analysis also shows that these growth path options stage at conditions close to the reference Shuttle case, except for the LFBB with Centaur (20-Klb payload) configuration. The staging conditions for the 20-Klb lift vehicle can be improved by employing the concepts described above (figs. 11.3-1 and 11.3-2).

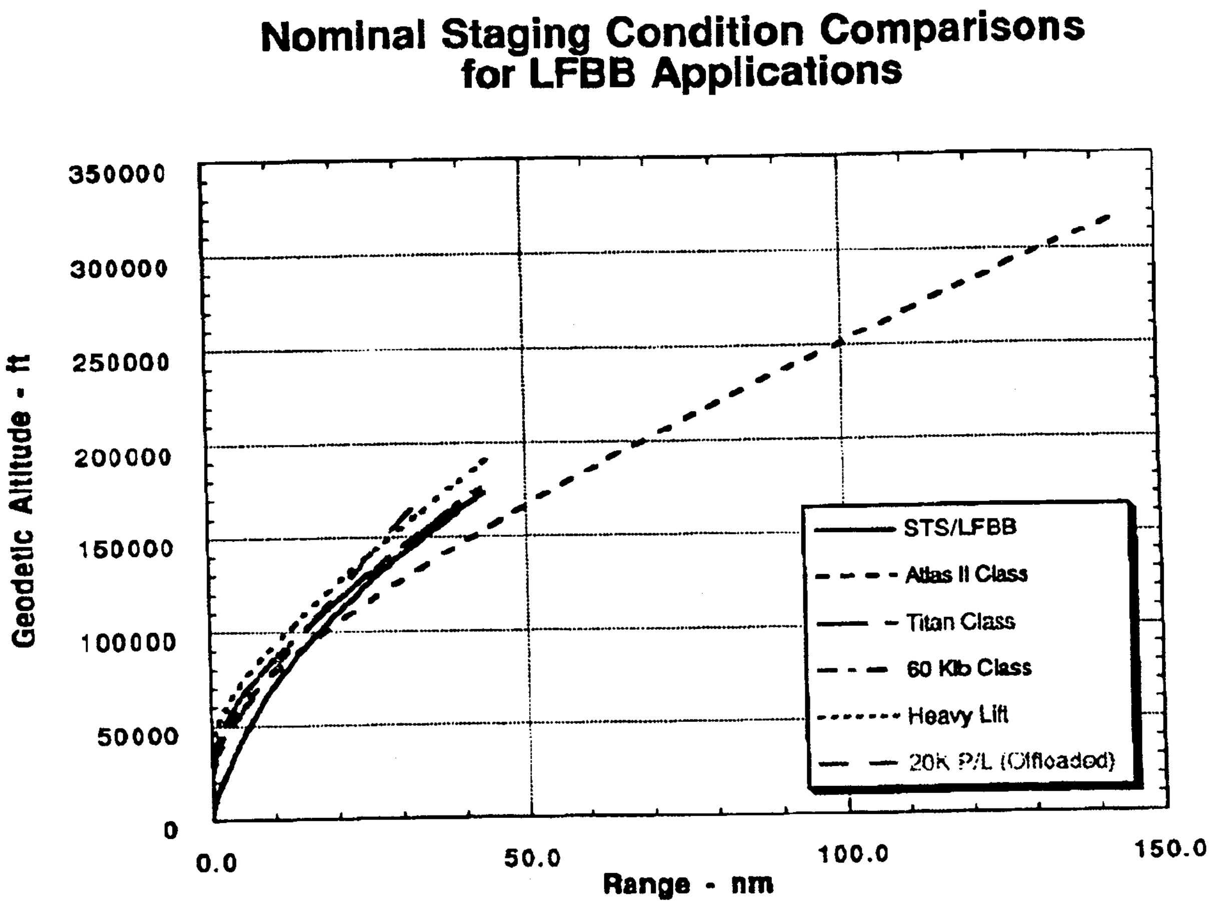

Figure 11.3-1 Altitude vs range for growth path options.

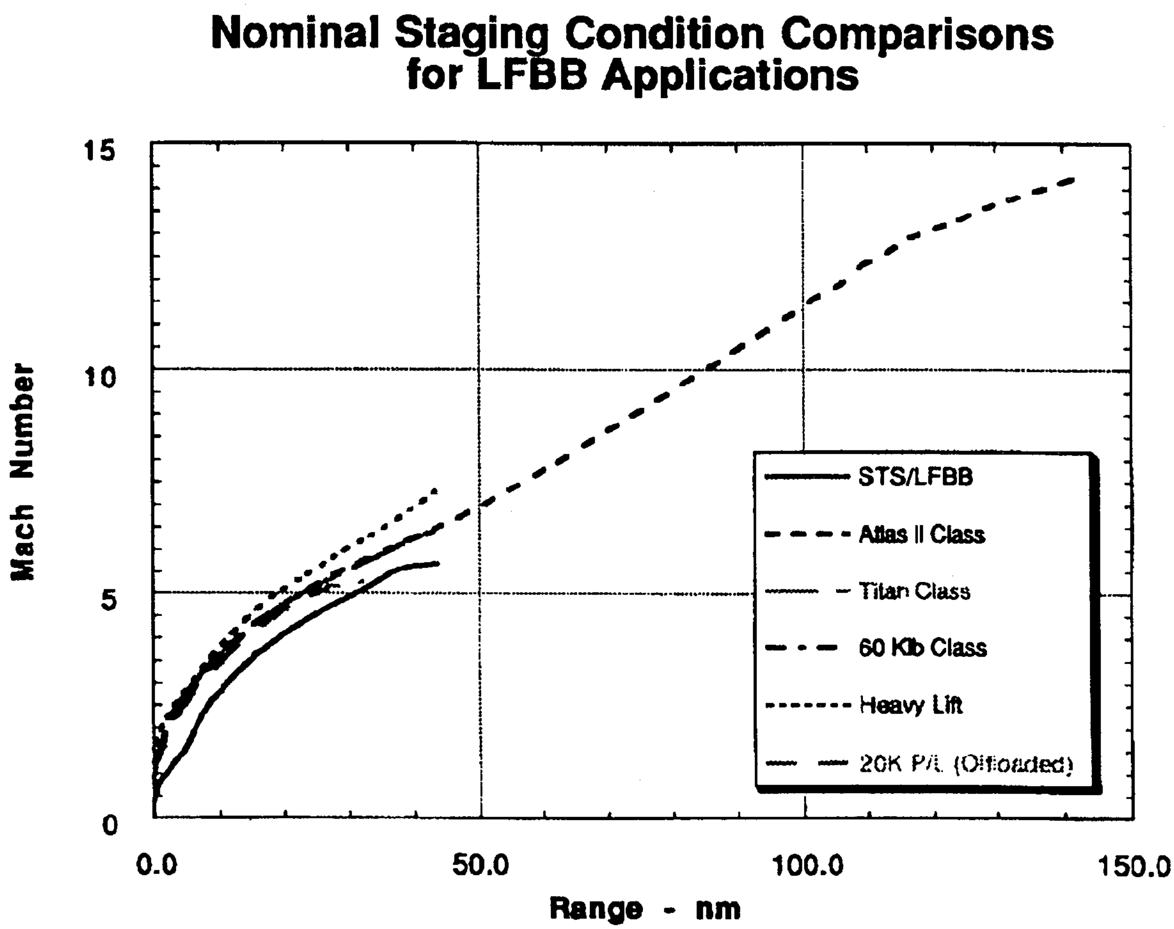

Figure 11.3-2 Mach number vs range for growth path options.

11.4 Summary and Conclusions

The reference LFBB concept shows great potential as a first stage for replacement vehicles in all classes of existing and proposed launch vehicles. The LFBB can also replace expended elements of existing ELVs to reduce payload launch costs for those vehicles.

The smallest payload classes will have more impacts to the reference LFBB design than the larger payload classes. Impacts could include the requirement for the capability to share RP between the LFBB ascent engines and the ABE. The use of a Shuttle Orbiter-style TPS may also be required. The option of varying the LFBB propellant load and using a newly developed upper stage also exists, which would minimize impacts to the reference LFBB design.

The assessment of LFBB growth paths will be expanded in Phase A, including further analysis of the HLLV and TSTO paths. The possibility of a LFBB-derived 1st stage (a scaled LFBB) for new launch vehicles is also a possibility. The development of a set of requirements to fulfill the baseline mission and growth options will continue.

SECTION 12
CONCLUSIONS AND RECOMMENDATIONS

12.1 Results

All of the study objectives discussed in section 1.2 were met in this initial design effort. Annual booster operation costs were reduced from $559M per year for the RSRMs to less than $150M per year for the LFBBs in 1994 dollars. Injection mass to 220 nmi at an inclination of 51.6° has been increased by approximately 56,000 lbs. Capability exceeding the maximum Orbiter payload capacity can be used for RTLS or TAL abort elimination, increased launch probability, increased launch window, lower SSME throttle setting, or design margins.

The LFBB provides abort options where none currently exist, greatly enhancing crew safety. Engine-out capability is achieved with the RD-180 engines. RTLS and TAL aborts are available off the pad. Because PTM is available at tower clear, LFBBs offer the potential for increased probability of mission success relative to the RSRMs.

Promising growth paths for future transportation systems have also been identified. The growth paths can utilize existing expendable stages, build new stage elements, or utilize the LFBB in a fully reusable TSTO program. Heavy-lift and 20-Klb options are being assessed.

LFBBs also provide additional benefits. Space station replacement modules can be transported with the additional performance available. Development of a reusable insulated cryogenic tankage system benefits future launch systems. The LFBB's low toxicity propulsion system benefits future launch systems and possibly Shuttle. Day-of-launch ground support and software maintenance levels are reduced by utilizing adaptive first-stage guidance.

12.2 Conclusions

The LFBB Phase I study has concluded that an LFBB is feasible and offers significant benefits to the Shuttle Program. Cost and schedule risks are reasonable and minimal new technology requirements exist. Savings in Shuttle booster recurring costs can be realized. LFBBs offer increased performance and abort capability. Growth paths from the Shuttle application exist and can take advantage of shared development.

12.3 Recommendation

Based on results of the Phase I study, a follow-on effort is warranted leading to a Non-Advocate Review in the May 1995 time period. A recommendation is made to continue LFBB definition in an in-house Phase A study that would involve JSC, KSC, and MSFC. Civil service personnel will be utilized to the maximum extent possible.

The Phase A study objectives are to refine the reference concept with a specific goal of reducing up-front costs, developing alternate concepts precluded in Phase I due to time and resources, performing more detailed assessments of the growth options and architecture implications, and re-examining key technical issues. These issues include, but are not limited to, the RD-180 engine, GO_2/RP RCS, cryogenic tankage and insulation, aerodynamics and aerothermodynamics, stack interactions and impacts, hold-down mechanism, lift-off dynamics, separation sequence, and air-breathing engine impacts.

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APPENDIX A - ISSUES LIST

LFBB Issues List

ID#	Issues
1.0	**Programmatics**
1.01	What test and verification procedures are required to certify a FBB (inc. flight test)?
1.02	Baseline propellant class (liquid versus solid)
1.03	Baseline liquid propellant type (LO2/RP-1)
1.04	Minimum fault tolerance
1.05	Subsystem Maturity Level
1.06	Type of FBB landing site (land versus water)
1.07	What happens to the FBBs after a first stage abort?
1.08	Is a RTLS abort preferred over a TAL abort?
1.09	Should excess FBB performance be used to eliminate TAL as an intact abort option?
1.10	Design systems for maximum compatibility with the Shuttle (@2000) or new technology?
1.11	What is the transition period between the use of the current SRBs and the FBBs? (maintain the required flight rate of 8 flts/year?)
1.12	What is the fleet size of the LFBBs? (How many flight sets?)
1.13	How does the FBB schedule coincide with the Space Station schedule?
1.14	What is the projected program start date?
1.15	What is the projected first flight date?
2.0	**Safety/Reliability/Risk**
2.01	FBB safety and reliability comparison to current SRB
2.02	Should a Range Safety System be incorporated into FBBs?
2.03	FBB subsystem fault tolerance for ascent phase
2.04	FBB subsystem fault tolerance for the post-separation phase
2.05	Reliability of air-breathing engines in FBB flight environment?
2.06	Restrictions on flying over populated areas during flyback?
2.07	Effects on overall STS launch probability
3.0	**Ascent/Abort Performance**
3.01	Maximum allowable dynamic pressure during ascent
3.02	Should excess FBB performance be used to reduce ascent loads by reducing nominal dynamic pressure (q) below the max allowable?
3.03	Should excess FBB performance be used to reduce q-alpha below current levels?
3.04	What is the minimum allowable liftoff thrust-to-weight ratio (T/W) for the STS/FBB configuration?
3.05	Minimum allowable SSME power level (throttle setting) from startup through liftoff
3.06	What is the SSME throttle profile?
3.07	What are the nominal staging conditions for the FBBs? (time, velocity, altitude, q)
3.08	Main Engine Type (RD-170 versus F-1A)
3.09	Type of FBB main engine throttling (continuous versus step)
3.10	Range of FBB main engine throttling required (percent)
3.11	Number of main engines per FBB
3.12	What are the TAL abort constraints?
3.13	What performance is required to eliminate TAL?
3.14	Quantify the abort timeline of the FBB
3.15	Relationship of booster diameter, length, liftoff T/W and max q to STS injected mass performance
3.16	Performance of single-engine booster configurations (F-1A & RD-170)
3.17	Performance of dual-engine booster configurations (F-1A & RD-170)
3.18	F-1A thrust level, throttling capability and gimbal limits
3.19	RD-170 thrust level, throttling capability and gimbal limits
3.20	What is the impact of an early FBB engine shutdown on the return trajectories of the FBB and the Orbiters?
3.21	Should excess FBB performance be used to reduce the maximum SSME throttle setting? (SSME reliability as a function of throttle setting)

3.22 Should we use excess performance to eliminate the early throttle-down of the SSMEs? (Impacts of eliminating early SSME throttling during ascent)
3.23 What ascent constraints have been selected for this study and what trades can be made?
3.24 What is the performance sensitivity to changing staging conditions (flight-path-angle, velocity, altitude)
3.25 What are the capabilities of 4 RD-180s per booster?
3.26 What max-q are we going to design for during ascent?

4.0 Reentry/Flyback Performance

4.01 Turnaround Maneuver (powered versus aerodynamic)
4.02 Powered cruise vs. gliding return (rocket, air-breathing, gliding)
4.03 Can the boosters land with a 20 knot tailwind? What are the crosswind limits? Do winds drive you to an alternate runway?
4.04 What are the pitch, roll and yaw rates experienced in the LFBB trajectory and how are they accommodated by the LFBB?

5.0 Booster Configuration

5.01 FBB fuel and oxidizer tankage location and separation
5.02 FBB wing geometry constraints related to physical factors (clearances)
5.03 Disposable forward tank section reduces landing mass & eliminates the reusable cryogenic tank
5.04 Active FBB wing angle of incidence control
5.05 Booster Fineness Ratio (diameter and length)
5.06 Integration of the wing with the FBB external moldline
5.07 Integration of the pitch control device with the FBB external moldline
5.08 Integration of the yaw control device with the FBB external moldline
5.09 Integration of the air-breathing engines with the FBB external moldline
5.10 Type of thermal control (active versus passive)
5.11 Integration of the main landing gear with the FBB external moldline
5.12 Integration of the nose landing gear with the FBB external moldline
5.13 Air induction control for the air-breathing engine during ascent (none, covered cowl or duct, deployable duct, etc.)
5.14 Ascent Engine Orientation (parallel or perpendicular to the Orbiter wings)?
5.15 Are left and right LFBBs unique?

6.0 Aerodynamics

Lift Device

6.01 Class of lift device: none, ring wing, standard wing, parafoil, parawing, etc.
6.02 Ring-wing effectiveness at high angles of attack?
6.03 Type of lift device: fixed versus deployed
6.04 Subtype of deployed wing: folded, scissor, swing, inflatable/rigidized, etc.
6.05 Airfoil selected for lift device (symmetric versus cambered)
6.06 Landing CL vs. wing size
6.07 Landing CL vs. aspect ratio
6.08 Wing location/orientation relative to booster fuselage
6.09 Wing location/orientation relative to STS stack
6.10 Wing planform (span, chord, taper, sweep)
6.11 Wing deployment strategy (if applicable)
6.12 Geometry of wing-mounted control surfaces

Yaw Control

6.13 Class of yaw control device: none, winglets, single rudder, etc.
6.14 Type of yaw control device: fixed versus deployed
6.15 Airfoil selected for yaw control device (symmetric versus cambered)
6.16 Lateral-directional stability during reentry and flyback vs. beta and Mach (stable, neutral, unstable)
6.17 Yaw control device location/orientation relative to booster fuselage

6.18 Yaw control device location/orientation relative to STS stack
6.19 Yaw control device planform (height, chord, taper, sweep, tail volume)
6.20 Yaw control device deployment strategy (if applicable)
6.21 Geometry of yaw control surfaces

Pitch Control

6.22 Class of pitch control device: none, canards, horizontal tail, V-tail, etc.
6.23 Type of pitch control device: fixed versus deployed
6.24 Subtype of deployed pitch control device: folded, scissor, bayonet, etc.
6.25 Airfoil selected for pitch control device (symmetric versus cambered)
6.26 Pitch stability during reentry and flyback vs. alpha and Mach (stable, neutral, unstable)
6.27 Pitch control device location/orientation relative to booster fuselage
6.28 Pitch control device location/orientation relative to STS stack
6.29 Pitch control device planform (span, chord, taper, sweep)
6.30 Pitch control device deployment (if applicable)
6.31 Control strategy for pitch control device ("full flying" vs. control surface)
6.32 Geometry of actuated pitch control surface (if applicable)

General Aero Issues

6.33 FBB ascent interference effects on ET and Orbiter
- FBB length, diameter and nosecone geometry
- FBB moldline smoothness (external protuberances)

6.34 FBB aerodynamic performance coefficients (CL & CD) versus alpha and Mach
6.35 Dispersions on aerodynamic coefficient estimates
6.36 Minimum glide slope angle
6.37 Yaw excursion limits on the Orbiter's vertical tail (due to FBB engine-out?)
6.38 Will a landing flare be used for the FBB?
6.39 Design landing angle of attack for the FBB
6.40 Design landing speed for the FBB
6.41 Consider bending loads on forward booster attach structure due to lift from wings
6.42 Size control surfaces and hinge moments.
6.43 All moving canard vs. canard with control surface.
6.44 What is the sweep angle required to eliminate supersonic snap roll?

7.0 Aerothermodynamics

7.01 What are the aerothermal environments (heating rate and peak temperatures) for the predicted range of FBB separation states? (Mach 4.0 to 6.0)
7.02 How will the FBB impact the ascent aerothermal environment of the STS?
7.03 Entry heating environment of LFBB.
7.04 1 ft Reference Heating (Cold Wall and Hot Wall)

8.0 Structures/Landing Gear

8.01 Rebound loads resulting from a LFBB engine shutdown on the pad
8.02 Loads on the ET resulting from a FBB engine shutdown in flight
8.03 Booster axial stiffness (less stiff than RSRB, equal stiffness to RSRB)
- What is the stiffness of the filament wound cases proposed for Shuttle
- What stiffness was chosen in previous LRB studies

8.04 Load Factor - Maximum
8.05 FBB structural and tankage materials selection (Al, Al-Li, Ti, etc.)
- materials limits (heating and loading environments)
- material durability/toughness (fatigue, stress corrosion cracking, etc.)
- material compatibility (oxidizer, fuel, pressurant, etc.)

8.06 Type of main and nose landing gear (skids vs. tires)
8.07 Main and nose landing gear design
8.08 Maximum landing angle of attack (tailscrape angle including attenuation stroke, flat tires, etc.)
8.09 Nosecone geometry (cone, biconic, ogive, etc.)
8.10 TPS/Structure Combination
8.11 Quantify the inspection requirements for reusable cryogenic tankage

8.12 What cryogenic tank inspection methods are available that will satisfy the req'ts and promote quick turnaround (NDE techniques, physical inspection, pressure test)
8.13 What cryogenic tank design safety factor should be used?
8.14 What is the maximum ullage pressure seen in the FBB main propellant tanks?
8.15 LO2 tank will shrink on the order of 1 ft during propellant loading. How does the structure accommodate this?
8.16 What structure is required on the upper surface of the LFBB?

9.0 Thermal Protection

9.01 How can we avoid the use of external TPS?
9.02 If external TPS is required, how can we facilitate ground operations (inspections, etc.) to achieve quick turnaround?
9.03 If external TPS is required, can we fly (FBB return cruise) in adverse weather conditions without incurring costly TPS damage?
9.04 Actual/fabrication limits, installation requirements for minimum TPS thickness.
9.05 Fabrication/installation/servicing of insulation required to prevent ice buildup on cryogenic tanks
9.06 Cost, schedule, certification of advanced TPS (AETB-8, CFBI, etc.)
9.07 TPS materials suitable for FBB mission
9.08 Reusability of TPS (installation, inspection, maintainability, durability)

10.0 Ascent Propulsion

10.01 Main propulsion system design
10.02 FBB ascent propellant depletion procedure (fuel versus oxidizer depletion)
10.03 Should the residual FBB ascent propellant be dumped?
10.04 Hydrocarbon fuel specifications for the F-1A engine
10.05 Hydrocarbon fuel specifications for the RD-170 engine
10.06 Modern specifications for a hydrocarbon fuel (RP-1)
10.07 Fuel commonality (MPS, RCS, air-breathing engine)
10.08 Oxidizer commonality (MPS, RCS)
10.09 Separate tanks for ascent/RCS/ABE propellant
10.10 Propellant slosh damping and natural frequency
10.11 F-1A and RD-170 operability, maintainability, serviceability
10.12 Does the system require a POGO suppression system
10.11 Determine replacement ascent engine credit by using parts count or some other method.
10.12 Do engine purges use missile grade air or GN2?
10.13 Engine startup sequence and thrust levels
10.14 What is the procedure for landing with LO2 and venting?

11.0 Separation Propulsion

11.01 What is the booster separation mode if initiated prior to FBB burnout?
11.02 Separation motor propellant (solid / liquid)
11.03 Sizing (thrust, duration) of FBB separation motors

12.0 RCS Propulsion

12.01 Liquid RCS propellant options (MMH/NTO, LO2/RP-1, etc.)
12.02 Fuel commonality (MPS, RCS, air-breathing engine)
12.03 Oxidizer commonality (MPS, RCS)
12.04 RCS thruster location(s)
12.05 Estimated RCS propellant requirement (mass)
12.06 Estimated RCS thrust level requirements
12.07 What are the specifics of implementing LO2/HC for Orbiter OMS/RCS?

13.0 Power

13.01 Identify supported functions for each mission phase
13.02 Identify integral power sources (e.g. main engine thrust vector control)
13.03 Power source (trade to achieve desired power density and energy density)

13.04 System redundancy requirements during ascent and decent
13.05 Definition of power system components
-source (battery, fuel cell...)
-distribution and control (switching, cable...)
-loads (busses and end users)
13.06 How much Orbiter electrical power is supplied to the boosters during pre-launch & ascent?
13.07 Can the jet engine be used as a primary power source during flyback?
13.08 Will the jet engine supply electrical and/or hydraulic power?

14.0 Actuation
14.01 Method of Mechanical Actuation

15.0 GN&C
15.01 RD 170 uses single or dual port electro hyd. actuator. May not be adequately redundant
15.02 Eight actuators to control for each RD-170 engine
15.03 Orbiter/Booster Command Interface-Are Orbiter avionics and software affected by the FBB or does a new interface box translate all Orbiter commands?
15.04 What is the booster guidance (adaptive, force feedback?)

16.0 Data Management
16.01 Rocket Engine Controller Reqt. (HW & SW). Who is Responsible?
16.02 GN&C Integrated Flight Management Unit (IFMU) Fault Tolerance
16.03 STS FSW impacts due to the FBB
16.04 Definition of the DMS
16.05 What Orbiter software mods are required to be able to shutdown a booster engine?
16.06 Document Orbiter avionics hardware changes.

17.0 Tracking & Communications
17.01 Use GPS or MSBLS? (trade)
17.02 If GPS, then either DGPS or Pseudolite (trade)
17.03 If MSBLS, then either SLF or other landing site (trade)
17.04 Antenna coverage analysis is required to determine placement locations (trajectory information rqd)
- Can MILA/BDA/PDL support 3 vehicles at the same time?
- TDRS versus ground stations versus handoff (trade)
17.05 Data rate requirements - may drive the system design.
17.06 Redundancy consideration-independent strings vs. cross-strapping (size/wt/pwr vs. reliability)
17.07 Radio Frequency Interference (RFI) environment characterization - how will this affect the coverage? and what can be done to minimize the effects? what about multipath effects to acquisition (false lock considerations)?
17.08 Is 2-way comm required? Operational cost needs to be considered.

18.0 Reserved

19.0 Air-breathing Engines (ABEs)
19.01 Operational regime for the ABEs (trade supersonic vs. subsonic)
19.02 If subsonic, what type of ABE (trade turbojet vs. turbofan)
19.03 Number of air-breathing engines (trade)
19.04 Thrust per air-breathing engine (maximum sea level thrust)
19.05 Design cruise altitude (trade)
19.06 Design cruise range
- downrange (based upon LFBB separation state) plus dispersions
- winds
- redesignation of landing site
- cruise margin for unpredicted events
19.07 Design cruise endurance

- loiter time (go-around capability in a standard flight pattern)
- loiter margin for unpredicted events+B253+B251

19.08 Air-breathing engine environment (pressurized versus non-pressurized)
19.09 Air-breathing engine configuration (deployed versus fixed)
19.10 Air-breathing engine location (external versus internal)
19.11 Mass of air-breathing system
19.12 Constraints on ignition conditions for an air-breathing engine
19.13 External support needed to assist in an air-start of air-breathing engine
19.14 Use of air-breathing engine TVC for trim control?
19.15 Can air-breathing engine be fueled by main RP tank using an air-breather sump for fuel flow?
19.16 Separate or integrated ABE fuel tanks?
19.17 Number and size of ABE fuel tanks
19.18 Air-breathing takeoff capability
19.19 Is the air-breathing engine airstarted or electrically started?
19.20 Is ABE airstart part of commercial acceptance testing?

20.0 Flight Operations

Booster operation strategy

20.01 Nominal ascent operations
20.02 Nominal flyback, approach and landing for two boosters
20.03 Post-landing operations strategy (taxi capability, etc.)
20.04 What are the booster separation constraints (alpha, beta, q, thrust, etc.)
20.05 What happens to the aft ET/Booster attach links after separation?
20.06 Can the LFBB be towed on its landing gear?
20.07 Booster/Engine startup (do all engines need to be operating nominally before the hold down bolts are released?)
20.08 Flyback Control Strategy (autonomous, RPV, limited reconfig)
20.09 How do LFBBs interact with other aircraft in flight (i.e. helicopters, STA FAA aircraft)?

21.0 Ground Operations

21.01 Primary land landing site trade (SLF, Skid Strip, Patrick AFB, new strip)
21.02 Alternate land landing site
21.03 What is the propellant loading sequence and location?
21.04 What is the minimum turnaround after a launch scrub?
21.05 What are the present Shuttle procedures and constraints that the LFBBs must operate within?
21.06 What is the KSC position on landing with LO2?
21.07 Identify what gases are considered hazardous.
21.08 What are the savings associated with eliminating hypergols including LCC of shutting down the HMF?
21.09 KSC needs more info on RD-170 maintenance.
21.10 LFBBs towed on gear or transporter, road bearing strength, and tire design. Can the booster be towed on beach road?

22.0 Facilities/GSE

22.01 What are the costs associated with pad, VAB, and MLP (KSC facilities)?
22.02 Tower clearance constraints
22.03 Maximum booster length/diameter constraints related to VAB physical limits
22.04 Maximum booster length/diameter related to launch pad constraints
22.05 Mobile Launch Platform (MLP)
22.02 What is the clearance between the LFBB aft skirt and the launch tower if no drift is assumed?
22.06 Develop hold-down post design and recommend appropriate cost model.

23.0 Orbiter Modifications

23.01 Identify the modifications required on the Orbiter
23.02 What are the costs associated with the Orbiter mods?

24.0 ET Modifications

24.01 Identify the modifications required on the ET
24.02 What are the costs associated with the ET mods?

25.0 Software mods

26.0 Vehicle Health Management

26.01 Level of VHM? (trade)
26.02 Architecture of VHM? (trade)
26.03 VHM Recording/Telemetry Requirements
26.04 Manual override capability?
26.05 What are the VHM requirements for each system? (TPS, Structure, Avionics, RCS, etc.)
26.06 What are the goals, operational issues, and issue/trades associated with VHM?

APPENDIX B - ISSUES RATIONALE STATEMENTS

1.0 Programmatics

1.1 What test and verification procedures are required to certify a LFBB (inc. flight test)? Zetka/Tuntland

Rationale: Subsystem level testing would be per the experience base with Shuttle and previous NASA programs. A protoflight unit will be used for vehicle level testing along with a dedicated structural test article. Confidence in the LFBB system in the year 2003 due to existing databases, improvements in technical analysis (e.g., CFD), and the LFBB technology readiness levels is qualitatively reasoned to be well advanced of where the Shuttle Program was at the time of STS-1, but not quite as good as the knowledge of the integrated Shuttle vehicle at STS-61.

A full-scale flight test program in a subsonic, horizontal flight regime is advocated. Auxiliary propulsion (e.g., JATO rockets) will be used for LFBB horizontal take-off. Ascent phase powered flight test is not recommended due to the fact that the Shuttle ascent environment would be impossible to replicate. Benign, conservative flight environmental limits will be advocated for the initial LFBB-integrated stack flights. Analysis and ground testing should provide sufficient confidence and testing of the load-relief, post-separation descent phase maneuvers are not required.

1.2 Baseline propellant class (liquid versus solid) Peterson

Rationale: Liquid propellant has more potential for a quick turnaround at the launch site. KSC does not have the capability to pour solids on-site and disassembly of the vehicle for remote processing was not seen as a viable concept. Liquids were groundruled over solids and hybrids at study initiation.

1.3 Baseline liquid propellant type (LO_2/RP-1) Peterson

Rationale: LO_2/RP-1 was selected at study initiation due to the availability of engines. An engine with a high thrust rating is required and F-1As and RD-170s were seen as the only viable engine candidates due to their near term availability.

1.4 Minimum fault tolerance Peterson

Rationale: The minimum fault tolerance for booster systems is single fault tolerant with the exception of structure, TPS, air-breathing engine, and ascent engines and propellant tanks. Booster avionics and power system were chosen to be two fault tolerant.

1.5 Subsystem Maturity Level Peterson

Rationale: A technology readiness level of 6 by 1998 was selected as the minimum maturity level for each system.

1.6 Type of FBB landing site (land versus water) Peterson

Rationale: Autonomous land landing on a runway at or near the launch site was selected as a study requirement.

1.7 What happens to the FBBs after a first stage abort? Templin

Rationale: The Orbiter always has priority to return to the SLF after a first stage abort. If a booster engine is lost between T+TBD seconds and T+74 seconds, an intact abort will be attempted. If an RTLS is attempted, the Orbiter will return to the SLF and the boosters will recover at a separate runway. If a booster engine is lost between liftoff and T+TDB seconds, a contingency abort may be attempted. If possible, the Orbiter will be separated from the stack and a bailout would be attempted. During contingency aborts, the Orbiter and Boosters would be ditched or destroyed.

1.8 Is an RTLS abort preferred over a TAL abort? Peterson

Rationale: This decision was viewed as being out of the scope of this study. It is an operational decision. Results from this study have shown that elimination of TAL aborts can be done with the available performance and shaping of the ascent trajectory.

1.9 Should excess FBB performance be used to eliminate TAL as an intact abort option? Peterson

Rationale: Yes. The performance capability of the selected booster design offers this capability which in turn can reduce the operational costs associated with TAL aborts.

1.10 Design systems for maximum compatibility with the Shuttle (@2000) or new technology? Peterson

Rationale: A technology readiness level of 6 by 1998 was selected as a system maturity guideline. New technologies should be addressed in order for an operationally efficient system to migrate onto the Orbiter.

1.11 What is the transition period between the use of the current SRBs and the FBBs? (maintain the required flight rate of 8 flts/year?) Feaster

Rationale: The transition period from RSRMs and LFBBs will take approximately 8 years due to the requirement to maintain a flight rate of 8 per year. The flight rate of 8 per year will be reduced to 7 for three years during the transition period due to facility modification constraints. The RSRMs will not be phased out until 2008.

1.12 What is the fleet size of the LFBBs? (How many flight sets?) Feaster

Rationale: Per discussion at the Configuration Review at JSC on February 16 - 17, 1994 and recorded in the Action Items list from that review under "The Baselined LFBB Study Assumptions" #4, 8 flight vehicles will be costed.

1.13 How does the FBB schedule coincide with the Space Station schedule? Peterson

Rationale: Study Assumption - The LFBBs will not affect the Space Station schedule.

1.14 What is the projected program start date? Peterson

Rationale: Study Assumption - Begin Phase B in 1997 and Phase C/D in 1998.

1.15 What is the projected first flight date? Peterson

Rationale: Study Assumption - The IOC date is 2003.

2.0 Safety/Reliability/Risk

2.1 FBB safety and reliability comparison to current SRB Valentine

Rationale: The LFBB with two RD-170s per booster would offer equal or better probability for mission success than RSRMs. It would offer abort capabilities where none currently exist. An LFBB with four RD-180s would offer a greater probability of mission success than the RSRM or RD-170 LFBB and proportionally greater probability of abort success. Details in final report.

2.2 Should a Range Safety System be incorporated into FBBs? Peterson

Rationale: Study Assumption - The vehicle will be scarred for thrust termination and destruct.

2.3 FBB subsystem fault tolerance for ascent phase Subsystem Leads

Rationale: The minimum fault tolerance for booster systems is single fault tolerant with the exception of structure, TPS, air-breathing engine, and ascent engines and propellant tanks (see issue 1.4). The avionics and electrical power system have been designed to be two-fault tolerant. The RCS is single-fault tolerant to credible failures.

2.4 FBB subsystem fault tolerance for the post-separation phase Subsystem Leads

Rationale: Same as issue 2.3

2.5 Reliability of air-breathing engines in FBB flight environment? Robertson

Rationale: Open

2.6 Restrictions on flying over populated areas during flyback? Cockrell/Tuntland

Rationale: The approach of flying the LFBBs back to the launch site was to not fly over populated areas. The boosters will fly to a waypoint over the water until a command is uplinked to bring them in for final approach and landing. Runway 15 at the Shuttle Landing Facility is the prime runway and runway 31 at the Cape Canaveral Skid Strip is the alternate. These runways were selected so the boosters would not fly over populated areas or the KSC industrial complex.

2.7 Effects on overall STS launch probability — Vantino

Rationale: Estimation of launch probability for LFBB using current STS definition, defined as probability that day-of-launch winds and atmospheres will not result in excessive vehicle ascent loads, requires configuration-dependent aerodynamics and loads models, which are not available at this point in the study. It is known that ascent loads are very sensitive to vehicle ascent angle-of-attack and angle-of-sideslip, which for LFBB will probably not be very different from the current STS range of values. Ascent loads are also highly sensitive to first stage dynamic pressure. For the LFBB early design phase, the best way to maximize launch probability is to reduce ascent dynamic pressure well below the currently-used STS level of 670 psf.

3.0 Ascent/Abort Performance

3.1 Maximum allowable dynamic pressure during ascent — Templin

Rationale: Study Assumption - Maximum allowable dynamic pressure during ascent will be 670 psf. This is the maximum allowed for a current STS ascent using a June launch assumption.

3.2 Should excess FBB performance be used to reduce ascent loads by reducing nominal dynamic pressure (q) below the max allowable? — Templin

Rationale: Study Assumption - Yes. This will provide an increase in the launch probability. The reduction will be limited to the point where a 15-second overlap between abort-to-orbit and negative RTLS exists.

3.3 Should excess FBB performance be used to reduce q-alpha below current levels? — Templin

Rationale: This is outside of the scope of the study. This is not an FBB hardware design issue.

3.4 What is the minimum allowable liftoff thrust-to-weight ratio (T/W) for the STS/FBB configuration? — Templin

Rationale: The minimum allowable liftoff T/W will be 1.2, subject to meeting tower clearance constraints.

3.5 Minimum allowable SSME power level (throttle setting) from startup through liftoff? — Templin

Rationale: Minimum allowable startup throttle setting for the SSMEs is 90% (NSTS 08209 Volume IV, #01000). The minimum allowable throttle setting for dynamic pressure and acceleration limiting will be 67% per current STS flight rules.

3.6 What is the SSME throttle profile? — Templin

Rationale: The SSMEs are brought up to 100% throttle while on the pad. When the vehicle achieves a velocity of 60 ft per second, the SSMEs are throttled up to 104%. The SSMEs are not throttled again until required to maintain the 3 g loading on the vehicle late in the second stage.

3.7 What are the nominal staging conditions for the FBBs? (time, velocity, altitude, q) — Templin

Rationale: Baseline FBB configuration staging conditions:

Time: 142 seconds after liftoff
Velocity: Mach 5.8, 6300 ft/sec
Altitude: 185,000 ft.
q: 17 psf

3.8 Main Engine Type (RD-170 versus F-1A) — Templin

Rationale: Selection of the RD-170 engine was made based on a performance comparison only. This was adequate for this study. A more rigorous selection based on operability, maintainability, reliability, and cost should be made in Phase A.

3.9 Type of FBB main engine throttling (continuous versus step) Templin
Rationale: Continuous. Both of the candidate engines are capable of continuous throttling throughout the throttle range, per the manufacturers' specifications. Continuous throttling provides maximum performance.

3.10 Range of FBB main engine throttling required (percent) Templin
Rationale: The RD-170 on the baseline FBB configuration will be required to throttle from 100% down to a minimum of 65.7% during maximum dynamic pressure. The F-1A will be required to throttle from 100% down to its minimum throttle setting of 69.4% during maximum dynamic pressure.

3.11 Number of main engines per FBB Templin
Rationale: The number of main engines per FBB will be two. The performance of single engine boosters, using the candidate engines, was deemed inadequate for consideration in this phase of the study.

3.12 What are the TAL abort constraints? Templin
Rationale: Current TAL abort landing weight constraint for a high inclination (51.6 deg) mission is 235,000 pounds. The Orbiter would have to be recertified to a higher limit to accommodate the mission objectives for this study. Orbiter impacts will need to be addressed in Phase A.

3.13 What performance is required to eliminate TAL? Templin
Rationale: The nominal ascent trajectory for the baseline FBBs has sufficient performance and ascent shaping to allow for the elimination of TAL aborts.

3.14 Quantify the abort timeline of the FBB
Rationale: The abort timeline for the baseline FBB is as follows:
Single SSME failure options:

RTLS and TAL	Capabilities exist for an SSME failure at liftoff
Earliest ATO	MET = 2:37
Negative RTLS	MET = 3:06
Earliest Press to MECO	MET = 3:57

Single RD-170 failure options (requires opposite FBB engine(s) throttling or shutdown):

Earliest RTLS	MET = 0:24
Earliest TAL	MET = 0:49
Earliest ATO	MET = 1:07
Earliest Press to MECO	MET = 1:14

Single RD-180 engine failure options (requires opposite FBB engine(s) throttling or shutdown):

Earliest RTLS	MET = 0:00
Earliest TAL	MET = 0:00
Earliest ATO	MET = 0:00
Earliest Press to MECO	MET = 0:02

Two RD-180 engine failure options: Times are the same as single RD-170 engine failure times.

3.15 Relationship of booster diameter, length, liftoff T/W and max q to STS injected mass performance Templin
Rationale: Five different combinations of booster length and diameter were selected for analyses in this study phase. Liftoff T/W was allowed to vary with geometry. Maximum dynamic pressure was constrained to the study assumed maximum of 670 psf. The total increase in STS injected mass versus current STS performance for the boosters is:

170' x 18' Step throttled F-1A	36,000 lbs.
170' x 16' Step throttled F-1A	12,000 lbs.
170' x 18' Continuous throttle F-1A	56,000 lbs.
170' x 16' Continuous throttle F-1A	33,000 lbs.
170' x 18' RD-170	93,000 lbs.
170' x 16' RD-170	71,000 lbs.
150' x 16' RD-170	56,000 lbs.

3.16 Performance of single-engine booster configurations (F-1A & RD-170) Templin
Rationale: Performance of the single-engine booster configurations was deemed unacceptable during initial booster sizing analyses. No single-engine booster configuration achieved a liftoff thrust-to-weight of one or more.

3.17 Performance of dual-engine booster configurations (F-1A & RD-170) Templin
Rationale: The baseline dual-engine booster configuration (150 ft tall x 16 ft diameter, 2 RD-170 engines) provides an additional 53,000 pounds of injected mass capability versus current STS capability. The remaining study dual-engine configurations and the additional injected mass capability achieved by each is as follows:

170' x 18' Step throttled F-1A	36,000 lb
170' x 16' Step throttled F-1A	12,000 lb
170' x 18' Continuous throttle F-1A	56,000 lb
170' x 16' Continuous throttle F-1A	33,000 lb
170' x 18' RD-170	93,000 lb
170' x 16' RD-170	71,000 lb

3.18 F-1A thrust level, throttling capability and gimbal limits Templin
Rationale: F-1A specifications:

Thrust level:	1.80 Mlbf - Sea Level
	2.02 Mlbf - Vacuum
Throttle Range:	100% & 75% (Step)
	100% - 69.4% (Continuous)
Gimbal Limit:	$\pm 8^{o}$

3.19 RD-170 thrust level, throttling capability and gimbal limits Templin
Rationale: RD-170 specifications:

Thrust level:	1.632 Mlbf - Sea Level
	1.777 Mlbf - Vacuum
Throttle Range:	100% - 50% (Continuous)
Gimbal Limit:	$\pm 8^{o}$

3.19a RD-180 thrust level, throttling capability and gimbal limits
Rationale: RD-180 specifications:

Thrust level:	827 Klbf - Sea Level
	900 Klbf - Vacuum
Throttle Range:	100% - 50% (Continuous)
Gimbal Limit:	$\pm 8^{o}$

3.20 What is the impact of an early FBB engine shutdown on the return trajectories of the FBB and the Orbiters? Templin
Rationale: Should an FBB engine shut down at or after 76 seconds during the first stage, it is assumed that a simultaneous shutdown of the opposing booster engine will be accomplished to avoid prolonged exposure to asymmetric thrust. Under these conditions, a booster engine out press to MECO is possible. Should a booster engine fail before 76 seconds, a booster engine out RTLS may be achievable enabling the Orbiter and boosters to be recovered. If a contingency abort (ditch, bailout) is attempted, it may necessitate the immediate shutdown of all booster

engines. The loss of the all vehicle elements is likely under the latter scenario. Further study of all FBB engine out abort scenarios will be required in Phase A.

3.21 Should excess FBB performance be used to reduce the maximum SSME throttle setting? (SSME reliability as a function of throttle setting) Templin
Rationale: No. The baseline trajectory for this study assumes that the SSMEs will be brought to 104% throttle at a vehicle ascent velocity of 60 ft/second. Reducing the maximum SSME throttle setting is possible and should be the subject of a trade study in Phase A.

3.22 Should we use excess performance to eliminate the early throttle-down of the SSMEs? (Impacts of eliminating early SSME throttling during ascent) Templin
Rationale: Yes. The baseline trajectory assumes that the SSMEs are brought to 100% throttle on the pad and are throttled to 104% once the vehicle achieves 60 ft/seconds of velocity during ascent. The SSMEs are not throttled down until necessary in the second stage to stay within the 3 g acceleration constraint. Booster engines are throttled during first stage for dynamic pressure, attach load and acceleration regulation.

3.23 What ascent constraints have been selected for this study and what trades can be made?
Rationale: The basic ascent constraints used for this phase of the study are:

Launch month:	June
Max-q:	670 psf
Max acceleration:	3 g
Booster-ET attach shear loads:	1.60E06 lbs compression
	1.65E05 lbs tension
Q-alpha limit:	-3250 psf-deg
Staging max-q:	75 psf
Attitude Rates:	

Stage 1

Angular Rate Limit:	15.0 deg per sec
Angular Acceleration Rate Limit:	5.0 deg per sec^2

Stage 2

Angular Rate Limit:	5.0 deg per sec
Angular Acceleration Rate Limit:	1.5 deg per sec^2

High Loads Region (Mach 0.6 to Mach 2.3)

Sideslip Angle: 0 degrees from Mach 0.6 to staging

Roll Angle: 180 degrees (Boost Reference frame) from end of SAR to staging

Angle of Attack: from Mach 0.6 to approximately Mach 2.3, alpha is computed to yield desired Q-alpha as a function of Mach. Near Mach 2.3 the commanded angle of attack reaches 2.0 degrees and is set to a constant value of 2.0 degrees until staging. From staging until an altitude of 200 Kft the total angle of attack is limited to 2.0 +/- 5.0 degrees.

3.24 What is the performance sensitivity to changing staging conditions (flight-path-angle, velocity, altitude)?
Rationale: The baseline trajectory was derived using the top level constraints outlined in 3.23. The staging conditions for this baseline case resulted by attempting to maximize ascent injected mass at MECO. Staging conditions were not targeted for this phase of the study but will be

subject to trade should the separation/entry/flyback portion of the booster trajectory warrant constraints for staging conditions.

3.25 What are the capabilities of a 4 RD-180 engine booster?
Rationale: A booster equipped with 4 RD-180 engines will have equivalent ascent performance to a booster using 2 RD-170 engines. Intact abort capability of the RD-180 booster will significantly improve however. (see 3.14)

3.26 What max-q are we going to design for during ascent? (see 3.1)
Rationale: The maximum dynamic pressure allowed during ascent of the STS with FBBs is 670 psf. This constraint is the current STS design max-q (includes knockdowns for dispersions from 819 psf). When or if any of the vehicle element ascent load limits are exceeded using this baseline trajectory, the maximum design q will be adjusted accordingly. The minimum max-q at which the design mission is achievable and sufficient intact abort option overlap is provided is 425 psf.

4.0 Reentry/Flyback Performance

4.01 Turnaround Maneuver (powered versus aerodynamic) Bryant
Rationale: An aerodynamic turnaround was selected due to less operational complexity and lower mass. A powered pitch around maneuver would require an engine restart and significantly more propellant.

4.02 Powered cruise vs. gliding return (rocket, air-breathing, gliding) Bryant
Rationale: The booster separation state vector (Mach 5.7) requires a powered return to the launch site. An air-breathing engine was chosen for the return propulsion.

4.03 Can the boosters land with a 20 knot tailwind? What are the crosswind limits? Do winds drive you to an alternate runway? Labbe/Masciarelli
Status: Closed for pre-Phase A design study. Revisit in Phase A.
Rationale: The low value of directional stability, along with a substantial rudder size, result in a high cross wind capability. This is based on the ability to offset sideslip with rudder deflection. However, considering utilizing only the rudder to offset large sideslip angles (i.e. cross winds) indicated that 10 deg. of rudder deflection is sufficient to handle 40 knot cross winds (13 deg. sideslip).
Suggested Trade: An investigation into lateral/directional coupling and interaction is required to review 6-DOF vehicle motions during landing. Further evaluation in follow-on phases is recommended.

4.04 What are the pitch, roll and yaw rates experienced in the LFBB trajectory and how are they accommodated by the LFBB? Robertson/Bryant
Rationale: The maximum angular rates that Lee Bryant has noted for the Flyback Booster (FBB) during the flyback trajectory are approximately 1.0 to 2.0 deg/s (0.017 to 0.035 rad/s) in pitch and roll. While these rates may not represent the dynamic extremes of angular rate, it appears that the selection of an FBB air-breathing engine (commercial vs military) will not be driven by angular rates of motion. The FBB air-breathing engine should operate in a relatively benign environment during the flyback phase of the mission.

Representatives of air-breathing propulsion companies have indicated that commercial aircraft engines are designed for an angular rate limit of 28.6 deg/s (0.5 rad/s) and military aircraft engines are designed for an angular rate limit of 171.9 deg/s (3.0 rad/s). Although the design angular rate limits for existing aircraft engines far exceed the current FBB requirements, this parameter should be monitored as the FBB design matures.

5.0 Booster Configuration

5.1 FBB fuel and oxidizer tankage location and separation — Robertson

Rationale: For the purposes of the Pre-Phase A FBB study, an aft LO_2 tank configuration was selected. There are several factors that favor an aft LO_2 tank. First, an aft LO_2 tank location shortens the length of the cryogenic oxygen feed line and reduces the diameter of the propellant downcomer from the forward tank (the oxidizer mass flow rate is higher than the fuel mass flow rate). Second, ice formation on an aft LO_2 tank is considered to be less of a safety threat to the Orbiter than ice formation on a forward LO_2 tank. Third, the aft FBB heating environment is more benign than the nose heating environment, resulting in a lower temperature differential across the skin of an aft LO_2 tank. An aft LO_2 tank also enables the use of high-temperature structural materials in the FBB forward fuselage that are incompatible with LO_2 (e.g. titanium) to reduce the need for external TPS. Finally, an aft LO_2 tank configuration places the intertank farther forward in a location that can be used to stow the nose landing gear. The main objection to an aft LO_2 tank configuration is the fact that the wing support structure must be attached to a cryogenic tank, which experiences significant dimensional fluctuations from the loading and unloading of cryogenic propellants. The intertank separation distance of 6 ft was selected to enable the installation of a fuel downcomer line (diameter and bend angles), and to provide volume for the packaging of components and assemblies, such as the nose landing gear.

5.2 FBB wing geometry constraints related to physical factors — Robertson

Rationale: The FBB wing physical constraints involve two areas: ground facilities constraints and launch stack geometry. The ground facilities constraints are documented under issues 22.3, 22.4 and 22.5. One of the primary launch stack geometrical constraints is the need to locate large FBB fixed lifting surfaces below the wing of the Orbiter. As the Space Industries booster configuration showed, FBB wings oriented normal to the Orbiter wings are severely constrained, both in wing chord and in axial location. At the point where the FBB wings pass under the Orbiter wings, the FBB wing chord is limited to approximately 20 ft between the trailing edge of the Orbiter elevons and the MLP deck. The wings must also be located at the extreme aft end of the FBB which results in a need for large canards for pitching moment control, even with an FBB cg location in the 75% L_{body} range. Also, the FBB wings are protruding into areas currently occupied by the Tail Service Masts (TSMs) and the rotating service structure (RSS). As the wing is rotated about the longitudinal axis of the FBB to bypass the chord constraint, launch tower clearances come into play. The FBB wing chord must be increased to compensate for the reduction in wing span, which increases the expected interference effects with the Orbiter wing. As the wing is rotated even more to provide clearance between the FBB wings and the Orbiter wings (towards a parallel orientation), the launch tower further constrains the maximum FBB wing span and the ET begins to influence the required wing dihedral. For a parallel wing attached to a 16-ft diameter FBB, the required dihedral for ET clearance is estimated to be in the range of 25 to 30 degrees. Because of the physical constraints imposed on FBB fixed wing configurations and the uncertainty associated with FBB/Orbiter interference effects, the decision was made to focus on deployable wing configurations in this phase of the FBB study.

5.3 Disposable forward tank section reduces landing mass & eliminates the reusable cryogenic tank — Robertson

Rationale: The option of using a disposable cryogenic tank did not fall within the scope of this study. In response to the emphasis on the reduction of recurring flight costs, an emphasis was placed on developing a fully-reusable FBB configuration. The technical risks (both design and operational) associated with reusable cryogenic tankage have been noted.

5.4 Active FBB wing angle of incidence control — Robertson

Rationale: An analysis of using active wing angle of incidence control did not fall within the scope of this Pre-Phase A study. Specific aerodynamic control design alternatives will be traded in later phases of the FBB study.

5.5 Booster Fineness Ratio (diameter and length) — Templin

Rationale: A maximum booster geometry of 18 ft in diameter and 170 ft in length was initially established for the FBB performance analyses. The diameter limit was based upon MSFC wind tunnel data of maximum dynamic pressure versus booster diameter. The booster length limit of

170 ft was based upon earlier liquid rocket booster studies which noted several design breakpoints for booster length based upon both facilities constraints and STS aerodynamic interference factors. Booster lengths greater than 170 ft would require modification of the launch pad GO_2 vent arm.

After performing ascent performance analyses for both F-1A and RD-170 main engines, a design geometry of 16 ft in diameter and 150 ft in length was established for the baseline FBB configuration. With 16x150-ft dimensions and two RD-170 engines per FBB, the STS/FBB would have approximately 372 Klbm injected mass capability, compared to the current RSRB capability of 319 Klbm.

5.6 Integration of the wing with the FBB external moldline — Masciarelli
Rationale: The wing will be folded in a scissors configuration on top of the FBB (high wing). During ascent, the wing will be covered by an aerodynamic fairing that will be jettisoned before wing deployment. When integrated with the Shuttle vehicle, the FBB wings will be on the side of the booster facing the -z (ET coordinates) direction. This configuration will minimize the impacts to the Shuttle vehicle during ascent.

5.7 Integration of the pitch control device with the FBB external moldline — Masciarelli
Rationale: A very large horizontal tail would be required to provide pitch control because the predicted location of the FBB cg is 73% of its length. A large horizontal tail would interfere with existing Shuttle vehicle geometry, the launch platform, and tower. Pitch control will be provided by canards that have a controllable incidence angle. The canards will fold together on top of the FBB body, and will be covered by the same aerodynamic fairing covering the wing. Deployable canards are required in order to avoid serious detrimental effects to the Shuttle ascent aerodynamics. RCS located in the booster's aft compartment will provide pitch control until the aerodynamic surfaces become effective.

5.8 Integration of the yaw control device with the FBB external moldline — Masciarelli
Rationale: A vertical tail with controllable rudder located on top of the FBB will provide yaw control. The vertical tail will be located below the Orbiter and extend in the -z (ET coordinates) direction, thus minimizing impacts to ascent aerodynamic loads on the Orbiter. RCS located in the booster's aft compartment will provide yaw control until the aerodynamic surfaces become effective.

5.9 Integration of the air-breathing engines with the FBB external moldline — Masciarelli
Rationale: A single ABE will be located in the vertical tail of the FBB. During ascent, an aerodynamic cover will be over the engine inlet. The cover will be jettisoned before engine startup.

5.10 Type of thermal control (active versus passive) — Lafuse
Rationale: Passive. Given the current power and mass of the avionics components, and the short duration of the mission, passive thermal control techniques should be adequate to maintain equipment within temperature limits. These techniques include placing equipment to maximize use of the LO_2 tanks as a heat sink, using phase change materials, and purging.

5.11 Integration of the main landing gear with the FBB external moldline — Masciarelli
Rationale: Tricycle type landing gear will be used. The main gear will be located near the aft of the vehicle and fold up into the aft compartment. This location provides sufficient clearance from tail scrape, and is the only space available aft of the booster cg to fold the landing gear without adding external pods to the booster. External pods are not desirable since they will have a larger impact on ascent aerodynamics. The nose gear will be located at and fold into the intertank area. The nose gear is located here (rather than in the FBB nose) to minimize slap-down loads.

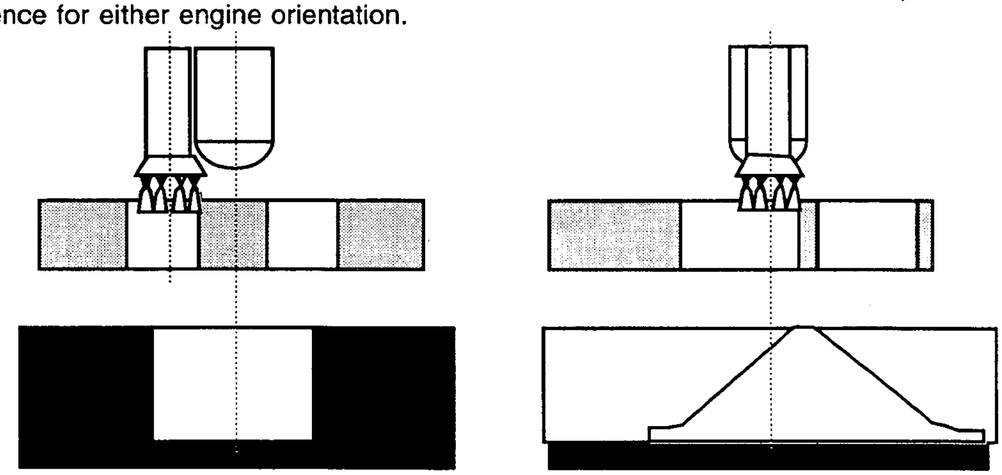
5.12 Integration of the nose landing gear with the FBB external moldline — Robertson
Rationale: The nose gear is stowed in the intertank region.

5.13 Air induction control for the air-breathing engine during ascent (none, covered cowl or duct, deployable duct, etc.) Robertson

Rationale: The air-breathing engine will have a deployable fairing covering the engine inlet during ascent. This fairing will be jettisoned just prior to engine ignition.

5.14 Ascent Engine Orientation Robertson

Rationale: For a two-engine FBB, the orientation of the main engines is defined by a line connecting the centerlines of the two engines. Considering the current booster exhaust cutouts in the MLP, the most obvious orientations for the engines are perpendicular or parallel to the Orbiter wings. Geometry showing both engine orientations were reviewed by KSC personnel. In either case the MLP booster cutouts will have to be modified, and KSC did not express a preference for either engine orientation.



Parallel Engine Orientation Perpendicular Engine Orientation

For a FBB configuration with the wings mounted on the booster side farthest away from the Orbiter, a parallel engine orientation is preferred. A parallel engine orientation places the flared aft fuselage of the FBB in a better orientation for flight and landing, facilitating the integration of main landing gear and tail surfaces. The main concern with the parallel engine orientation is possible clearance problems between the flared aft fuselage and the launch tower/umbilical arms (e.g. the LH_2 vent arm at the ET intertank). The ascent engine orientation decision is closely tied to other configuration decisions, such as the wing location/orientation relative to the STS launch configuration (Issue 6.9).

5.15 Are left and right LFBBs unique? Peterson

Rationale: Access to booster subsystems on the launch pad, booster attachment, and attachment of the separation motors are the three design issues that must be considered in the decision of whether the boosters are left and right compatible. A list of interface items is given below:

<u>LFBB Interface Items:</u>

Intertank Access (for avionics access)
Forward Skirt Access
RP-1 Tail Service Mast
LO_2 Tail Service Mast
JP-1 Tail Service Mast
Electrical/Data Line Connection
O_2 Vent Umbilical Attachment
Booster Separation Motor Integration-Fwd Nosecone
Booster Separation Motor Attachment-Aft Skirt
RSRM Thrust Post (292.6 lb)
RSRM Thrust Post Fitting (799.1 lb)

RSRM Separation Motor Mounts (197.2 lb)
RSRM Attach Structure (2435.2 lb) *External ring frame and attachment which should accommodate either left or right attachment.

It is theoretically possible to have all of the launch pad interfaces along the centerline of the LFBBs. It may be very difficult to locate the O_2 vent umbilical along the centerline of booster with the wing box on the upper surface. The LFBB nosecones would need to be unique to the left or right since the separation motors are integral to the nosecone. Additional equipment would be required for mounting of the separation motors, forward thrust post, and aft attachment struts. This duplication would add approximately 2000 lb to the LFBB.

For the purposes of this study 6 flight units are assumed (3 left, 3 right). In this scenario, if a booster is removed from service, then the opposite booster must be removed temporarily as well. Having boosters that can be used on either side of the launch stack offers operational flexibility, but will not reduce the required number of flights units down to 5. This issue should be addressed in further detail in a Phase A study.

6.0 Aerodynamics

Lift Device

6.1 Class of Lift Device: none, ring wing, standard wing, parafoil, parawing, etc. Labbe
Status: Closed for pre-Phase A design study, should be revisited in Phase A.
Selection: Wing is required; deployable 'standard' wing design selected.
Rationale: The deployable 'standard' wing design provides the required aerodynamic performance for LFBB flyback and landing while minimizing ascent aerodynamic loads impacts to the Orbiter and ET. Fixed wing configurations were eliminated based principally on group discussions and perceived impacts (SSLV & pad geometric constraints and ascent interference effects) and design complications, however no detailed analysis was completed. Note, it has been assumed that ascent aerodynamic interference effects to the Orbiter and ET are more expensive to account for than designing and operating deployable wing, canard systems. Swing wings (e.g. F-14, B-1B) packaging was not practical given the aft cg location. Ring wing was considered incapable of providing required landing performance. Parafoil/parawing was eliminated due to perceived technical risk.
Suggested Trade: Because the deployable wing concept was selected, in part, to facilitate the pre-Phase A design study schedule, Aerodynamics believes insufficient consideration has been given to the complications “deployable” systems present. Therefore, develop deployable, fixed and swing wing concepts and evaluate in detail for ascent load impacts, geometric constraints and design complexity.

6.2 Ring-wing effectiveness at high angles of attack? Labbe
Rationale: Research material available indicates application of ring wings to be limited to low angle-of-attack flight (e.g. missiles, submarines) vehicles that do not land. Interference effects of the fuselage/body on the ring wing effectiveness are expected to be considerable at high angle-of-attack (>20°) flight.
Suggested Follow Up: Continue research for application to other vehicles.

6.3 Type of lift device: fixed versus deployed Robertson
Rationale: As noted in the rationales for issues 5.2 and 22.2 through 22.5, the span and chord for fixed wing FBB configurations are severely limited by both physical and aerodynamic constraints. Deployed wings, in general, and scissor or oblique wings, in particular, offer greater dimensional freedom in the design of the wing. Because they can be packaged in-line with the FBB fuselage, the scissor and oblique wing configurations also offer reduced ascent aerodynamic interference problems. These benefits must be traded with the disadvantages of greater design complexity and increased mass. Considering the potentially serious aerodynamic effects of increasing the booster diameter from the RSRB diameter of 12.5 ft to the proposed FBB diameter of 16 ft, the decision was made to adopt a deployed wing configuration for the Pre-Phase A FBB study. Several Computational Fluid Dynamics (CFD) runs will be performed to assess the impacts of increased booster diameter and a packaged FBB wing module on the STS ascent environment.

Assuming that the loads and heating results are acceptable, fixed wing configurations can be revisited in future phases of the FBB study along with FBB plume effects and other ascent issues.

6.4 Subtype of deployed wing: folded, scissor, oblique, swing, inflatable/rigidized, etc. Robertson

Rationale: The scissor and oblique wing concepts were felt to offer the most advantages. In both concepts the wing is aligned with the FBB fuselage during the ascent phase, which minimizes the ascent aerodynamic interference from the wing. Also, since the wing is shielded by the FBB fuselage, a non-symmetrical airfoil can be used to improve the performance characteristics of the wing. An oblique wing, which pivots as a single unit, is preferred from a structural and mechanism standpoint. But the far aft cg of the FBB favored the scissor wing concept, in which both halves of the wing are pivoted forward at the root for stowage during ascent, because of the limitations on the span of an oblique wing. The folded wing concepts suffered the mechanism complexities of the scissor and oblique wing concepts, but did not offer the aerodynamic advantages since large aerodynamic surfaces were left to protrude into the free stream flow. Swing wings (e.g. B-1, F-14, etc.) offered few advantages and suffered essentially the same physical and aerodynamic constraints as the fixed wing concepts. The inflatable/rigidized concept, essentially a variation on the scissor wing concept, was not considered to be within the scope of this study. Specific wing design alternatives will be examined in later phases of the FBB study.

6.5 Airfoil selected for lift device. Labbe

Status: Closed for pre-phase A design study. Revisit in Phase A.
Selection: NACA 65-012 (ref. Theory of Wing Sections, pgs. 363, 616,617)
Rationale: Wing design is for subsonic performance. Given the limited wing area available for a deployed wing system, maximizing lift was the primary consideration for airfoil selection, so as to meet vehicle landing performance requirements, without the need for complex high lift devices - trailing edge flaps are utilized in this design. This airfoil is also relatively thin providing high lift to drag characteristics which should enhance flyback performance. Finally limiting the pitching moment at zero angle-of-attack minimizes the required canard size for longitudinal trim. (It should be noted that the deployable wing system gives the designer the luxury of considering cambered airfoils. For fixed wing configurations, with the wing exposed during ascent, the designer is driven towards symmetric airfoils to minimize the buildup of wing loads during high dynamic pressure ascent flight conditions.)
Suggested Trade: Optimize wing airfoil definition to provide for aerodynamic performance requirements while minimizing the need for high lift devices and allowing for wing leading edge aerothermodynamic/TPS considerations.

6.6 Landing CL vs. wing size Robertson

Rationale: One of the initial FBB design considerations was the size of the wing in relation to the design landing speed. The three primary variables in the lift equation are velocity (dynamic pressure), wing area (S) and coefficient of lift (CL):

$$\text{Lift} = (1/2 * r * V^2) * S * CL$$

For a desired sea level landing speed of 170 knots, a matrix of wing area solutions (ft^2) was generated by varying landing mass (lift required in lbm) and the maximum landing CL. The maximum CL is driven by several variables including wing geometry (e.g. aspect ratio, airfoil, etc.), landing angle of attack and control surface deflections (e.g. use of elevons as landing flaps to increase CL). Based upon a preliminary aerodynamic assessment of a high aspect ratio wing configuration, it was felt that a landing CL of 1.3 could reasonably be achieved at an angle of attack of 10degrees. A CL-1.3 corresponds to a required wing area in the range of 1,800 ft^2 for a FBB landing mass of 225,000 lbm. A more precise determination of the wing area/CL issue will be pursued in future phases of the FBB study.

Landing CL vs. Wing Size

Landing CL	W=175,000	W=200,000	W=225,000	W=250,000
0.5	3582	4094	4605	5117
0.6	2985	3411	3838	4264
0.7	2559	2924	3290	3655
0.8	2239	2559	2878	3198
0.9	1990	2274	2559	2843
1.0	1791	2047	2303	2559
1.1	1628	1861	2093	2326
1.2	1493	1706	1919	2132
1.3	1378	1575	1771	1968
1.4	1279	1462	1645	1828
1.5	1194	1365	1535	1706
1.6	1119	1279	1439	1599

6.7 Landing lift coefficient (CL) versus aspect ratio. Labbe
Discussion: Required landing lift coefficient is a function of landing mass, landing speed and landing strip atmospheric conditions. Wing lift coefficient is primarily a function of wing geometry (airfoil, aspect ratio, thickness to chord ratio, etc.), landing angle-of-attack (limited by tail drag) and high lift devices/strategies (e.g. trailing edge flaps, canards, etc.). Taken together, these factors determine the wing geometry based on aerodynamic performance alone. Other factors (geometric constraints, flight envelope, wing loading, etc.) must also be considered in developing the wing design. With regards to LFBB and aspect ratio, the only noted advantage of a low aspect ratio wing is a reduction in wing weight. Otherwise high aspect ratio wings tend to increase aerodynamic performance (high lift and low drag).

6.8 Wing location/orientation relative to booster fuselage Robertson
Rationale: The FBB wing is deployable and is stowed in-line with the FBB fuselage to reduce ascent aerodynamic interference effects. See issues 6.3 and 6.4 for a more detailed rationale.

6.9 Wing location/orientation relative to STS launch configuration Robertson
Rationale: The FBB wing is mounted on the side of the FBB fuselage that is farthest away from the Orbiter. This configuration offers the best probability of minimizing ascent aerodynamic effects from the FBB on the Orbiter.

6.10 Wing planform (span, chord, taper, sweep, etc.) Labbe
Status: Closed for pre-Phase A design study. Revisit in Phase A.
Selection: (S=1750 sq. ft, b=112.9 ft, c=15.5 ft, Δ=l=0.0, A=7.28)
Rationale: This relatively high aspect ratio wing provides the necessary aerodynamic lift to meet landing performance requirements. The chord length was limited by the booster diameter of 16 ft. Given c, the span was defined by the required wing area necessary to meet landing performance. The wing sweep and taper are set to zero to maximize landing performance. Because of the limited flight time at supersonic speeds, optimization of the wing for this flight regime was not considered to be beneficial and subsequently subsonic considerations drove the design. See 6.44 for more info.
Suggested Trade: Optimize wing planform definition to provide for aerodynamic performance requirements (subsonic) and verify adequate supersonic characteristics (i.e. control issues).

6.11 Wing deployment strategy (if applicable) Robertson
Rationale: The wings will be deployed near the apogee of the FBB trajectory in a low dynamic pressure environment. Current trajectory simulations indicate that the FBB will coast to altitudes in excess of 250,000 ft after separation from the ET.

6.12 Geometry of wing mounted control surfaces Labbe

Status: Closed for pre-Phase A design study. Revisit in Phase A.
Selection: Elevator & aileron combination trailing edge flaps were incorporated into the design. These control surfaces are 20% of chord (Elevator from 160" to 466" span, Aileron 466" to 677").
Rationale: The 'flaps' were sized to provide lift augmentation to the basic wing to meet landing performance requirements. Full span flaps were not required. The ailerons (outboard) were positioned to provide roll control, however no vehicle roll requirements were developed, so the sizing is preliminary.
Suggested Trade: Optimize wing control surfaces to provide for aerodynamic performance requirements (TBD) throughout the flight profile.

6.13 Class of yaw control device: none, winglets, single rudder, etc. Labbe

Rationale: A vertical tail yaw control device was selected because the deployed wing system rules out the use of winglets.

6.14 Type of yaw control device - fixed vs. deployed Labbe

Status: Closed for pre-phase A study. Could be revisited.
Rationale: A vertical tail yaw control device was selected because the deployed wing system rules out the use of winglets. A fixed vertical tail configuration is assumed because the current launch configuration allows for placement of the vertical tail on the LFBB opposite the Orbiter, thereby minimizing interference effects. Finally if a fixed surface is feasible, the use of a deployed system unnecessarily complicates the design.
Suggested Trade: As part of the Class of Lift Device trade, the vertical tail configuration may require a new approach and therefore use of a deployed yaw control device or winglets should not be ruled out.

6.15 Airfoil selected for yaw control device Labbe

Rationale: The vertical tail yaw control surface will be a symmetric airfoil located on the vehicle center-line to assure no lateral-directional aerodynamic effects at zero angle-of-sideslip. The actual airfoil has not been designated and will be determined based on the necessary operational range of the control device (i.e. necessary for hypersonic/supersonic or subsonic/landing control).

6.16 Lateral directional stability during reentry & flyback vs. angle-of-sideslip & Mach Labbe

Status: Closed for pre-Phase A.
Rationale: Vehicle is designed to be stable throughout the flight regime. Characteristics of this stability are to be provided by analysis (APAS & QUADPAN). Note that to achieve stability the VT (see 6.19) is relatively large, due mostly to the short moment arm between the VT and the cg. Because of the high angle-of-attack above M=1.0 the vertical tail is sized for subsonic performance characteristics. It is assumed that hypersonic/supersonic lateral control will be augmented by a robust RCS.

6.17 Yaw control device location/orientation relative to booster fuselage Robertson

Rationale: The single vertical tail will be mounted on the same side of the FBB fuselage as the wing, resulting in a high-wing configuration. Stability considerations dictate an aft mounted tail. This decision is directly related to Issue 6.8.

6.18 Yaw control device location/orientation relative to STS launch configuration Robertson

Rationale: The single vertical tail will point away from the Orbiter when the FBB is attached to the STS. This decision is directly related to Issue 6.9.

6.19 Yaw control device planform (height, chord, taper, sweep, etc.) Labbe

Status: Closed for pre-Phase A. Revisit in Phase A
Selection: Vertical Tail with NACA 65-010 airfoil section (ref. Theory of Wing Sections, pg. 362) (S=682.4 sq. ft, c(root)=29.17 ft, c(tip)=13.3 ft, Δ=26.38deg, l=0.457, h=32.9 ft, A=1.59)
Rationale: This symmetric airfoil and VT planform provide necessary lateral directional stability for the LFBB during landing and cruise. Because of the integrated jet engine and the short moment arm, verification of these analytically derived characteristics is required.

Suggested Trade: First verification that the sizing and performance is accurate. If analysis indicates a larger vertical tail, trade single with twin VT configurations and jet engine integration.

6.20 Yaw control device deployment strategy (if applicable) Robertson
Rationale: The single vertical tail will be fixed. The tail is mounted aft on the FBB fuselage and does not present a significant aerodynamic interference problem for the ET or Orbiter.

6.21 Geometry of yaw control surfaces Labbe
Status: Closed for pre-Phase A. Revisit in Phase A.
Selection: A rudder of 40% chord was defined to provide lateral control in yaw.
Rationale: Preliminary definition, requires verification. No yaw control requirements were defined. Note: Provides for approximately the same area ratio of rudder to VT as Orbiter.
Suggested Trade: First verification of sizing and performance. If analysis indicates a different rudder, size appropriately based on requirements. See also 6.19 Suggested Trade.

6.22 Class of pitch control device: none, canards, horizontal tail, V-tail, etc. Labbe
Status: Closed for pre-Phase A design study, should be revisited in Phase A.
Selection: Pitch control device required; deployable canard design selected.
Rationale: To maintain and trim the LFBB vehicle in the pitch plane requires the use of a pitch control device. Deployable canard design provides the required aerodynamic characteristics for LFBB flyback and landing while minimizing ascent aerodynamic loads impacts to the Orbiter and ET. Consideration of a horizontal tail was ruled out because 1) the large aft skirt geometry forces an effective horizontal tail surface outboard excessively and 2) (coupled with 1) geometry constraints of the currently proposed LFBB ascent configuration limit available HT span to less than preliminary sizing requirements.
Suggested Trade: See 6.1.

6.23 Type of pitch control device - fixed versus deployed Labbe
Status: Closed for pre-Phase A design study, should be revisited in Phase A.
Selection: Deployable canards.
Rationale: Deployable canard design provides the required aerodynamic characteristics for LFBB flyback and landing while minimizing ascent aerodynamic loads impacts to the Orbiter and ET. Fixed canard configurations were eliminated based principally on group discussions concerning packaging constraints and ascent aerodynamic interference effects, however no detailed analysis was completed.
Suggested Trade: See 6.1.

6.24 Subtype of deployable pitch control device-folded, scissor, bayonet, etc. Labbe
Status: Closed for pre-Phase A.
Selection: A scissor type canard device is proposed.
Rationale: Taking advantage of the fairing required for the deployable wings (scissored forward) the canards are scissored aft from their forward location. This allows one fairing to cover both major lifting components on ascent and eliminates any interference from the canards on ascent.
Suggested Trade: The canards are intended for use only during approach and landing and therefore would be deployed after cruise back and be all moving - a potentially complex design. This system should be evaluated and traded for efficiency, simplicity, reliability and weight.

6.25 Airfoil selected for pitch control device - symmetric vs. cambered Labbe
Status: Closed for pre-Phase A. Revisit in Phase A.
Selection: The canard is of a cambered airfoil section - NLF(1)-0215F
Rationale: This high cambered section provides large lift values at zero angle-of-attack, thereby offsetting the wing body pitching moment at zero angle-of-attack. This combination helps minimize the canard size and maximize the utilization of the available canard power to trim at high angles-of-attack.
Suggested Trade: Optimize vehicle control surfaces to provide for aerodynamic performance requirements (TBD) throughout the flight profile.

6.26 Pitch stability during reentry and flyback vs. angle-of-attack and Mach Labbe
Status: Closed for pre-Phase A design study.
Rationale: Vehicle is designed to be stable throughout the flight regime. Characteristics of this stability are to be provided by analysis (APAS & QUADPAN). At landing neutral to marginally stable design minimizes the control power required at high angle-of-attack and therefore minimizes the required canard size. Because of the high angle-of-attack above M=1.0 the canard is sized for subsonic performance characteristics and is not intended for use at supersonic flight conditions. It is assumed that hypersonic/supersonic pitch control will be augmented by a robust RCS.

6.27 Pitch control device location/orientation relative to booster fuselage Masciarelli
Rationale: The canards will fold together on top of the FBB body, and will be covered by the same aerodynamic fairing covering the wing. See rationale for issue number 5.7.

6.28 Pitch control device location/orientation relative to STS stack Masciarelli
Rationale: When integrated with the Shuttle vehicle, the canards will be on the side of the booster facing the -z (ET coordinates) direction. This configuration will minimize the impacts to the Shuttle vehicle during ascent. See also rationale for issue number 5.7.

6.29 Pitch control device planform - span, chord, taper, sweep, etc. Labbe
Status: Closed for pre-Phase A design study. Revisit in Phase A.
Selection: (S=160.4 sq. ft, b=21.5 ft, c(root)=12.75 ft, c(tip)=2.08 ft, Δ=44.6°, l=0.17, A=2.88)
Rationale: Canard is to be used for pitch control only in the landing phase of flight and as such was sized to provide necessary power to trim the craft at a high (12°) angle-of-attack, high lift landing condition (as well as packaging constraints). The low aspect ratio provides a large angle-of-attack range effectiveness. Note: The size / location of canard is dependent on the stability, packaging and wing characteristics - must not overpower the wing + elevator deflection pitching moment at landing angle-of-attack, which could limit the maximum lift coefficient and increase wing size.
Suggested Trade: Optimize vehicle control surfaces to provide for aerodynamic performance requirements (TBD) throughout the flight profile.

6.30 Pitch control device deployment (if applicable) Masciarelli
Rationale: Deployable canards are required in order to avoid serious detrimental effects to the Shuttle ascent aerodynamics. See also rationale for issue number 5.7.

6.31 Control strategy for pitch control device ("full flying" vs. control surface) Robertson
Rationale: The canards will be "full-flying" or pivoted from the root to maximize the control effectiveness of the aerosurface. The actuator for the canard will be mounted inside the FBB intertank.

6.32 Geometry of actuated pitch control surface (if applicable) Robertson
Rationale: Since the canards are "full-flying", there are not control surfaces on the canards. See issue 6.31.

General Aero Issues

6.33 Shuttle ascent environment interference effects of the LFBB on the ET & Orbiter Labbe/Gomez
Status: Closed for pre-Phase A design study. Revisit in Phase A.
Rationale: Utilizing the high fidelity computational fluid dynamics (CFD) analysis tool developed for evaluating the Shuttle Ascent wing loads environment a single point (Mach 1.25) assessment of the impact on the Orbiter and ET of replacing the RSRB with an LFBB was analyzed. The effect was computed for a no plume (SRB nor SSME) condition for two LFBB configurations. One a simple cylinder (16' D) with a flared aft skirt and a second that included a preliminary version of the wing/canard packaging fairing and an LFBB VT w/ABE. Results available indicate a reduction in wing root shear, bending and torsion. Results also indicate changes to the launch vehicle element force and moments (most notably an increase in booster drag and decrease in Orbiter

normal force) which could impact attach hardware sizing and/or re-design. Data has been forwarded to loads and structures (ES) for more detailed evaluation.
Suggested Trade: (Actually New Work) Update configuration to latest concept. Add LFBB plume model. Recompute environment changes at Mach 1.25. Support 6.1 Suggested Trade.

6.34 LFBB aerodynamic performance coefficients vs. AOA & Mach — Labbe/Royall
Status: Closed for pre-Phase A design study. Revisit in Phase A.
Rationale: Aerodynamic performance results for a preliminary concept of the LFBB bounded the characteristics. Further pre-Phase A iterations on the vehicle configuration did not considerably change the size of the major components (i.e. booster diameter, wing etc.) This data forwarded in Dec. 1993 and updated in Jan. 1994 can be used for pre-Phase A study trajectory design etc. Final pre-Phase A configuration aerodynamic characteristics will be provided at the end of the study.

6.35 Dispersions on aerodynamic coefficient estimates — Labbe/Robertson
Status: Open
Rationale: Lacking any wind tunnel test data to anchor the analytical tool (APAS & QUADPAN) predictions makes accurate dispersion estimates difficult. Typical values used in other studies (i.e. SSTO) using APAS are ±10%. Experienced users of these programs indicate that while this level of accuracy can be achieved, having a benchmark set of WT Test data is almost essential to capture the impact of such things as flow separation etc.
Suggested Trade: Utilize wind tunnel test results (TAMU WT Test etc.) during Phase A to develop a prediction accuracy on aero coefficients. Do trajectory trade studies to determine vehicle sensitivity to these dispersions.

6.36 Minimum glide slope angle — Robertson
Rationale: The maximum L/D ratio of the FBB is estimated to be approximately 8:1. That corresponds to a minimum glide slope of approximately -7.1 degrees.

6.37 Yaw excursion limits on the Orbiter's vertical tail (due to FBB engine-out? — McSwain
Rationale: There is concern that significant yaw torques from a booster engine failure will cause the vehicle to rotate outside the acceptable loads envelope. The time lag to determine that a FBB booster engine has shutdown and respond is about 160 to 200 ms (120 ms for 3 reports of failure + (40 - 80) ms to respond). The engine is assumed to fail in a controlled fashion i.e. the thrust tails off in a fashion similar to that experienced in nominal engine shutdown. A detailed analysis is beyond the scope of this effort. Instead a booster engine failure at a single point on the Shuttle ascent trajectory (maximum dynamic pressure) will be evaluated. The sideslip, roll and angle of attack induced by the failure will provide a clue as to whether the vehicle will suffer structural damage with a booster engine failure.
Recommendation: Locate the booster engine electronics required to interface with the Orbiter on the Orbiter side. (The RD170 does not have an engine controller). Cross strap the controllers so that an engine failure on one booster results in an immediate command from the electronics box to shutdown the corresponding engine on the other booster. This avoids the delay required to notify the GPC and respond but introduces some potential for a failure which will shutdown an engine for a false alarm (failed engine sensor).

6.38 Will a landing flare be used for the LFBB? — Labbe
Rationale: It should be assumed that a landing flare will be necessary to achieve necessary lift to meet landing performance requirements. Based on preliminary wing sizing coupled with trailing edge flaps, the use of angle-of- attack to increase lift is assumed to be more attractive than elaborate high lift devices.

6.39 Design landing angle of attack for the LFBB — Labbe
Status: Closed for pre-Phase A.
Rationale: Based on landing performance requirements, landing weight of the vehicle, pitch trim requirement and aerodynamic characteristics of the preliminary configuration - a landing angle-of-attack of 12° is baselined.

6.40 Design landing speed for the LFBB Labbe

Rationale: Study Assumption - Set at 170 knots. High relative to commercial jet aircraft (≈125 knots), low relative to Shuttle (195 knots).
Note: For VTD=170 knots -->VSTALL=148 knots. Then a landing weight of 230,000 lbs with a CLmax=1.6 requires a wing area of approximately 1950 sq. ft. For a 16 ft chord the required span is approximately 120 ft which is practical for the deployed wing concept currently under review.

6.41 Consider bending loads on forward booster attach structure due to lift from wings Robertson

Rationale: With deployable wings that are stowed in-line with the booster fuselage during ascent, this is not an issue. For fixed wing configurations significant rolling moments can be generated from asymmetric ascent flow over the FBB wings, impacting the design of the FBB/ET attach hardware.

6.42 Size control surfaces and hinge moments. ET4/EG3

Status: Closed for pre-Phase A design study. Revisit in Phase A.
Rationale: The control surfaces were sized to provide required landing performance aerodynamic characteristics (i.e. lift augmentation and trim.) The hinge moments on these surfaces have not been calculated, however it is felt that they can be approximated by assuming Orbiter elevon hinge moments. (Note: LFBB vehicle is approximately the same size & weight as the Orbiter and the LFBB elevon planforms are approximately 2/3s of the Orbiter's)
Suggested Trade: The relatively high max dynamic pressure on entry (1200+ psf vs. 300+ psf for the Orbiter) could be of concern to the LFBB control surface actuator sizing and LFBB wing load environments and should be addressed in more detail during Phase A.

6.43 All moving canard vs. canard with control surface. Labbe/Romere

Status: Closed for pre-Phase A design study. Revisit in Phase A.
Selection: All moving canard was baselined.
Rationale: The all moving canard provides necessary pitch stability for the LFBB during landing. This increases the efficiency of the canard at a wider range of angle-of-attack. Verification of these analytically derived characteristics is required. A trailing edge flap could be added to provide additional canard power if necessary.
Suggested Trade: First verification that the sizing and performance is accurate. If analysis indicates a need for more canard power, trade increased size with addition of trailing edge high lift device. Optimize vehicle control surfaces to provide for aerodynamic performance requirements (TBD) throughout the flight profile.

6.44 What is the sweep angle required to eliminate supersonic snap roll? Labbe/Stueber/Royall

Status: Closed for pre-Phase A design study. Revisit in Phase A.
Selection: A wing with zero sweep angle was baselined.
Rationale: During Space Shuttle Phase B wind tunnel testing of straight wing configurations, LaRC discovered a potential problem leading to a snap roll condition. This was most prevalent during the transition from high to low angle of attack subsonically. Because the current baseline LFBB trajectory has the transition from high to low angle of attack occurring supersonically it was felt that the LFBB would not be susceptible to this condition. Further the addition of spoilers on the wing upper surface can eliminate the cause of the condition - asymmetric boundary layer transition. Note: The required wing sweep would substantially degrade the LFBB's landing performance and therefore require a larger wing area design. This was considered unacceptable due to the limited packaged volume/length available.
Suggested Trade: Evaluate fully the potential susceptibility of the final LFBB configuration to the onset of asymmetric boundary layer transition during high to low angle-of-attack maneuver. If necessary baseline spoilers and incorporate them into the design.

7.0 Aerothermodynamics

7.01 What are the aerothermal environments (heating rate and peak temperatures) for the predicted range of FBB separation states? (Mach 4.0 to 6.0) Caram

7.01.1) Undisturbed aerodynamic heating to the booster.
Status: CLOSED for Pre-Phase A.
Analysis: A simplified engineering analysis will be performed on the LFBB because of geometry and trajectory differences. This analysis will provide heating rates and other required parameters for a limited number of surface locations on the booster for TPS and thermal analysis.
Rationale: Preliminary aerodynamic heating evaluation for nine selected body points on the LFBB was completed. The 9 body point locations selected were agreed upon by representatives from aerothermal, structures, and thermal protection disciplines. Hot wall and 350°F wall heating rates for each location during ascent were provided to ES3 for TPS evaluation. A more complete aeroheating analysis of the booster will be necessary during follow on phases of the program.

7.01.2) Interference heating between the ET and the LFBB (LFBB Impacts).
Status: CLOSED for Pre-Phase A.
Analysis: Reflected shocks and protuberances such as the attach points will result in increased localized heating to the LFBB. Previous analyses have shown that increases in the heating from the local undisturbed values can be as high as factor of 8 but are typically around 2. Again, note that this would be the increase to the local undisturbed values which in most cases for the ascent vehicle, assuming similar trajectories, are less than 1 BTU/ft2 sec. The interference patterns will be extremely difficult to define without the aid of wind tunnel test data and CFD solutions. For this study the protuberance heating to the attach points will only be considered and should not be expected to be significantly different from current SRB values. The heating factors will be provided in parallel to 7.1.1.
Rationale: A preliminary evaluation of the heating to the forward ET attach and attachment line areas of the LFBB was included in the analysis mentioned in 7.1.1. Undisturbed heating values were multiplied by factors between 2 and 1.6 and were used as general acreage heating to these areas. These factor were chosen by reviewing data in the SRB aeroheating databook. A more completed analysis which should include wind tunnel data will be necessary during follow on phases of this program.

7.01.3) Plume radiative heating to the LFBB base and aft skirt.
Status: OPEN
Analysis: Radiative output from the LFBB RD-170 engines is expected to be less than the solid fueled SRBs. However, factors that should be considered in following studies will be plume interaction and local base heating with view factors.

7.01.4) Plume recirculation convective heating to the LFBB base and aft skirt.
Status: OPEN
Analysis: Plume recirculation convective heating to the base and aft skirt of the LFBB during ascent will be significant enough to warrant further evaluation. An estimate of this heating can be developed by comparing Orbiter SSME engine specifications to RD-170 engine specifications and relative base areas of the vehicles. However, this should be evaluated in more detail in a Phase A study.

7.02 How will the FBB impact the ascent aerothermal environment of the STS? Caram

7.02.1) Impact to Orbiter.
Status: CLOSED
Rationale: Since most of the Orbiter TPS except for the base region and vertical tail is designed for entry and the location of the nose of the LFBB is unchanged from the SRB, the LFBB will have minimal to no impact on Orbiter TPS. The Orbiter base heat shield was primarily designed for the SSME radiative and plume recirculation convective heating environments. Radiative heating from the SRBs is observed on the base during SRB shut down. However, because of the reduced radiative output of the LFBB and lack of a shut down spike, any change in the base

heating to the Orbiter should not be significant. Thus, no impact to the TPS design of the Orbiter tiles in the base region is expected.

7.02.2) Impact to ET.
Status: CLOSED for Pre-Phase A.
Analysis: A) Shock interference and protuberance heating effects are the primary issue. Geometry differences between the LFBB and SRB such as nose radius, cone half angle, core diameter with wing storage area will result in different shock interference patterns impacting the ET. These differences will result in localized changes in the heating to the ET, primarily around the forward and aft attach points and separation motor plume impingement zones. The required analysis for this study was discussed in 7.01.2, however impact to the ET TPS in the interference and protuberance zones should be assessed during Phase A.
B) Outside of these areas, heating rates to the overall acreage of the ET should be unaffected as long as the ascent trajectory remains inside the ET certification data base. Certification envelopes for the tank will be provided to trajectory designers.
Note: Every effort should be made to minimize impacts to the TPS of the ET. Any required changes to the TPS of the ET will result in significant cost penalties.
Rationale: Preliminary analysis of the heating environment impact to the ET was performed using the ET aeroheating databook, information from ASRM analyses, and CFD Mach 1.25 LFBB integrated vehicle solutions. Results showed that there would be an increase peak heat rate of 200% while there would be a decrease in heat load of 16% compare to ET Generic Certification. Data was provided to Ron Toelle of MSFC for further analysis of the impact to the ET TPS.

7.02.3) Impact to ET base and aft attach region.
Status: OPEN
Analysis: As was noted in a previous study the primary factors affecting plume base heating are: number of engines; nozzle area ratio; combustion chamber pressure; nozzle exit location; plume radiation characteristics; and vehicle base geometry and pressures. As was mentioned in 7.1.3, radiative output of the LFBB plume is expected to be less than the current SRB. Unfortunately, the reduced amount of radiative heating to the base of the ET results in increase plume recirculation convective heating at the higher altitudes. This occurs because convective heating is a function of the wall temperature; i.e. for the same recovery enthalpy and film coefficient, a higher wall temperature, which in this example is induced by radiative heating, will result in lower convective heating. Vice versa for the case with reduced radiative heating conditioning. In addition to this, the increased base area of the LFBB may result in more recirculation of the booster plume resulting in higher convective heating. Assessment of the plume heating impact to the base of the ET will have to be done if the design proceeds beyond this phase.

7.02.4) Impact to the SSME Nozzles
Status: CLOSED
Rationale: Little change to the heating of the SSME nozzles is expected because of the reduced radiative output from the LFBB and no change of the convective environment around the Orbiter base.

7.03 Entry heating environment of LFBB.

7.03.1) Forebody heating environment of LFBB
Status: CLOSED for Pre-Phased A
Analysis: Once a preliminary geometry and an entry design trajectory for the LFBB has been agreed upon initial estimates of the distributed heating to the LFBB can be developed. The areas requiring the most attention will be the nose cap, forebody, canard, wing, and vertical stabilizer leading edges. Preliminary heating distributions over the LFBB for three angles of attack will be produced using geometric metric coefficients and Newtonian pressures.
Rationale: Preliminary aerodynamic heating evaluation for 9 selected body points on the LFBB was completed. The 9 body point locations selected were agreed upon by representatives from aerothermal, structures, and thermal protection disciplines. Hot wall and 350°F wall heating rates for each location during entry were provided to ES3 for TPS evaluation. A more complete

aeroheating analysis of the booster including wind tunnel testing will be necessary during follow on phases of the program.

7.03.2) Shock Interference effects on canard and wing.
Status: CLOSED for Pre-Phase A
Analysis: Shock interference effects should be expected on the canards and wing of the LFBB. Engineering models of the shock interaction heating to the Orbiter wing leading edge will be used to give initial estimates of the heating to the wing with and without shock interaction.
Rationale: Heating environments of the main wing leading edge of the LFBB were generated. Heating to the canards was not calculated because of the decision to deploy them well after the heating pulse is expected. Heating to the leading edge of the straight main wing was determined for the root, shock interaction region, and tip of the wing. Review of straight winged orbiter studies in the early 1970s indicated that a Type V shock interaction could exist resulting in an increase of 1.5 to 3 times the undisturbed heating in a very localized area. For this analysis a factor of two was chosen.

7.03.3) Entry heating to engine nozzles.
Status: CLOSED for Pre-Phase A
Rationale: If the type of material used in the LFBB nozzles and TPS is similar to the SSME's nozzles, the expected heating to the LFBB engine nozzles during the entry phase should be within the material limits. Further analysis will be needed if the design proceeds beyond this phase because of the differences between the SSME LH_2/LOX engine and the RD-170 -kerosene/LOX engine.

7.04) 1 ft Reference Heating (Cold Wall and Hot Wall)
Status: STAND BY
Rationale: As ascent and entry trajectories are produced, they are to be transmitted for aerothermal evaluation. These trajectories are then integrated so that they can be evaluated for peak heat rate and integrated load on the LFBB. Also, because these trajectories are nominal a factor of 1.3 will be applied to all film coefficients to cover any dispersions in the trajectory. This factor is based on Orbiter experience and covers dispersions in guidance, winds, atmosphere, thrust vector misalignment, etc.

8.0 Structures/Landing Gear

8.01 Rebound loads resulting from a LFBB engine shutdown on the pad — Feaster
Rationale: Vehicle-to-ground interface loads are typically generated by the RI/Downey loads group and are based on the thrust and weight characteristics of the launch vehicle. For the purposes of this study, a dynamic factor of 2 applied to the GLOW (4,723,750 lbs. for 16 ft. X 150 ft. w/2 RD-170s) will be sufficient. MLP assessments will be based on a vehicle rebound of 9,500,000 lbs.

8.02 Loads on the ET resulting from a FBB engine shutdown in flight — Toelle
Rationale: The analysis required to support this issue cannot be completed during this study. This issue must be re-addressed in a Phase A study.

8.03 Booster axial stiffness (less stiff than RSRB, equal stiffness to RSRB) — Wong
Rationale: The LFBB bending stiffness is ~30% of the SRB stiffness. This lower stiffness is acceptable. The reduction in stiffness will result in larger booster deflections as the SSME thrust builds on the launch pad. Larger deflections will cause higher base bending moments, will require longer umbilicals, and will increase the time for the vehicle stack to rock back to vertical. Loads on the ET due to shrinkage during cryogenic tanking should be reduced by using a less stiff booster. During ascent, the boosters "rolling" modal frequency may affect the vehicle control margins and should be assessed in the next phase of design. The filament wound SRB case considered by the USAF had less bending stiffness that the current D6AC steel SRB.

8.04 Load Factor - Maximum — Wong
Rationale: A maximum load factor (Nz) of 4 is recommended. Hypersonic 4g wing loads are about equivalent to the maximum subsonic wing loads (~2.5 g). These two load cases should be

equivalent for a minimum weight wing. If the LFBB hypersonic loads exceed 4g's then this load case will drive the wing sizing beyond what is needed for subsonic flight. The loads seen during booster reentry could not be reduced much below 4 g's and higher load factors would add excessive weight to the structural design.

8.05 FBB structural and tankage materials selection (Al, Al-Li, Ti, etc.) Wong
Rationale: For this phase of the study, 2219 aluminum has been selected for the structural material. Heating analysis shows that external TPS is not required on the forward fuselage. Titanium was considered, but weighed over 4000 pounds more. Aluminum-Lithium alloys can be considered in follow-on study phases.

Titanium Ti-6Al-4V was compared with aluminum 2219 for the booster structure. The evaluation of the TPS/structure configurations (Issue 8.10) indicated that large weight increases would result if the structure forward of the LO_2 tank were titanium rather than aluminum. Based on this projected weight increase for the use of titanium as well as the added material cost and manufacturing issues, aluminum alloys are preferable. 2219 is a weldable aluminum alloy that has been used successfully for other cryogenic tanks in past programs. Using 2219 aluminum for the LFBB tanks and other common aerospace aluminums (2024,7075,7050) for most other structure is recommended at this time. High temperature materials that may have applications in areas of extreme heating such as the nose cap and leading edges were not addressed. The next design phase can consider the benefits and problems associated with the use of aluminum lithium for reusable cryogenic tanks and other structural elements.

8.06 Type of main and nose landing gear (skids vs. tires) Wong
Rationale: A previous Orbiter trade study determined that a landing gear with a wheel configuration would weigh less than a skid design. This prediction would hold for the LFBB since it is approximately the same landing weight as an Orbiter. A wheel design would also offer more ground mobility. A steerable nose gear is located in the intertank region. And the main gear are located in the boattail region.

8.07 Landing Gear Design Masciarelli
Rationale: Current location of MLG is at 1369 inches from nose of vehicle. CG location of 1365 limits how far forward the MLG location can be. Moving the MLG forward about 10 ft provides a 14 degree angle of attack before tail scrape. Since this is close to the landing angle of attack, the MLG would have to be longer to move forward any farther. A 10 ft forward shift would still be in the aft skirt of the vehicle. The RP tank currently uses up most of the volume of the nose cone, and so there is not enough room to locate the NLG there. Moving the RP tank aft to make room for the NLG in the cone is not possible since there is a minimum length intertank required which is defined by the RP feed line. Intertank length required could be reduced by having the RP feed line run directly through the LO_2 tank, but this is undesirable. Therefore the most logical choice for the NLG location is the intertank.

8.08 Max landing angle of attack for tail scrape Masciarelli
Rationale: Current design and location of MLG at 1369 inches from the nose provides 32 degree angle of attack before tail scrape. This is well above the stall angle of attack, therefore tail scrape at landing is not considered a problem.

8.09 Nosecone geometry (cone, biconic, ogive, etc.) Labbe
Status: Closed for pre-Phase A design study, should be revisited in Phase A.
Selection: Sphere capped cone geometry selected.
Rationale: Assumption. Sized to maintain x-coordinate location of current SRB nose. Engineering judgment suggests that maintaining similar nose location and shape will minimize aerodynamic and aerothermodynamic impacts to the Shuttle ascent environments. The resulting increased cone angle and nose radius will introduce impacts that require assessment. A biconic or ogive nose has potential to increase lift and reduce drag if flyback performance becomes critical, however ascent environment impacts would be increased and perceived manufacturing cost is higher.

Suggested Trade: Evaluate potential flyback benefits of optimized 'nosecone' geometry versus Shuttle ascent environment impacts and cost of manufacturing.

8.10 TPS/Structure Combination — Curry/Wong

Rationale: The TPS/Structural concepts utilizing both heat sink structure (aluminum/Titanium) and TPS/Insulation (TABI/Rohacell) were provided at the March 14 LFBB review. For this phase of the study, 2219 aluminum has been selected for the structural material. Heating analysis shows that external TPS is not required on the forward fuselage. However, the TABI/Rohacell combination is required for LOX tank insulation. Wing TPS is assumed to be TABI blankets.

Three structure-TPS configurations were evaluated for their potential use for the LFBB structure forward of the LOX tank. This task was initiated to determine the effects of eliminating the proposed TPS in the forward region of the booster for the possible cost savings associated with maintenance reductions. The three configurations were:

1) Aluminum 2219 structure with TPS (TABI blanket) on regions forward of the RP-1 tank
2) Aluminum 2219 structure without TPS
3) Titanium Ti-6Al-4V structure without TPS

Configuration 2, the aluminum configuration without TPS on the structure forward of the LOX tank, is recommended of the three configurations. Results indicated that the internal loads caused by the thermal gradients were not severe. Although the combined effects of mechanical and thermal loading were not checked, it is anticipated that prelaunch and lift-off would enveloped other load cases for structure aft of the ET forward attach fitting. The aluminum configuration without TPS was found to weigh about 1000 lb. more than the aluminum-TABI blanket option. The additional weight was considered an acceptable trade for the elimination of TPS. Results of this assessment also indicated that the use of titanium for all structure forward of the LOX tank will lead to a large weight penalty over the aluminum configurations.

It should be recognized that the results from this assessment are not conclusive due to the many simplifying assumptions made to account for the immaturity of both the design loads and the structural definition. The next design phase (phase A) should investigate these and other options to a greater extent.

8.11 Quantify the inspection requirements for reusable cryogenic tankage — Toelle/Feaster

Rationale: The timelines presented at the February review have been discussed at length with the vehicle engineers. The available information on the RD-170 engine has been reviewed at length. The timelines for the SSTO have been reviewed. After all of this our position on the timelines for processing the LFBB in its processing facility were rearranged and modified but the duration of 22 calendar days did not change. The processing time in the VAB did change from 28 calendar days to 18 calendar days.

8.12 What cryogenic tank inspection methods are available that will satisfy the req'ts and promote quick turnaround (NDE techniques, physical inspection, pressure test) — Toelle/Feaster

Rationale: The inspection methods are unknown at this time and a significant effort in determining cost effective inspection methods for cryogenic tank systems with insulation is currently being pursued by SSTO personnel.

8.13 What cryogenic tank design safety factor should be used? — Wong

Rationale: Both the USAF and the Orbiter use a factor of safety of 1.5 for their tanks. Methods used to design the LFBB would not differ from those methods currently used by NASA for loads determination, street analysis, and material properties. Reusable cryogenic (LOX) tanks flew on X series aircraft.

8.14 What is the maximum ullage pressure seen in the FBB main propellant tanks? — Toelle

Rationale: The maximum pressure seen in the LO_2 tank is 92.6 psig. The maximum pressure seen in the RP-1 tank is 43 psig.

8.15 LO_2 tank will shrink on the order of 1 ft during propellant loading. How does the structure accommodate this? Masciarelli/Wong
Rationale: Only secondary structure to attach the wing fairing to the top of the booster is required on the upper surface of the booster. All bending loads will be carried through the tanks and intertank structure. Hard points for the wing and canard attachment will be required. Canard hard point should not be a problem since it will be located at the intertank. The wing attach point is aft of the LO_2 tank in the aft skirt area. The detail design of these attach points is not an issue because experience exists from design of winged X-vehicles that used cryogenic propellants. All structure will be designed to accommodate thermal contraction and expansion.

8.16 What structure is required on the upper surface of the LFBB? Masciarelli/Wong
Rationale: The only structure required on the upper surface of the booster is that needed to hold the wings and canards in place during ascent. This structure also accommodates the RP-1 downcomer. This structure does not support the axial loads seen during ascent. These loads are supported by the propellant tanks and the intertank.

8.17 Can wing fairing be eliminated? Masciarelli
Rationale: Wing fairing could be eliminated. However this may require an increase in wing structure to provide sufficient stiffness during ascent, an increase in wing TPS to handle the different heating environment, and possible adverse affects on the ascent aerodynamics of the Shuttle. A study to trade these impacts versus the operations costs associated with an expendable shroud is needed. Assume that the shroud is required until this trade study is completed.

9.0 Thermal Protection

9.1 How can we avoid the use of external TPS? Curry
Rationale: A thermal/structural assessment using a heat sink approach forward of the lox tank indicated that either aluminum or titanium could be used as a heat sink TPS. Thermal results indicate a TPS blanket must be bonded to the lox tank insulation to prevent exceeding the cryogenic insulation temperature limit.

9.2 If external TPS is required, how can we facilitate ground operations (inspections, etc.) to achieve quick turnaround? Curry
Rationale: Ground operations associated with the inspection of the orbiter AFRSI blankets should be reviewed and unnecessary steps/paper work eliminated to facilitate quicker turnaround.

9.3 If external TPS is required, can we fly (FBB return cruise) in adverse weather conditions without incurring costly TPS damage? Curry
Rationale: Adverse weather conditions will probably cause some damage to the Lox tank TPS/ insulation system. Ground tests/aircraft flight tests in adverse weather conditions should be conducted to establish threshold damage limits and extent of damage.

9.4 Actual/fabrication limits, installation requirements for minimum TPS thickness. Curry
Rationale: The TABI blankets have a minimum thickness of 0.25 inches. The Rohacell foam minimum thickness is not known.

9.5 Fabrication/installation/servicing of insulation required to prevent ice buildup on cryogenic tanks Curry
Rationale: The thermal analyses have used a minimum thickness of 1 inch of Rohacell foam thickness to prevent ice buildup on the LO_2 tank. This thickness is consistent with Orbiter ET tank values for SOFI.

9.6 Cost, schedule, certification of advanced TPS (AETB-8, CFBI, etc.) Curry
Rationale: The Access-To-Space Option 3 Team identified a 4.05M cost for the TABI blankets to go from a TRL 4 to TRL 6 in a 6 year time period. The cryogenic foam costs would be greater. NRA costs for a reusable cryogenic propellant tank system have been estimated at 36M over a 3 year period. The reusable cryogenic insulation is contained within this cost estimate.

9.7 TPS materials suitable for FBB mission — Curry
Rationale: TPS materials considered in this study are AFRSI and TABI blankets for TPS, Rohacell foam and SOFI (ET tank insulation) for cryogenic tank, Aluminum/Titanium for hot structure.

9.8 Reusability of TPS (installation, inspection, maintainability, durability) — Curry
Rationale: Reusability, installation, maintainability, durability can not be assessed without testing and actual part fabrication. Based on Shuttle experience, the proposed coated TABI blankets should provide increased reusability and durability.

10.0 Ascent Propulsion

10.1 Main propulsion system design — Toelle
Rationale: Main propulsion system design inputs have been received and are included in the Liquid Flyback Booster Data Base.

10.2 FBB ascent propellant depletion procedure (fuel versus oxidizer depletion) — Toelle
Rationale: The boosters will run until the oxidizer has run to depletion. When the depletion of oxidizer is sensed in the downcomer the engines will be shutdown. Depletion of the LO_2 relieves ground operations concerns of having cryogenics on-board at landing.

10.3 Should the residual FBB ascent propellant be dumped? — Toelle
Rationale: No. Residual propellant will remain on-board. This will increase the landing mass, but will alleviate environmental issues.

10.4 Hydrocarbon fuel specifications for the F-1A engine — Toelle
Rationale: Out of the scope of this study. Re-address in Phase A.

10.5 Hydrocarbon fuel specifications for the RD-170 engine — Toelle
Rationale: Out of the scope of this study. Re-address in Phase A.

10.6 Modern specifications for a hydrocarbon fuel (RP-1) — Toelle
Rationale: Out of the scope of this study. Re-address in Phase A.

10.7 Fuel commonality (MPS, RCS, air-breathing engine) — Toelle
Rationale: Separate tanks were selected to support the ascent propulsion, RCS, and air-breathing engine. This was seen as the least complex approach and the worst case from a packaging and mass standpoint. Detailed integration could be addressed in Phase A.

10.8 Oxidizer commonality (MPS, RCS) — Toelle
Rationale: Separate tanks were selected to support the ascent propulsion and RCS. This was seen as the least complex approach and the worst case from a packaging and mass standpoint. Detailed integration could be addressed in Phase A.

10.9 Separate tanks for ascent/RCS/ABE propellant — Toelle
Rationale: Separate tanks. See issues 10.8 and 10.7.

10.10 Propellant slosh damping and natural frequency — Toelle
Rationale: Detailed design in these two areas was seen as being beyond the scope of this study. However, historical factors were included in the mass estimates in order to capture the mass of these elements.

10.11 F-1A and RD-170 operability, maintainability, serviceability — Toelle/Westrope
Rationale: The operability, maintainability, and serviceability of the RD-170 engine is documented in the ICD provided by Pratt & Whitney. The F-1A would be similar in nature, but detailed information is not available at this time.

10.12 Does the system require a POGO suppression system Toelle
Rationale: The manufacturer of the RD-170 engine claims that a POGO suppression system is not required on the Energia boosters or on the Proton launch vehicle. The assumption for this study is that a POGO suppression system is not required. If POGO suppression is required, then different propellant valves can be used.

10.13 Determine replacement ascent engine credit by using parts count or some other method. Campbell
Rationale: The RD-170 was designed for ten flights. They currently believe that all the useful life for all components will be depleted by the end of the tenth flight. We must now assume no trade-in value, but it is a potential for future savings in the program. An extended life program can be initiated that will extend the life of some, if not all, components through refurbishment.

10.14 Do engine purges use missile grade air or GN_2? Campbell
Rationale: The ICD refers to the purge gas as "dry air", but in fact gaseous nitrogen is used. GN_2 should be OK to plan on. The SSME uses GN_2 and GHe in accordance with SE-S-0073. The ET is shipped to KSC with "Missile Grade Air" in the LO_2 and LH_2 tanks. Questions should be directed to James England at (407)867-2759.

10.15 Engine startup sequence and thrust levels Toelle
Rationale: The engine start sequence will have to be a staggered start. The exact sequence will be determined based on: startup and liftoff loads, percentage of engine(s) thrust level required at liftoff release, shutdown loads in case of an abort during start sequence, and other items. This will be refined post hold-down/release design, and the above data being generated. This is beyond the scope of this study.

10.16 What is the procedure for landing with LO_2 and venting? Campbell
Rationale: The LO_2 tank will be allowed to vent during flyback/landing/rollout. A positive pressure valve will keep atmospheric air from entering the tank. Safing procedures can start after approximately 5 minutes of landing. The tank will be venting a GO_2/GHe mixture. Tank may have as much as 3% LO_2 in the bottom. Tank pressure should be less than 0.2 psig.

The fuel tank will be pressurized with He to about 17 psig. After landing and rollout the tank pressure will be about 2 psig. Residual RP-1 will be in the bottom of the tank. There should be no constraints on safing operations.

11.0 Separation Propulsion

11.1 What is the booster separation mode if initiated prior to FBB burnout? Templin
Rationale: If a separation is required before booster burnout, then the boosters will be ditched in the ocean. The separation motors will still fire in the same manner as done for a nominal mission.

11.2 Separation motor propellant (solid / liquid) Toelle
Rationale: Solid Propellant. The booster separation motors used on the RSRMs were baselined for the LFBBs. A more comprehensive design should be pursued in a Phase A study.

11.3 Sizing (thrust, duration) of FBB separation motors Toelle
Rationale: The booster separation motors used on the RSRMs were baselined for the LFBBs.

12.0 RCS Propulsion

12.1 Liquid RCS propellant options (MMH/NTO, LO_2/RP-1, etc.) Riccio
Rationale: LO_2/RP was selected due to the potential technology transfer to the Orbiter. A LO_2/hydrocarbon could be included on the Orbiter in future builds. This selection should be re-addressed in a phase-A study and the selection should be based on the lowest life cycle cost system.

12.2 Fuel commonality (MPS, RCS, air-breathing engine) Riccio
Rationale: Fuel commonality is a mass and turnaround operational benefit. The booster design includes separate tankage for ascent propulsion, RCS, and air-breathing propulsion so common propellant is not a design issue.

12.3 Oxidizer commonality (MPS, RCS) Riccio
Rationale: Oxidizer commonality is an operational benefit. The booster design includes separate tankage for ascent propulsion and RCS so common propellant is not a design issue.

12.4 RCS thruster location(s) McSwain/Riccio
Rationale: Four thrusters are required for left and right yaw directions. Three jets are required for left-up, left-down, right-up, and right-down directions. There are a total of 20 thrusters in the same configuration as the Orbiter without verniers and +x thrusters. All of the thrusters are integrated into the aft boattail of the LFBB.

12.5 Estimated RCS propellant requirement (mass) Riccio
Rationale: The usable RCS propellant load is estimated at 936 pounds. 198 pounds of propellant has been allocated for reserves and residuals.

12.6 Estimated RCS thrust level requirements McSwain/Riccio
Rationale: The thrusters are assumed to be in the 500 to 1000 pound class.

12.07 What are the specifics of implementing LO_2/HC for Orbiter OMS/RCS? Riccio/Boyd
Rationale: The Access to Space Option 3 OMS/RCS input has been reviewed. In that effort, a candidate O_2/HC system using liquid oxygen storage and ethanol as the fuel was recommended for advanced Orbiter. The analysis performed showed that the LO_2/Ethanol system would fit volumetrically in the current mold line of the Orbiter. However, this effort assumes a Block II type Orbiter would be built including complete rework of the Orbiter and OMS/RCS. This effort would require design, analysis and layout of new tanks, components, engines, and pod structure.

O_2/RP-1 for Orbiter: Based on the analysis performed for the Access to Space Option 3 O_2/Ethanol effort, an O_2/RP–1 system would fit into the current mold line of the Orbiter. This is based on a comparison of expected performance and storage properties of RP-1 versus ethanol.

RCS: During the LFBB study, a O_2/HC system using GO_2 and RP-1 was recommended for implementation on the LFBB. DDT&E of this system would address approximately three-quarters of the Orbiter RCS implementation. Specifically it would not address RCS supercritical O_2 storage, vaporization and LO_2 control component issues.

OMS: The LFBB does not require an orbit insertion and deorbit system, therefore O_2/HC implementation for Orbiter OMS would not be address during the LFBB effort. This includes pressurization, tankage, control components and engine issues.

13.0 Power

13.1 Identify supported functions for each mission phase Le
Rationale: Pre-launch: avionics and power system components. Ascent: avionics and power system components. Separation: avionics, power system components, pyrotechnic initiators and booster separation motor ignitors. Reentry/Flyback: avionics, power system components, RCS, wing & canard deployment mechanisms, aerosurface actuation, and air-breathing engine (ABE) ignition. After ABE ignition the ABE provides vehicle power until wheelstop. This includes all EMSs, avionics and power system.

13.2 Identify integral power sources (e.g. main engine thrust vector control) Le/Loffi
Rationale: The boosters will operate on the 28VDC power system during ascent and separation. The main engine TVC was supplied by power bleedoff from the main engines. After separation the 28VDC power system will supply power to all equipment except the EMAs and deployment mechanisms. The 270VDC power system supplies power to the aero control surfaces until the

air-breathing engine is started. Once the air-breathing engine is started it can supply all of the required power needs of the vehicle.

13.3 Power source (trade to achieve desired power density and energy density) Le
Rationale: Rechargeable Silver-Zinc (Ag-Zn) batteries were selected due to their high rate deep discharge, reusability, availability, and the low energy requirements. The batteries have a good volumetric density and are less expensive than fuel cells. The batteries selected have a high charge retention and offer low complexity.

13.4 System redundancy requirements during ascent and decent Le
Rationale: The power system is assumed to be two-fault tolerant for all mission phases.

13.5 Definition of power system components Le
- -source (battery, fuel cell...)
- -distribution and control(switching, cable...)
- -loads (busses and end users)

Rationale: The power source consists of 3 28VDC silver zinc batteries (128 lb) and 3 270VDC silver-zinc batteries (189 lb). A battery management and distribution system provides charge/discharge logic, switching controls and interrupters, and status voltage/current to the flight data system. Cabling and connectors to all of the power users has been estimated and is listed in the mass properties statement.

13.6 How much Orbiter electrical power is supplied to the boosters during pre-launch & ascent? Le
Rationale: It is assumed that no power is supplied to the boosters from the Orbiter.

13.7 Can the jet engine be used as a primary power source during flyback? Robertson
Rationale: Air-breathing engines typically provide shaft power to drive auxiliary subsystems, including an electrical generator and a hydraulic pump. At this time we are assuming that the air-breathing engine can provide sufficient electrical power for the flyback and landing phases. No systems requiring hydraulic power have been identified. This question has been forwarded to individuals with expertise in air-breathing systems.

13.8 Will the jet engine supply electrical and/or hydraulic power? Robertson
Rationale: As noted in Issue 13.8, the shaft power from the air-breathing engine should be available to drive auxiliary devices such as hydraulic pumps. Whether or not we can purchase an off-the-shelf engine that meets the FBB power supply requirements remains unknown. This question has been forwarded to individuals with expertise in air-breathing systems.

14.0 Actuation

14.1 Method of Mechanical Actuation Loffi
Rationale: Electric actuation was chosen for movement of the aerodynamic control surfaces. Whether the actuators are EMAs or EHAs is beyond the scope of this study and should be pursued in a Phase A study.

15.0 GN&C

15.1 RD 170 uses single or dual port electro hyd. actuator. May not be adequately redundant McSwain
Rationale: The Shuttle depends on a four port TVC actuation system to vote the independent commands from the Orbiter four string avionics system to provide two fault tolerance. A single or dual port actuation system is inconsistent with the four string Orbiter avionics system.

Recommendation: Replace RD170 actuators with four port actuators consistent with Orbiter system.

15.2 Eight actuators to control for each RD-170 engine McSwain
Rationale: The Orbiter ATVC driver box can command six Orbiter main engine actuators and four booster actuators with the current configuration. For a LFBB booster configuration consisting of a right and left booster each with two RD170 engines there is a total of 32 actuators (28 additional from the current configuration). In addition the four bells of each engine must be gimbaled in unison to avoid bell collision.
Recommendation: Provide a controller box on the booster side that accepts the current output of the ATVC driver and outputs 8 identical commands to the RD170 actuators. This would allow the right and left side booster engine bells to be moved in unison in pitch and yaw. Roll motion of the vehicle would be achieved as it is with the SRBs by differentially moving the right and left bells in pitch. No provision would be made to independently move one bell at a time.

15.3 Orbiter/Booster Command Interface-Are Orbiter avionics and software affected by the FBB or does a new interface box translate all Orbiter commands? McSwain
Rationale: The Orbiter avionics and software are affected by the FBB in a number of ways. New boxes must be added to convert commands from the ATVC driver to be consistent with number of actuators required for RD170s. An electronics box to interface with the engine to allow control of throttle and shutdown of the engines must be added. A change to the abort logic in the software may be required because of increased staging velocity. Changes will be required to the onboard redundant set launch sequencer software. Software associated with monitoring the SRB chamber pressure to start preparations for and command separation for SRB separation must be removed and replaced with software to command the safe shutdown of the LFBBs.

15.04 What is the booster guidance (adaptive, force feedback) ? McSwain
Rationale: Adaptive guidance was selected for first stage guidance.

16.0 Data Management

16.01 Rocket Engine Controller Reqt. (HW & SW). Who is responsible? Ankney
Rationale: Definition of Rocket engine controller requirements was considered to be beyond the scope of this study. For the purpose of data bus loading estimation, the assumption was made that each rocket engine controller requirements are equivalent to that of the Orbiter main engine.

16.02 GN&C Integrated Flight Management Unit (IFMU) Fault Tolerance Ankney
Rationale: The issue posted was whether the reliability of a design with redundant boxes with physical separation can be duplicated in a single box configuration. The issue is considered to be beyond the scope of a feasibility study. For power, weight, volume and cost estimation, the study assumed separately housed boxes.

16.03 STS FSW impacts due to the FBB Ankney
Rationale: Assuming the booster rocket engine interface unit (EIU) I/O requirements are similar to the SSME controller, a preliminary study reveals a potential I/O handling problem with the current orbiter data processing system. There is not sufficient time margin to acquire the 4 EIUs worth of data, for the LRBs, and preserve sufficient margin for special processing, such as a one bus I/O error. This concern should be revisited in phase A study when the I/O requirements of the booster engine are better defined.

Transport Lag - Transport lag, for issuing opposing engine shutdown commands in the event of a LRB engine failure, was studied using the shuttle SSMEs as the model. PASS is capable of issuing a shutdown command in 20 - 60 milliseconds, depending on when the GPC polls occurs. However; current software requirements prohibit the software from acting upon a failure notification of an SSME for a count of 3 minor cycles (120 milliseconds). This was implemented to avoid taking action on a "transient" engine failure indication. It is assumed similar precautions would be taken for the LRB engines. Therefore, under the current implementation the time to issue a shutdown command is 120-160 milliseconds.

I/O Handling and Capacity - Most of the current SRB I/O (i.e. SRB acquisition, SRB rate gyro pitch and yaw inputs, SRB rock and tilt gimbal commands, and separation commands) will be maintained with the possible exception of SRB chamber pressure inputs, which may require burning a new PROM for the MDM. Additional I/O for SSME like EIUs require:

32 words input/EIU on MFE = 128 total
6 words input/EIU on HFE = 24 total
1 word output/EIU on HFE = 4 total

Preliminary analysis indicates that MFE I/O margin exists to accommodate additional words. *Based upon the current implementation of the HFE EIU I/O, there is not sufficient time margin to acquire the 4 EIUs worth of data, for the LRBs, and preserve sufficient margin for special processing, such as a one bus I/O error.*

Abort Mode Processing Source Lines of Code (SLOC) Estimate - It is probable that all manner of abort targeting will be affected by the addition of throttling LRBs. A conservative estimate would assume a 50% alteration in the existing core abort targeting software, which is currently 2000 SLOCs total. Therefore, it is estimated that 1000 SLOCs of abort software would be affected by this change.

Overall SLOC Estimate - The following is the estimated number of SLOCs that would be affected by this change.

Redundant Set Launch Sequencer (RSLS)		100
SOP/OPS		600
Flight Control TVC/SOP		300
Throttling (guidance)		50
Switches/displays		50
SSW I/O		150
Abort Targeting		1000
	Total	2250

Back-up Flight Software (BFS) - Impacts to BFS are estimated to be equal to PASS. Estimate 2250 SLOC changes.

16.04 Definition of the DMS — Ankney

The LFBB is controlled during booster phase by the Space Shuttle Orbiter, and after separation and during return to base by on board stored commands with the capability to accommodate ground initiated commands.

The primary function of the LFBB Data Management System (DMS) is to provide telemetry data gathering and downlink service. It also provides system initialization, configuration control, command processing, timing control, Fault Detection Isolation and Reconfiguration (FDIR), data processing and computation for all on board subsystems other than GN&C system. The DMS monitors, records and sends to the ground by telemetry the health and status of the various vehicle systems as developed by distributed Vehicle Health Management System (VHMS) and the interfaces with the communication system for receipt of ground initiated commands and for telemetry formatting.

DMS is a fail operational, fail safe system. It consists of four DMS General Avionics Processors (GAP), two Pulse Code Modulation Master Unit (PCMMU), and seven operational instrumentation (OI) Multiplexer/Demultiplexer (MDM) units. There are twelve 1553B buses which provide internal communications within the LFBB throughout the mission. External communication with the orbiter are similar to the analog/discrete signal connections currently exist. The Downlink telemetry functions are performed via OI MDM and PCMMU. A phase A trade study may be prudent to determine the economical benefits of moving PCMMU downlink functions into GAP and reducing the DMS fault tolerance to be one fault tolerance. For this study phase, two fault tolerance of the DMS was assumed to be achieved by a voting process in a four computer set. A preliminary avionics functional architecture is shown in Figure 5.9.3.1-1 of the main document.

Each of the four DMS GAPs consists of a processor board, an internal mass storage device and an interface to three 1553B data busses. One of the 1553B data busses is used for interface to vehicle command and control flight critical busses and the other two 1553B data busses for interface to the PCMMUs and the OI MDMs. The sensors vehicle systems OFI and DFI interface with the OI MDMs. A functional block diagram of the GAP is provided in Figure 5.9.3.1-1.

Major Hardware Components
- General Avionics Processors (4)
- PCMMU (2)
- MDM (7)
- 1553B data cables (12)

Software Line of Code (SLOC) Estimation

GN&C:	79,000 SLOC
SDS I/O & System Mgt.	60,000 SLOC
SDS Operating System:	40,000 SLOC
SDS Data/File Management:	15,000 SLOC
Vehicle Health Monitor:	20,000 SLOC
Booster Engine Controller:	15,000 SLOC
Command Processor:	5,000 SLOC
Comm. & Track Control:	1,000 SLOC
Test & Checkout:	25,000 SLOC
Downlink telemetry	30,000 SLOC
Total:	290,000 SLOC

16.05 What Orbiter software mods are required to be able to shutdown a booster engine? McSwain

Rationale: The Pratt & Whitney discussion of the operating characteristics of the RD170 indicate that the RD170 should be throttled to 50% thrust level to minimize water hammer. The engine is then shutdown pneumatically by commanding the thrust control valve to cutoff fuel flow to the preburners. The pneumatic valves automatically close during engine deceleration as propellant pressures drop below the level required to keep them open.

Estimate: Software modifications would consist of comparing navigated velocity magnitude against desired velocity magnitude for 50% throttle point, issuing a command to throttle to 50%, comparing velocity magnitude against the desired staging velocity and issuing the command to close the thrust control valve when within a delta v equivalent to what's imparted during tailoff of the desired staging velocity. Source lines of code included in the EK estimate.

Recommendation: A provision to monitor for fuel depletion cutoff should be provided. Both boosters should be commanded off at the same time. Any significant lag between shutdown of the right and left booster would cause the stack to under go yawing and rolling motion similar to what is experienced during SRB tailoff with a thrust mismatch.

16.06 Document Orbiter avionics hardware changes. Ankney

Rationale: Orbiter hardware changes are limited to the addition of engine interface units for the LFBBs. These units would be placed on the Orbiter along with a power and data connections.

17.0 Tracking & Communications

17.1 Use GPS or MSBLS? (trade) Nuss

Rationale: GPS was selected for the LFBBs. It is assumed that Differential GPS technology will be mature enough to make this a cost effective solution over MSBLS. This approach can also be used to bring GPS on-board the Orbiter if it is not already in place.

17.2 If GPS, then either DGPS or Pseudolite (trade) Nuss

Rationale: This is a design issue which will be addressed during a phase A study.

17.3 If MSBLS, then either SLF or other landing site (trade) Nuss
Rationale: Since GPS was selected this is a non-issue. MSBLS does not need to be installed at the landing sites.

17.4 Antenna coverage analysis is required to determine placement locations (trajectory information rqd) Nuss/Sham

- Can MILA/BDA/PDL support 3 vehicles at the same time?
- TDRS versus ground stations versus handoff (trade)

Rationale: Locations of antennas (2 omni antennas planned) cannot be determined yet due to insufficient trajectory and vehicle attitude information available. Definite locations can be determined by performing computer simulation and analysis base on coverages. However, the antennas will be flush mounted (without need of antenna booms or deployment) and be placed 180° away from each other to provide maximum coverage. The size of the antenna is approximately 10 inches in diameter and 4 inches deep.

- Can MILA/BDA/PDL support 3 vehicles at the same time?

Based on preliminary description of LFBB flight path and the known communications range requirement (250 nmi), MILA should be able to support the necessary comm requirement. MILA has 8 receivers and 2 antennas currently and will be able to support comm with multiple vehicles simultaneously with the SSO. However, potential modifications to the data bus capacity and data handling/routing system may be required. Cost impact needs to be assessed. MILA personnel will need to determine the potential impact and its associated cost.

- TDRS comm vs. GSTDN direct comm vs. handoff (trade)

Handoff from direct ground link to TDRS will complicate the comm system tremendously due to signal format incompatibility and other data processing changes. Employing a direct comm system using the existing NASA STDN ground stations will be the most cost efficient way to go, accounting both design/development and operational costs. If use of TDRS is desired, the multiple access (MA) protocols and signal formats must be following (note that the Shuttle uses the TDRS single access (SA) system) and thus complicate the design of this comm system. The TDRS MA service is used by many other users/vehicles which means scheduling conflict may arise from time to time. If we can use the GSTDN link and satisfy the requirements, it is the recommended way to go. The obvious trade of between using TDRS and GSTDN is performance vs. cost. A more detailed study is required to determine exactly how much can be gained by using TDRS.

17.5 Data rate requirements - may drive the system design. Ankney
Rationale: Definition of the data rate requirements of each subsystem was considered to be beyond the scope of this study. For the purpose of this feasibility study, assumption was made that the data rate requirement of each booster is same as the Orbiter.

17.6 Redundancy consideration-independent strings vs. cross-strapping (size/wt/pwr vs. reliability) Nuss/Sham
Rationale: The LFBB 2-way comm system will consist of 2 independent strings of electronics sharing a set of omni antennas (2). Assumptions were made by the Avionics team that loss of comm will not impact the ability of the boosters to safely land. This system will provide a 1-fault tolerant system. Based on the reliability of the electronics (basically off-the-shelf equipment with minor modifications) and the unlikelihood of losing both transmit and receive capabilities of the system simultaneously, it was determined that a dual-string system will satisfy the requirements. A single RF switch is employed in the design to switch between the 2 antennas and between the strings. Only one switch is used based on its past failure history and its known reliability; the switch will failed closed to ensure an open path to an antenna. Only one set of antenna is required because antennas are passive elements and have a minimal likelihood of failure. Size/weight/power consideration is not a driver since the modern electronics consume much less resources and use less space (volume/weight) than existing Shuttle equipment.

17.7 Radio Frequency Interference (RFI) environment characterization - how will this affect the coverage? and what can be done to minimize the effects? what about multipath effects to acquisition (false lock considerations)? Sham
Rationale: It is difficult to accurately characterize the RFI environment without extensive data collection and subsequent verification of the data. However, based on the known ground station capability and other operational requirements (i.e., the relatively close range of operation), RFI should not affect this link (not a driver to system design-- no mitigation is required). The coverage to the LFBB from the ground stations within line-of-sight will be provided but continuous communication cannot be guaranteed due to physical limitations. Effects of these temporary and short "blackouts" should not affect the operation of the booster. False acquisition will be mitigated by the inherent design in the onboard receiver. No impact.

17.8 Is 2-way comm required? Operational cost needs to be considered. Sham
Rationale: 2-way communication is assumed to be required. The planned LFBB comm system will provide a 10 kbps uplink (command) and 192 kbps downlink (telemetry) capability using the existing STDN capability (direct comm between LFBBs and ground station).

18.0 Reserved

19.0 Air-breathing Engines (ABEs)

19.1 Operational regime for the ABEs (trade supersonic vs. subsonic) Robertson
Rationale: Subsonic cruise has been baselined for the FBB because the cruise range is relatively short (less than a few hundred nautical miles) and it is much simpler to integrate a subsonic propulsion system. Because of its moldline (blunt nose, relatively thick wings and flared aft fuselage), the FBB would require a very high thrust level to sustain supersonic cruise flight.

19.2 If subsonic, what type of ABE (trade turbojet vs. turbofan) Robertson
Rationale: For the purposes of completing a feasible Pre-Phase A design, a single turbofan engine has been selected for the FBB. The thrust-to-weight ratios of turbofan and turbojet engines are comparable, roughly 5 lbf of thrust per lbm of engine. The primary advantage of a turbofan is its low thrust specific fuel consumption (0.3 to 0.5 lbm/hr/lbf). A typical turbofan engine also provides several times more thrust (in a non-afterburning more) than a typical turbojet engine. The disadvantage of a turbofan is the large frontal area that is required to provide the fuel efficiency and high thrust level.

Turbojets are smaller in size and may be more easily packaged. The possibility also exists that we can use afterburning thrust to provide FBB takeoff capability if that becomes a requirement. The turbojet/turbofan trade has been forwarded to individuals with expertise in air-breathing systems. This issue should be revisited in future design phases.

19.3 Number of air-breathing engines (trade) Robertson
Rationale: The estimated maximum sea level thrust of 45 to 50 Klbf required to sustain FBB cruise flight at 20 Kft can be supplied by a single commercial aircraft turbofan engine. This decision is directly related to Issues 19.1 and 19.2.

19.4 Thrust per air-breathing engine (maximum sea level thrust) Robertson
Rationale: The available thrust required to sustain FBB cruise flight at an altitude of 20 Kft is estimated to be in the range of 27 Klbf, which translates to a maximum sea level thrust in the range of 45 to 50 Klbf. Candidate commercial turbofan engines in that thrust class include the General Electric CF6-80A series (Boeing 767 and Airbus A310) and the Pratt & Whitney JT9D-7 series (Boeing 747/767 and Airbus A300). The thrust-per-engine is directly related to the number of engines and the cruise altitude (Issues 19.3 and 19.5).

19.5 Design cruise altitude (trade) Robertson
Rationale: In order to establish a benchmark for the air-breathing system mass, a cruise altitude of 20 Kft has been selected for the FBB. A low cruise altitude is preferred from the standpoint of minimizing air-breathing system mass (hardware plus fuel). The air-breathing system mass is not particularly sensitive to altitude, however, and the capability to cruise at higher altitudes may offer

practical advantages, such as climbing to avoid adverse weather. Some thrust margin should be retained at the design cruise altitude (i.e. the design cruise altitude should not coincide with the operational ceiling of the FBB).

19.6 Design cruise range — Robertson

- downrange (based upon LFBB separation state) plus dispersions
- winds
- redesignation of landing site
- cruise margin for unpredicted events

Rationale: The FBB should be designed to provide a cruise range of approximately 350 nmi including a 3-s headwind profile based upon a nominal return trajectory simulation and a set of rough assumptions. The nominal downrange distance for a Mach 5.8 FBB separation state is approximately 250 nmi. The downrange dispersions have not yet been calculated. Using a 20% bogey on the nominal downrange, the dispersion would be 50 nmi. Redesignation from the Skid Strip to either Patrick AFB or the SLF should only require about 10 nmi. A 350 nmi cruise range then leaves approximately 40 nmi of range margin.

This cruise range should cover requirements arising from an STS launch, but may be insufficient for stand-alone operation of the FBB. Related sub-issues are the range dispersions associated with off-nominal flights (empty Orbiter, single-engine failure on the booster, etc.).

19.7 Design cruise endurance — Robertson

- loiter time (endurance flight in a standard flight pattern)
- loiter margin for unpredicted events

Rationale: For loiter (endurance) the FBB will trim at or near the angle of attack that provides the maximum L/D ratio. A standard jet aircraft loiter mode consists of two two-minute turns with straight legs of xxx minutes between the turns, resulting in a "racetrack" pattern with a cycle time of approximately xxx minutes. An assumption has been made that xxx cycles (xxx minutes) will provide sufficient margin for FBB phasing and contingencies.

19.8 Air-breathing engine environment (pressurized versus non-pressurized) — Robertson

Rationale: It has been assumed that the air-breathing engine can tolerate the near-vacuum that exists at the apogee of the FBB trajectory (approximately 250 Kft). Air-breathing engines routinely function at altitudes of 35 Kft and greater, where the ambient static pressure is approximately 30% or less of standard sea level ambient pressure. The intent of this assumption is to avoid adding complexity and additional failure modes which may reduce the STS launch probability. This issue has been forwarded to individuals with expertise in air-breathing engine operation.

19.9 Air-breathing engine configuration (deployed versus fixed) — Robertson

Rationale: The air-breathing engine will be fixed.

19.10 Air-breathing engine location (external versus internal) — Robertson

Rationale: For the purpose of completing a feasibility analysis for the FBB, a fixed external air-breathing engine (ABE) location has been adopted. The trade between internal and external ABE mounting involves a number of factors including internal subsystem packaging volume, aerodynamic flow effects of an external ABE and the ABE design environment (Issues 19.1 and 19.8). There is also a deployed versus fixed mounting subtrade (Issue 19.9) for an internally-mounted ABE. Air could be routed to an internally-mounted ABE via a fixed or deployed air duct (Issue 5.13) rather than deploying the engine, itself, into the free stream flow.

19.11 Mass of air-breathing system — Robertson

Rationale: The dry mass of the air-breathing propulsion system is primarily driven by the maximum required sea level thrust of the jet engine (T/W ~ 5.0). The maximum required thrust is defined by the FBB aerodynamic performance coefficients, the maximum flight weight of the FBB and the FBB cruise flight parameters (altitude, angle of attack, dynamic pressure, etc.). Secondary dry mass effects include cruise range (tank mass) and various air-breathing propulsion system design factors (e.g. deployable versus fixed pylons).

The fuel mass for the air-breathing cruise is primarily a function of the thrust delivered at the cruise altitude, the thrust specific fuel consumption (TSFC, lbm/h/lbf) and the cruise range. The TSFC is typically reported for the maximum static sea level thrust condition, although there are secondary effects related to the cruise flight conditions (altitude and velocity). The cruise range is propagated from the FBB separation state.

The mass sensitivity of the air-breathing propulsion system was evaluated for the following variables: cruise range, cruise altitude and aerodynamic dispersions.

The effect of increased range is fairly straightforward. As expected, most of the mass increase is additional fuel with small related increases in engine and tankage masses.

The effect of increased altitude is more complex. For fixed attitude flight (constant angle of attack) the thrust required for straight-and-level flight remains fairly constant with altitude, except for small performance variations due to Mach number effects. However, the thrust available from a turbine engine decreases with altitude. Thus an air-breathing engine must have a higher maximum sea level thrust rating to enable sustained flight at a given altitude than is required for sea level cruise. In order to produce 41 Klbf of thrust at altitudes of 10,000 ft or 20,000 ft, for example, an engine must have a maximum sea level thrust of approximately 52.9 Klbf or 69.9 Klbf, respectively. The benefit of the increase in the cruise altitude is that the true airspeed also increases, resulting in a shorter cruise and reduced jet fuel consumption. Typical commercial and military aircraft realize a net mass benefit from high altitude cruise since their sea level thrusts have already been sized for takeoff. For vehicles that are designed by cruise thrust requirements, however, an increase in the design cruise altitude results in net increases in both the total and inert vehicle masses. The larger air-breathing engine is also more difficult to integrate into the vehicle configuration.

Significant dispersions on the FBB lift and drag coefficients have been shown to produce relatively small effects on the overall vehicle mass. The combination of a 20% increase in the FBB drag coefficient and a 20% decrease in the lift coefficient, for example, results in a landing mass increase of approximately 2.2% (assuming that the design landing CL can still be achieved). However, aerodynamic dispersions can have a significant effect on the thrust required to maintain straight-and-level flight, particularly with the worst case combination of dispersions. As shown for the cruise altitude, the key design factor is packaging an air-breathing engine that provides the required thrust at the design cruise altitude.

The following two tables demonstrate the mass sensitivities of the air-breathing system to variations in altitude, range and aerodynamic dispersions. The FBB was assumed to have a weight of 220 Klbf (less the weight of air-breathing propulsion system) at the beginning of cruise. A cruise angle of attack near six degrees was found to produce a minimum mass system. Unless otherwise noted, the results were computed for cruise at sea level.

The following variables are in lbf and lbm:

Wveh = vehicle weight at the start of cruise
Wlanding = vehicle landing weight
ABS = weight of the air-breathing system (inert plus fuel)
ABS inert = inert weight of the ABS
Jet Fuel = loaded weight of jet fuel
Thrust Req'd = available thrust required to maintain straight-and-level flight at the given altitude
L/D Ratio = lift-to-drag ratio at the cruise conditions

Cruise Range: 200 nmi

Mission Description	Wveh	Wlanding	ABS	ABS inert	Jet Fuel	Thrust Req'd	L/D Ratio
Reference (sea level)	235506	229028	15401	8275	7126	26326	8.9
Reference @ 10,000 ft	237190	231321	17085	10629	6456	27338	8.6
Reference @ 20,000 ft	239931	234606	19824	13968	5857	28606	8.3
Reference @ +20% CD	238809	230955	18688	10049	8640	31968	7.4
Reference @ -20% CL	239045	231532	18926	10661	8265	33918	7.0
Reference @ +20% CD and -20% CL	243162	234030	23024	12979	10045	41292	5.8

Cruise Range: 350 nmi

Mission Description	Wveh	Wlanding	ABS	ABS dry	ABS fuel	Thrust Req'd	L/D Ratio
Reference (sea level)	241313	229792	21257	8494	12763	27021	8.9
Reference @ 10,000 ft	242496	232071	22353	10884	11468	27994	8.6
Reference @ 20,000 ft	244808	235360	24665	14272	10393	29230	8.3
Reference @ +20% CD	245959	231941	25790	10370	15420	32992	7.4
Reference @ -20% CL	245895	232494	25729	10989	14741	34959	7.0
Reference @ +20% CD and -20% CL	251647	235291	31456	13464	17992	42834	5.8

Reference Mission Description:
- sea level cruise
- 6 degrees angle of attack (mass optimum)
- 15 kt headwind
- 10% fuel mass margin

19.12 Constraints on ignition conditions for an air-breathing engine Robertson
Rationale: The ignition constraints that are being used in the flyback trajectory simulation are a maximum ignition altitude of 40 Kft and an maximum ignition Mach number of 0.7. These values are within the operational envelopes of the turbine aircraft engines that are under consideration. A more precise definition of airstart requirements and reliabilities has been requested from aircraft engine manufacturers.

19.13 External support needed to assist in an air-start of air-breathing engine Robertson
Rationale: Typical commercial aircraft engines incorporate electric starters which can be used to assist in an airstart operation. Typical military aircraft engines are not expected to incorporate an electric starter and, unless modified, must rely on dynamic pressure spin-up for an air restart. The decision on whether or not to add an auxiliary airstart system will be based upon the predicted reliability of achieving airstart for the selected engine. Unless engine-out capability is designed into the FBB air-breathing propulsion system, the reliability of the airstart procedure largely defines the overall probability of safely recovering the FBB.

19.14 Use of air-breathing engine TVC for trim control? Robertson
Rationale: The air-breathing engine thrust will not be vectored to control pitch and/or yaw.

19.15 Can air-breathing engine be fueled by main RP tank using an air-breather sump for fuel flow? Robertson
Rationale: This issue, which addresses a design approach for common fuel tankage, is a subset of Issue 19.16. This is a detailed design issue which is out of the scope of this Pre-Phase A study.

19.16 Separate or integrated ABE fuel tanks? Robertson
Rationale: For the purposes of this study, it has been assumed that separate fuel tanks will be used for the air-breathing propulsion system. This issue is linked to Issue 10.7, which addresses the potential for fuel commonality between the main rocket engines, the RCS thrusters and the air-breathing propulsion system. The option for common tankage does not exist without the use of common propellants. See also related Issues 10.4, 10.5, 10.6, 10.8, 10.9, 12.2 and 12.3.

19.17 Number and size of ABE fuel tanks Robertson
Rationale: The current configuration has two cylindrical fuel tanks that are located in the top side of the aft fuselage, near the rudder. The tanks are currently sized to hold a total of 10,000 lbm of jet fuel. The fuel load is expected to change as the FBB design matures.

19.18 Air-breathing takeoff capability Robertson
Rationale: Study Assumption - Booster takeoff capability is not a requirement. Sizing of the air-breathing engines for level cruise at altitude will provide go-around capability. If takeoff is desired, the design options include incorporating the additional thrust into the baseline FBB, scarring for additional engine attach points and controls, and providing thrust augmentation using rockets or external mechanical aids.

19.19 Is the air-breathing engine airstarted or electrically started? Robertson
Rationale: Representatives from air-breathing propulsion companies have indicated that high-bypass turbofans will probably require an electric starter to assist in air-starting the engine. Because of the criticality of the airstart procedure, it seems reasonable to assume that an electric starter should be baselined for the FBB regardless of the engine selection (high-bypass or low-bypass turbofan).

19.20 Is ABE airstart part of commercial acceptance testing? Robertson
Rationale: Industry representatives have indicated that air-breathing jet engines are subject to an extensive test program that includes airstart capability. Their feeling was that the jet engine selected for the Flyback Booster would require little or no additional airstart testing.

19.21 What are the angle of attack limits for the air-breathing engine? Robertson
The answer to this question is a function of the location of the air-breathing engine with respect to the FBB, the flight regime of the air-breathing engine and the design of the engine inlet. The fact that the FBB jet engine is only intended to operate subsonically greatly lessens the criticality of the engine location and inlet design relative to the design requirements for an efficient supersonic aircraft propulsion system. The FBB design goal is to provide an unobstructed, uniform flow field to the jet engine inlet over a wide range of angles of attack. The current design of the Flyback Booster booster is far from ideal in that respect. The tail-mounted engine is located above a large, flat platform that supports the scissor wings during ascent. Without a detailed assessment it is difficult to estimate the angle of attack limit. It should be possible to achieve maximum thrust at relatively high angles of attack (15 degrees or so), although design modifications may be required.

20.0 Flight Operations

Booster operation strategy

20.01 Nominal ascent operations Cockrell/Tuntland
Rationale: During nominal ascent, the vehicle guidance will be controlled by the Orbiter. Command and control of the Shuttle is at JSC beginning at tower clear. Ground monitoring procedures are the same as current RSRM strategies. Range safety is limited to thrust termination. Each LFBB communicates directly with ground. Operation will be within current Shuttle procedures and constraints.

20.02 Nominal flyback, approach and landing for two boosters Cockrell/Tuntland
Rationale: Each LFBB is managed separately. The LFBBs have priority airspace until clear. A dedicated team will be located at KSC for the flyback command and control. The LFBBs have

adaptive guidance capability. Limited ground monitoring is assumed based on onboard redundancy and a short mission duration. Ground monitoring is limited to critical systems and trajectory (e.g., thrust, fuel remaining, gear down, guidance and targeting errors. The ground also monitors weather, runway availability, and corridor clear. After separation and reentry the LFBBs each fly to a predesignated waypoint over the water where they go to a loiter mode until a ground command is given for approach and landing. Each booster will have 30 minutes of loiter capability. Runway 15 at the Shuttle landing facility is prime and skid strip 31 will be used for a backup in the event of an Orbiter RTLS or other conditions causing a redesignate. Command and control can command thrust termination and pitch down in order to abort the LFBB mission.

20.03 Post-landing operations strategy (taxi capability, etc.) Cockrell/Tuntland
Rationale: The first booster will land on the runway and will automatically taxi off of the runway to a safe area. The second LFBB lands on the same runway and remains on the runway after wheelstop. The boosters will then be safed and transported back to the processing facility.

20.04 What are the booster separation constraints (alpha, beta, q, thrust, etc.) Templin
Rationale: Current separation constraints:

Alpha : +2.0 degrees - This is done to minimize the amount of aerodynamic heat soak the external tank will experience during boost ascent.
Beta: 0.0 degrees - Flight design groundrule for sideslip angle.
Dynamic Pressure: $\leq$63.0 lbf/ft^2 - STS/SRB flight design value knocked down for 3-siqma cold SRB protection.
Thrust: Study Assumption - FBB engine thrust shall be zero pounds force at booster separation.

20.05 What happens to the aft ET/Booster attach links after separation? Peterson
Rationale: The booster attach links will separate in the same manner as the SRB/ET links. The links will explosively separate with half of the link remaining on the ET and the other half remaining on the booster.

20.06 Can the LFBB be towed on its landing gear? Peterson
Rationale: Yes. Rolling gear are part of the booster design. Transport of the boosters from a remote site (Skid strip) can be accomplished on a transporter modified for this purpose.

20.07 Booster/Engine startup (do all engines need to be operating nominally before the hold down bolts are released?) Peterson
Rationale: Study Assumption - All Orbiter and booster engines must be operating nominally before the hold down bolts are released.

20.08 Flyback Control Strategy (autonomous, RPV, limited reconfig) Peterson
Rationale: Study Assumption - Control of the boosters is autonomous with limited reconfiguration capability. Two-way communication with the boosters is required. Redirection of the boosters to an alternate landing site after an Orbiter RTLS is an example of the limited reconfiguration capability.

20.09 How do LFBB interact with other aircraft in flight (i.e. helicopters, STA FAA aircraft)?(What aircraft are flying during countdown and launch?)
Rationale: The following represent the aircraft that normally support a launch. For any given launch there may be some variations. (1) NASA Shuttle Training Aircraft over LC39, (2) "Search 1" and possibly a backup helicopter over the Banana River, (3) HC-130 about 170 - 200 miles down Range, (4) "Relay 1" light aircraft radio relay 4,000 - 8,000 ft. over Indian River, (5) "Clearance 1" Falcon HU-25A off Port Canaveral (Coast Guard), (6) "Patrol 1 & 2 BE-90 over Indian River. There are also "Ready Alert" aircraft usually at Jacksonville, Florida; Brunswick, Georgia; Charleston, South Carolina; and several local "Jolly Green Giant Hueys' that may be up if an RTLS develops.

21.0 Ground Operations

21.01 Primary land landing site trade (SLF, Skid Strip, Patrick AFB, new strip) Cockrell/Tuntland

Rationale: The primary landing site will be runway 15 at the SLF.

21.02 Alternate land landing site Cockrell/Tuntland

Rationale: The alternate landing site will be runway 31 the Cape Canaveral Skid Strip.

21.03 What is the propellant loading sequence and location? Feaster

Rationale: Assuming that there no hypergols associated with the LFBB.
The RP-1 and the JP-4 would be loaded at some convenient point in the processing flow following arrival of the vehicle stack at the launch pad but prior to beginning the countdown. LO_2 would be loaded into the boosters after loading the ET to minimize icing and GO_2 overboard dump. GO_2 venting from each LFBB will be to atmosphere away from the Orbiter with no umbilical.

The LFBB propellants (both LO_2 and RP-1) will be loaded from umbilicals located at the aft of the boosters through new Tail Service Masts (TSMs). This will require some onboard piping to fuel the forward tank. The alternative would be to construct a new umbilical tower to the east of the launch vehicle at the pad and modify the existing pad Fixed Service Structure with a new swing arm to fuel the forward tank of both LH and RH boosters. The aft umbilicals are less of a KSC impact since the MLP will already require extensive modifications. It is anticipated that the JP-4 will be loaded with drag on lines from a tanker.

21.04 What is the minimum turnaround after a launch scrub? Feaster

Rationale: Minimum LFBB turnaround time after a launch scrub will probably be dictated by Shuttle turnaround operations. For a pre-ignition scrub, turnaround will depend on the cause of the scrub and the required work to resolve the problem. Historically, scrubs are usually caused by liquid propulsion problems or day of launch weather problems. For a post-ignition scrub, assuming LFBB engines will either start after SSME ignition or at the same time as the SSMEs, SSME scrub turnaround takes approximately three weeks to prepare for the next launch attempt. This could be longer depending on the nature of the problem and the amount of time required to resolve the problem. The major LFBB post-ignition scrub turnaround task would be engine inspections and fuel flush operations which are estimated to take five work days.

21.05 What are the present Shuttle procedures and constraints that the LFBBs must operate within? Feaster

Rationale: (1) The VAB becomes a non-hazardous area and thus an area to house those working in the vicinity of the VAB on a routine basis and as a result old temporary offices now in use won't need to be replaced or refurbished, (2) all facilities associated with SRBs could be eliminated or reassigned, (3) eliminate the need for on-site as well as off-site support in processing the SRBs , (4) start the process of eliminating hypergol systems and hydraulic systems with a proof of concept demonstration on the LFBB for consideration for use on the Orbiter.

21.06 What is the KSC position on landing with LO_2 (Residuals)? Feaster

Rationale: There is concern with the quantities of LO_2 at landing and the potential for a fire in an oxygen rich environment. To help with these concerns the design should include an overboard dump of residuals to minimum quantity/pressure to the point of avoiding tank collapse or moisture contamination. Ground safing and processing may be workable provided ground monitoring capability is provided. This is an issue that will require more evaluation during the next phase of the study but at this point it is felt that this is a workable issue.

21.07 Identify what gases are considered hazardous. Feaster/Thornburg

Rationale: The list of hazardous gasses is very long. It would be better if the list of intended gasses were provided for our review. We could then determine which are classified by safety as hazardous and what special handling methods are required and maybe recommend an alternate.

21.08 What are the savings associated with eliminating hypergols including LCC of shutting down the HMF? Feaster/Thornburg

Rationale: HMF costs are shown below.

No Hypergolics

Quantifiable Reductions:	Costs Fixed	Costs Recurring
SCAPE		
Suits 375 @ $12k/suit =	$4,500k	
replace 15% / year (maintenance) =		$675k
Vans 8 @ $28k/van =	$224k	
replace 15% / year (maintenance) =		$33.6k
Backpacks 120 @ $20k/ea =	$2,400k	
replace 15% / year (maintenance) =		$360k
SCAPE	~ $7,124k	~$1,069k/yr
	only CoF, 1994 $s	
Facilities		
Hypergolic Maintenance Facility (21 people) =	$30,112k	$1,680k
Scrubbers 18 @ $1,000k/each =	$18,000k	
Hanger S Annex (76 people) =	$17,154k	$6,080k
Facilities	~ $65,266k	~$7,760k/yr

Non Quantifiable Reductions:

"Paper Trail" required for all SCAPE operations

"Area Clear" required for all SCAPE operations

All SCAPE personnel Highly Trained and Certified to handle Hypergolics

Special Training for fire dept on controlling this type of substance

Thorough physical exam given to each new SCAPE employee

Yearly "fit-checks" given to each SCAPE employee

Routine physical exam given to each SCAPE employee every 3 years

Special ventilation in buildings no longer required

Other Considerations:

Hypergolics used by Air Force, USBI, EG&G, NASA (will they all go away?)

Eliminating 80 or 90% does not eliminate the Infrastructure

Reduction in processing time and pad time

Hypergolics are very expensive relative to conventional fuels note, these are 1993 costs (MMH $25.70 /lb, N_2H_4 $24.00 /lb vs LO_2 $0.035 /lb, LH $1.50 /lb, RP-1 $2.60 /gal.)

30% H_2O_2, used for cleanup, is expensive at $ 5.45 /gal.

The yearly Quantifiable costs for Hypergolics are ~ $ 8.9 M.

The Sunk costs for Hypergolics are at least $ 72.3 M.

21.09 KSC needs more info on RD-170 maintenance. Peterson

Rationale: Mr. Charles Limerick is responsible for government engine business at United Technologies Pratt & Whitney. He can be reached at (407) 796-7924 or the following mailing address:

Mail Stop 702-91
P.O. Box 109600
West Palm Beach, FL 33410-9600.

A facsimile was forwarded from the RD-170 Operating & Interface Document detailing the engine operating characteristics. Included will be engine pre-start/pre-launch preparation and turnaround between operations. Contact has been made with Pratt Whitney and some data has been provided. Even with this data there is still a lot that is not known about what tasks must be performed between flights. After reviewing the data provided and talking to several people KSC's preliminary timelines for the processing of the RD-170 remains unchanged.

21.10 LFBBs towed on gear or transporter, road bearing strength, and tire design. Can the booster be towed on beach road? Peterson/Schultz
Rationale: Tire selection is based on design approach outlined in Aircraft Design: A Conceptual Approach by D. P. Raymer. A rolling mass of 225,000 lb. is assumed for the LFBBs for towing purposes. The load distribution on the landing gear will be 90% for the main gear and 10% for the nose gear. The load per tire for a 4-wheel main gear is 50,625 lb. A "Three Part Name" tire was selected from a table of tire outlining specific tire data. Tires selected for the main gear are rated for 235 knots and a maximum load of 63,700 lb. The maximum width is 20.5 inches and maximum diameter is 52 inches. The tire's contact area with the pavement is 353 square inches. With a weight on the wheel of 50,625 lb, the tire pressure required is 143 psi. Therefore, if the boosters are towed on their own gear the load bearing strength of the road used for transportation of the boosters must be greater than 143 psi.

A transporter will be needed for moving the LFBB from its processing facility to the VAB. This allows closeout of the landing gear system prior to processing in the VAB. This transporter could be designed to include the capability to transport the LFBB from the contingency landing site (Skid Strip) to its processing facility with the landing gear down but not making contact with the roadway. This would eliminate most of the changes to the roadways from the Skid Strip to the LFBB Processing Facility. Use of a transporter for movement of the boosters will be costed.

22.0 Facilities/GSE

22.01 What are the costs associated with pad, VAB, and MLP (KSC facilities)? Feaster
Rationale: The KSC response has been provided by Chris Winiewicz to Richard Whitlock on March 3, 1994 with an update on March 16, 1994. Questions concerning this response should be directed to Chris at (407)867-7752.

22.02 Tower clearance constraints Masciarelli/Mathews
Rationale: The primary tower clearance constraint is with respect to the ET H_2 vent arm. Currently the static clearance is 19.93 ft between the RSRM cylinder and the fixed arm (17.34 ft from RSRM skirt). The RSRM clearance considering a northerly drift is 5.04 ft for the RSRM cylinder and 2.54 ft for the skirt. The increase diameter of the LFBBs and the addition of a wind shroud reduce these clearances significantly. The minimum static distance is 9.99 ft. The northerly drift distance is 2.21 ft for the LFBB fuselage. The LFBB aft skirt currently has no clearance. The intersection distance is 5.71 ft.

22.03 Maximum booster length/diameter constraints related to VAB physical limits Feaster
Rationale: The VAB transfer aisle width between main load bearing columns is 90 ft. The booster wingspan must fit between the load-bearing columns. The horizontal tow height is limited to 50 ft due to the VAB transfer aisle north door. The VAB high bay east doors limit the booster width to 70 ft at an elevation of 60 ft above the MLP deck.

22.04 Maximum booster length/diameter related to launch pad constraints Feaster
Rationale: This issue is addressed by issues 3.4 and 5.14. Clearance with the ET GH_2 vent arm must be considered as well as the current flame trench. Clearance with the vent arm will be a result of configuration, T/W ratio at liftoff, and drift. These issues are each being considered in developing the booster configuration. The flame trench will not have to be modified, but new deflectors will have to be designed to accommodate the RD-170 plumes.

22.05 Mobile Launch Platform (MLP) Feaster
Rationale: The mobile launch platform will have to be modified to accommodate the LFBBs. Modified engine exhaust holes will have to be cut in the deck and new release mechanisms will be required. It is assumed that the Orbiter tail service masts cannot be modified. The clearance between the Orbiter elevons and the MLP deck is 20 ft. Raising the Orbiter relative to the deck is not a practical alternative.

22.06 Develop hold-down post design and recommend appropriate cost model. Schultz
Rationale: The recommended design of the hold-down mechanisms is similar to the STS hold-down mechanism (as opposed to Saturn 1B or Saturn V). Four points would be used and the dimensional envelope has been defined. The assumed reliability is the same as STS. The loads, drift, exhaust environment, stiffness, interface details, and release mechanisms are still not defined. The appropriate cost model to use would be the hold-downs for STS.

23.0 Orbiter Modifications

23.01 Identify the modifications required on the Orbiter Peterson
Rationale: Orbiter modifications are limited to avionics and software (see issues 16.03 and 16.06). Loads on the Orbiter cargo bay due to the liftoff "twang" would have to be reassessed.

23.02 What are the costs associated with the Orbiter mods? Whitlock
Rationale: Development, production, and implementation of the LFBB engine interface units for the Orbiter fleet has been estimated at $15M in 1994 dollars. Modification of 4500 software lines of code is estimated a t $2M for a total of $17M.

24.0 ET Modifications

24.01 Identify the modifications required on the ET Toelle
Rationale: Potential impacts on the ET are based on weight and c.g. changes of the LFBBs, changes in reaction loads at ET/SRB attach due to larger diameter tank, and no booster hold-down (free liftoff). It is assumed that the impacts occur in time ranges where thrust and inertia are dominant. Thrust profile tailoring could be used to alleviate some of the problems. It is also assumed that looking at ET design areas where the factor of safety is below 1.55 will identify most impacts. Significant design exceedances are predicted for aft ET/SRB interfaces and adjacent 2058 ring structure.

24.02 What are the costs associated with the ET mods? Whitlock
Rationale: Two past studies were used as analogies for determining the cost of modifying the ET. The space station Option C study estimated the impacts to cost $5M in 1993 dollars. A previous LRB study determined the effects to cost $20M in 1987 dollars. A cost of $20M in 1994 dollars was selected as an appropriate point between the two estimates.

25.0 Software mods

26.0 Vehicle Health Management

26.01 Level of VHM? (trade) Ankney
Rationale: Guidelines and Groundrules for Vehicle Health Management System (VHMS) functionality.

The basic concept behind VHMS is that auxiliary information captured during operational use can be used to determined/ predict the health and readiness of a subsystem for its next recycle. Teardown inspections and special ground testing are the target for elimination. For an operational go/no-go to support fault detection, isolation and recovery, the instrumentation information and boundary conditions may be quite different from that needed to answer the question is the system showing weakness. Auxiliary information refers to instrumentation information captured to answer weakening question.

For specifications and requirements, subsystems should separate Fault Detection, Isolation and Recovery (FDIR) from those of VHMS:

> Consider FDIR to be an operational category based on required system's fault-tolerance.
>
> Consider VHMS to be a ground support category intended to facilitate maintenance and turnaround activities in subsystem reuse.

Actual design implementation may overlap and utilize common elements or functionality in meeting requirements from each category. It is probably a safe assumption that FDIR is a subset of VHMS.

This concept is to be considered for all the elements of the subsystem: instrumentation, effectors, controls and monitors. Sound system engineering should be applied to each augmentation beyond the fault-tolerance scope. Complexity/reliability, power, weight, and cost have to be traded against the value of the information for recycle maintenance.

The design of a subsystem should accommodate the capture and retention of both FDIR and VHMS instrumentation and state data. That data should be captured by a logical element that is by design a local monitor to the subsystem element of interest; for fault tolerant subsystem this should be the local monitor Fault Containment Region(1). This will require logic to capture, time stamp, retain, and disperse the information. Retention must be non-volatile to power loss with capacity sized to support an operational interval.

The subsystem should assume that VHMS data reduction and analysis is a ground based function. In cases where the magnitude of data drives the retention capacity to an extreme, data compression/reduction logic should be considered.

The data capture element design should also have a dedicated ground support port to be utilized to extract the data and reset the retention area for the next operational usage. The ground support port should be common across systems, facilitating a common ground communication bus for VHMS data. The subsystem elements shall act as a remote terminal on this port, acting only in response to ground commands.

The data capture element should support data dispersion to the ground port during ground operational intervals as well as for ground turnaround testing. Reset of the data area will be a unique ground command.

For ground turnaround testing, all that is required for the retention element to support is that local power is available, and the ground bus is in communication.

All electrical logical elements shall incorporate built-in-test logic and fault detection mechanisms that provide 95 % failure detection within the element. That status data will be used in both FDIR and VHMS.

(1) Fault- tolerant designs require partitioning or grouping for failure independence in hardware. A grouping can be referred to as a Fault Containment Region (FCR). A FCR is a collection of components that will operate correctly regardless of arbitrary or electrical failures outside of the region and conversely a failure in a FCR can not cause a failures outside it own domain. A FCR is electrically isolated from other design related FCR domains, its power source must be independent of other related domains, and for logical units the clocking sources are also independent.

Some Fault-tolerant systems design may also require physical separation of FCRs for environmental effects or physical damage control. By definition fault-tolerant designs will contain multiple FCRs driven by the fault-tolerance required in the system and the specifics of the design implementation.

There are two types of FCRs, those being monitor and control. For a single functional path control and monitor FCRs will be independent , although it is possible for a monitor or control FCR for one functional path to also serve as the same or opposite type for an independent function.

Monitor FCRs appear to be the logical choice for the unit to focus VHMS specific guidelines on.

26.02 Architecture of VHM? (trade) Ankney
Rationale: For a feasibility study, the net effect on the system of any VHM architecture would be quite subjective. VHM guidelines were established. For this study a small percentage of addition to DDT&E cost was established.

26.03 VHM Recording/Telemetry Requirements Ankney
Rationale: See Issue 26.1

26.04 Manual override capability? Ankney
Rationale: The C&T system was based on continuous two way communication capability; therefore manual override issues all become part of detailed requirements definition in software.

26.05 What are the VHM requirements for each system? (TPS, Structure, Avionics, RCS, etc.) Peterson
Rationale: Definition of the VHM requirements for each subsystem was considered to be beyond the scope of this study. Subsystem VHM requirements should be addressed in Phase A.

26.06 What are the goals, operational issues, and issue/trades associated with VHM? Ess
Rationale:
System Goals:
- Final system design should enable KSC turnaround to be restricted to servicing and addressing in-flight anomalies. On-board VHM system will flag all in-flight anomalies and impending failures.

Operational Scenarios:
- Information is sensed on-board and stored (maybe compressed) on a data recorder. Logic is present to capture, time stamp, retain and disperse information. Data is retrieved on the ground through a common bus by providing local power.
- Each system is responsible for its own VH Monitoring system.
- All electrical logical elements shall incorporate built-in-test and fault detection mechanisms.
- Health data should be taken whenever the system/component is activated.

System Trades/Issues
- The resulting increase in system complexity should be traded against the believed reduction in operations costs.
- Technical impediments to implementing a VHM system should be identified.
- Designers should trade the cost of including a VHManagement system (automated FDIR) against the cost savings associated with reducing the number of flight controllers. (A VHManagement system will automatically perform the FDIR function, with little or no ground intervention.)

APPENDIX C - TRADES LIST

1.0 Programmatics

Trade		Trade Options				Responsible Engineer	Due Date	Issue #
1.a	Minimum Fault Tolerance - Baseline	None	**Single**	Dual	**System Dependent**	Peterson	Closed	1.40
1.b	Subsystem Maturity Level	Current Shuttle	Projected Shuttle-2005	**TRL 6 by 1998**		Peterson	Closed	1.10
1.c	Transition period	1 year	2 years	3 years	> 3 years	Feaster	2/14/94	1.11
1.d	Flight rate During Transition Period	< 8 flts/year	**8 flts/year**	> 8 flts/year		Feaster	2/14/94	1.11
1.e	LFBB Fleet Size Considerations	Processing Time	Spares	Vehicle Life	**All**	Thornburg	2/14/94	1.12
1.f	Flight Test Program	Scaled Prototype Demonstrator	Full Scale Aeroflight Test	Full Scale Launch/Recovery	All	Tuntland/Zetka	3/7/94	
1.g	Full Scale Launch/Recovery Test Article	Prototype	Protoflight			Tuntland/Zetka	3/7/94	

Trade		Trade Options				Responsible Engineer	Due Date	Issue #
2.a	Range Saftey System-Thrust Termination	Incorporated	Not Incorporated	**Scarred**		Peterson	Closed	2.20
2.b	Range Saftey System-Destruct	Incorporated	Not Incorporated	**Scarred**		Peterson	Closed	2.20
2.c	Advanced Engine Fault Detection	**Detects 50% of Cat Failures**	No			Peterson	Closed	
2.d	Engine Out Capability off the pad	Yes	**No**			Templin	Closed	

3.0 Ascent/Abort Performance

Trade		Trade Options				Responsible Engineer	Due Date	Issue #
3.a	Primary Ascent Trajectory Goal	**Launch Probability**	**Increased Performance**			Templin	Closed	
3.b	Ascent Loads Reduction By Lowering maxQ	**Yes**	No			Templin	Closed	3.02
3.c	Dynamic Pressure Ascent - Maximum	**≤ 670 psf**	670 psf	> 670 psf		Templin	Closed	3.01
3.d	Main Engines - Number	1	**2**			Templin	Closed	3.11
3.e	SSME Throttle Setting	<100%	100%	**104%**		Templin	Closed	3.06
3.f	Staging Point	Same as SRB	**SRB > Stg Pnt < Mach 6**	Mach 6		Templin	Closed	3.07
3.g	Main Engine Throttle Capability	Step	**Continuous**			Templin	Closed	3.08
3.h	Main Engine Type	F-1A	**RD-170**	RD-180	Rubber	Templin	Closed	3.09
3.i	Minimum Thrust to Weight ratio (T/W) at liftoff	<1.2	**≥1.2**			Templin	Closed	3.04
3.j	Launch month used for simulation	**June Launch**	December Launch			Templin	Closed	
3.k	Ascent Aerodynamics	**STS ascent aero**	Modified STS ascent aero	CFD ascent aero		Templin	Closed	
3.l	Orbiter and ET mass properties	**Current mass properties**	Orbiter with SLWT mass prop			Templin	Closed	
3.m	First stage Orbiter/ET load limits	**Current Limits**	New Limits			Templin	Closed	
3.n	Booster/ET attach load limits	**As defined by LRB studies**	As defined by SRB			Templin	Closed	
3.o	Roll Angle from end of SAR to staging	**Heads Down (180°)**	Heads Up			Templin	Closed	
3.p	First stage fligh path angle profile	**Det. by q-alpha constraint**	Fixed Profile			Templin	Closed	
3.q	Liftoff Strategy	Soft release w/throttle-up	High T/W for tower clearance			Templin	2/14/94	3.04
3.r	Tower Clearance Strategy	Configuration	Side-step	High T/W		Templin	2/14/94	3.04
3.s	Release Mechanism	Explosive Bolt w/high loads	Mechanical release w/throttle-up			Templin	2/14/94	3.04

Trades List

4.0 Reentry/Flyback Performance

Trade	Trade Options				Responsible Engineer	Due Date	Issue #
4.a Turnaround Maneuver	**Aerodynamic**	Powered pitch around	Pitch-up maneuver		Lee Bryant	Closed	4.01
4.b Powered vs. Glideback	**ABE powered return**	Aerodynamic glide return	Rocket		Lee Bryant	Closed	4.02

5.0 Booster Configuration

Trade	Trade Options				Responsible Engineer	Due Date	Issue #
5.a Oxidizer/Fuel Tank Locations	Oxidizer Forward	**Oxidizer Aft**			Robertson	Closed	5.01
5.b Booster Fineness Ratio	170' l x 18' d	170' l x 16' d	**150' l x 16' d**		Templin/Robertson	Closed	5.05
5.c Internal thermal control (avionics, power sys)	Radiant	Active coolant loop	**Heat Sink**	Air Cooled	Lafuse	Closed	5.10
5.d Location of Main Gear	**Aft Fuselage**	Wing Box	External Pod		Masciarelli	Closed	5.11
5.e Location of Nose Gear	**Intertank Region**	Nosecone Region	External Pod		Masciarelli	Closed	5.12
5.f ABE Air induction control	None	Covered Cowl	Duct	Deployable Duct	Masciarelli	Closed	5.13
5.g Ascent Engine Orientation	**Parallel to ET/Booster Plane**	Perpendic to ET/Booster Plane			Masciarelli	Closed	5.14

6.0 Aerodynamics

Trade	Trade Options				Responsible Engineer	Due Date	Issue #
6.a Wing Shape	Ring Wing	Oblique Wing	**Straight Wing**	Delta Wing	Labbe	Closed	6.01
6.b Wing Operation	Fixed	**Deployable**			Robertson	Closed	6.03
6.c Wing Deployment Method	Folded	**Scissor**	Swing	Inflate/Rigidized	Robertson	Closed	6.04
6.d Wing Airfoil	Symmetric	**Cambered**			Labbe	Closed	6.05
6.e Landing CL vs. Wing Size	CL = 0.7, S = large	**CL = 1.3, S = medium**	CL > 1.3, S = small		Robertson	Closed	6.06
6.f Landing CL vs.Wing Aspect Ratio	low AR, low CL	med AR, med CL	**high AR, high CL**		Labbe	Closed	6.07
6.g Wing Orientation to Fuselage at landing	Low Wing	**High Wing**			Robertson	Closed	6.08
6.h Wing Orientation to Stack	**Opposite side from Orbiter**	Opposite side from ET	Angled		Robertson	Closed	6.09
6.i Yaw Control Device	**Single Rudder**	Dual Rudder	Winglets	None	Labbe	Closed	6.13
6.j Yaw Control Operation	**Fixed**	Deployed			Labbe	Closed	6.14
6.k Yaw Device Airfoil	**Symmetric**	Cambered			Labbe	Closed	6.15
6.l Lateral-directional stability	Stable	Neutral	Unstable		Labbe	2/1/94	6.16
6.m Pitch Control Device	**Canards**	Horizontal Tail	None		Labbe	Closed	6.22
6.n Pitch Device Operation	Fixed	**Deployable**			Labbe	Closed	6.23
6.o Pitch Device Deployment Method	None	Folding	Bayonet	**Scissor**	Labbe	Closed	6.24
6.p Pitch Device Airfoil	Symmetric	**Cambered**			Labbe	Closed	6.25
6.q Pitch stability	Stable	Neutral	Unstable		Labbe	2/7/94	6.26
6.r Location of Pitch Device	Intertank Region	Conformal to Fwd fuselage	Nosecone Region	**Within Wing Fairing**	Masciarelli	Closed	6.27
6.s Control Strategy for Pitch Control Device	**Full Flying**	Control Surface			Robertson	Closed	6.31
6.t Glideslope Angle - Maximum	**< Orbiter**	Same as Orbiter	> Orbiter		Robertson	Closed	6.36
6.u Landing Flare	**Yes**	No			Labbe	Closed	6.38
6.v Landing Speed - Design	160 knots	**170 knots**	≥ 180 knots		Labbe	Closed	6.40

8.0 Structures/Landing Gear

Trade	Trade Options				Responsible Engineer	Due Date	Issue #
8.a Booster Bending Stiffness	**< SRB Stiffness**	Same as SRB	> SRB Stiffness		Wong	Closed	8.03
8.b Load Factor - Maximum	<1.5 g's	**≤4 g's**	<6 g's		Wong	Closed	8.04
8.c Structural Materials	Aluminum	Aluminum-Lithium	Titanium		Wong	2/1/94	8.05
8.d Landing Gear Type	**Wheels**	Skids			Wong	Closed	8.06
8.e Tailscrape angle	8°	10°	12°	>12°	Masciarelli	2/1/94	8.08
8.f Nosecone Geometry	**Cone**	biconic	ogive		Labbe	Closed	8.09
8.g Cryogenic Tankage	**Reusable**	Disposable			Peterson	Closed	
8.h Cryogenic Tank Inspection Methods	NDE	Physical	Pressure		Toelle/Feaster	2/14/94	8.12
8.i Cryogenic Tankage Safety Factor	1.25	**1.5**	2	>2	Wong	Closed	8.13

9.0 Thermal Protection

Trade	Trade Options				Responsible Engineer	Due Date	Issue #
9.a TPS/Structure Combination	External TPS	Hot Structure			Curry/Wong	2/7/94	
9.b Ice suppression on cryo tank	**External insulation on Tank**	Internal insulation on Tank	Dewer Tank	Active Ice Suppression Sys	Curry/Wong	Closed	
9.c Cryogenic Insulation Material	SOFI	**Rohacell Foam**			Curry/Wong	Closed	

10.0 Ascent Propulsion

Trade	Trade Options				Responsible Engineer	Due Date	Issue #
10.a Fuel vs. Oxidizer Depletion	**Run LOX to Depletion**	Run Fuel to Depletion			Toelle	Closed	10.02
10.b Residual Propellant Dump	Yes	**No**			Toelle	Closed	10.03
10.c Fuel Commonality	Ascent/RCS/ABE	Ascent/RCS	Ascent/ABE	**Not Required**	Toelle	Closed	10.07
10.d Oxidizer Commonality	Ascent/RCS	**Not Required**			Toelle	Closed	10.08
10.e Single Fuel Tank or Separate	Single	**Sep. tanks for ascent/RCS/ABE**			Toelle	Closed	10.09
10.f Single Oxidizer Tank or Separate	Single	**Sep. tanks for ascent/RCS**			Toelle	Closed	10.09
10.g Purge Engines After Separation	**Yes**	No			Toelle	Closed	

11.0 Separation Propulsion

Trade	Trade Options				Responsible Engineer	Due Date	Issue #
11.a Separation motor propellant	**Solid**	Liquid			Toelle	Closed	11.02

12.0 RCS Propulsion

Trade	Trade Options				Responsible Engineer	Due Date	Issue #
12.a RCS Propellant	**LOX/RP**	LOX/Ethanol	NTO/MMH	Monopropellant	Riccio	Closed	12.01
12.b RCS Systems	**Aft only**	Fwd and Aft			Riccio	Closed	12.04

13.0 Power

Trade	Trade Options				Responsible Engineer	Due Date	Issue #
13.a Power Generation (non TVC)	Batteries	Fuel Cells	APU/EAPU	ABE hydraulic bleedoff/SPGG	Le	Closed	13.03
13.b Power Generation phase (non TVC)	AC	DC			Le	Closed	13.03
13.c Power Generation (TVC)	**Hydraulic (eng bleedoff)**	Batteries	Fuel Cells	APU	Le	Closed	13.03

14.0 Actuation

Trade	Trade Options				Responsible Engineer	Due Date	Issue #
14.a Non-TVC Actuation	Hydraulic	**EMA/EHA**			Loffi	Closed	14.01

15.0 GN&C

Trade	Trade Options				Responsible Engineer	Due Date	Issue #
15.a Orbiter/Booster Command Interface	No mods to Orbiter	Mods to Orbiter			McSwain	2/2/94	15.03

16.0 Data Management

Trade	Trade Options				Responsible Engineer	Due Date	Issue #
16.a Housing of redundant systems	Different Boxes	Same Box			Ankney	2/7/94	

17.0 Tracking & Communications

Trade	Trade Options				Responsible Engineer	Due Date	Issue #
17.a Navigation Aid	**GPS**	MSBLS			Nuss	Closed	17.01
17.b Type of GPS	DGPS	Pseudolite			Nuss	2/1/94	17.02
17.c If MSBLS, then what landing site	SLF	other site	**N/A**		Nuss	Closed	17.03
17.d Communication Link	TDRS	ground stations			Nuss/Sham	2/7/94	17.04
17.e Redundancy Consideration	**Independent Strings**	Cross-strapping			Nuss/Sham	Closed	17.06
17.f Is 2-way comm required	**Yes**	No			Shame	Closed	17.08

19.0 Airbreathing Engines (ABEs)

Trade	Trade Options				Responsible Engineer	Due Date	Issue #
19.a Airbreathing Engine Operational Regime	**Subsonic**	Supersonic			Robertson	Closed	19.01
19.b Airbreathing Engine Type	Turbojet	**Turbofan**			Robertson	Closed	19.02
19.c Airbreather Engines Number/Thrust Level	**1**	2			Robertson	Closed	19.03
19.d Airbreathing Engine Cruise Range Margin	None	**10%**	>10%		Robertson	Closed	19.06
19.e ABE Go-around capability at landing	Yes	**No**			Robertson	Closed	19.07
19.f Airbreathing Engine Loiter Time	None	10 min	**20 min**	>20 min	Robertson	Closed	19.07
19.g Airbreathing Engine Environment	Pressurized	Unpressurized			Robertson	2/1/94	19.08
19.h Airbreathing Engine Configuration	**Fixed**	Deployed			Robertson	Closed	19.09
19.i Airbreathing Engine Location	**External**	Internal			Robertson	Closed	19.10
19.j Airbreathing Engine for Trim Control	Yes	**No**			Robertson	Closed	19.14
19.k Airbreathing Engine Propellant Tankage	**Standalone**	Draws from main tank			Robertson	Closed	19.15,.16
19.j Airbreathing Takeoff Capability	Yes	**No**			Peterson	Closed	19.18

20.0 Flight Operations

Trade	Trade Options				Responsible Engineer	Due Date	Issue #
20.a Booster transportation on the ground	On Booster Landing Gear	On Transporter	**Both**		Peterson	Closed	20.06
20.b Flyback Control Strategy	Autonomous	Capable of RPV	RPV	**Autonomous w/Command**	Peterson	Closed	20.08

21.0 Ground Operations

Trade	Trade Options				Responsible Engineer	Due Date	Issue #
21.a Runway Options	**SLF**	**Skid Strip**	Patrick AFB	New Strip	Tuntland	Closed	21.01
21.b Where is the fuel loaded	in the VAB	on the way to the pad	at the pad		Feaster	2/25/94	21.03

26.0 Vehicle Health Management

Trade	Trade Options				Responsible Engineer	Due Date	Issue #
26.a Level of VHM	Monitoring	Hybrid	**Management**		Ess	Closed	26.01
26.b Architecture of VHM	**Distributed**	Centralized			Ess	Closed	26.02
26.c Telemetry	System Status	**Variable**	Detailed system data		Ess	Closed	26.03

APPENDIX D - MASS PROPERTIES AND DESIGN DETAILS

MASS PROPERTIES AND DESIGN DETAILS
LIQUID FLYBACK BOOSTER
(April 4, 1994)

Baseline Configuration Details:	
Number & Type of Engines -->	4 RD-180
Booster Diameter -->	16 ft
Booster Length -->	150 ft

LIQUID FLYBACK BOOSTER SUBSYSTEM:	# Req.	Total Mass (lbm)	Xcg (inches)	Ycg (inches)	Zcg (inches)	COMMENTS (SOURCE, TECHNOLOGY, HERITAGE, VENDER, ETC.)
1.0 Structure:		**89,312**	**1,101**	**0**	**(21)**	**Sized by Ken Wong/ES2 & Jim Masciarelli/ET2 (JSC)**
Wing Group		9,951	1,172			Historical Sizing
Wings & Elevons	2	9,130	1,219	0	(119)	
Canards (9% of wing estimate)	2	822	645	0	(118)	
Tail Group		1,434	1,600			Historical Sizing
Vertical Tail / Rudder	1	1,434	1,600	0	(227)	
Body Group		59,638	979			Historical Sizing
RP-1 Tank	1	9,709	397	0	0	
LO2 Tank	1	22,155	1,102	0	0	
Forward Body Skin	1	1,925	255	0	(23)	
Intertank Lower Skin	1	6,500	664	0	59	
Midbody Skin	1	2,478	951	0	(76)	
Aft Skirt	1	12,000	1,597	0	(3)	
Cone	1	1,971	118	0	0	
ABE Engine Fairing	1	700	1,639	0	(240)	
Over Wing Fairing	1	2,200	1,100	0	(160)	
Thrust Structure	1	14,216	1,574	0	0	Historical Sizing
ET Attach Structure		4,073	883			SRB
Forward	1	1,629	242			
Aft		2,444	1,311			
Aft Ring	1	1,897	1,311			
Aft Struts	4	547	1,311			

LIQUID FLYBACK BOOSTER SUBSYSTEM:	# Req.	Total Mass (lbm)	Xcg (inches)	Ycg (inches)	Zcg (inches)	COMMENTS (SOURCE, TECHNOLOGY, HERITAGE, VENDER, ETC.)
2.0 Protection:		**2,726**	**1,120**	**0**	**(18)**	**Sized by Don Curry/ES32 (JSC)**
Wing Group TPS		412	1,219	0	(119)	(Hot Wall, Mach 6, CFBI/FRSI)
Tail Group TPS		0	0			
Body Group TPS		0	0		0	
Insulation		2,314	1,102	0	0	
Fuel Tank Insulation		0	0			
Oxidizer Tank Insulation		2,314	1,102	0	0	ROHACELL + THIN TPS

MASS PROPERTIES AND DESIGN DETAILS
LIQUID FLYBACK BOOSTER
(April 4, 1994)

LIQUID FLYBACK BOOSTER SUBSYSTEM:	# Req.	Total Mass (lbm)	Xcg (inches)	Ycg (inches)	Zcg (inches)	COMMENTS (SOURCE, TECHNOLOGY, HERITAGE, VENDER, ETC.)
3.0 Propulsion:		**72,160**	**1,680**	**(1)**	**(7)**	
Ascent Propulsion System		70,736	1,681			**Sized by Hugh Campbell/EP22 (MSFC)**
Base Heat Shield	1	5,816	1,734	0	0	PRATT & WHITNEY
Gimbal Mechanism	2	8,316	1,730	0	0	PRATT & WHITNEY
RD-170 Engines	4	41,080	1,730	0	0	PRATT & WHITNEY
Hazardous Gas Detection System	1	77	1,574	0	0	
Aft compartment		0				Pacific Scientific
RP-1/LO2 Intertank		0				Pacific Scientific
RP-1 Feed System		2,051	1,285			
520mm (20.5") Feed Line		1,706	1,227	(57)	(57)	
RP-1 Tank Outlet Assembly	1	0				
RP-1 Line Assembly	1	660				Arrowhead Products
Intertank Elbow	2	65				
Aft Compartment Elbow	2	60				
Bellows	6	441				
RP-1 POGO Suppression	1	75				Arrowhead Products
RP-1 Engine 400mm (15.75") Feed Line	2	84				Arrowhead Products
RP-1 Engine Prevalve	2	320				Fairchild Controls
200mm (8") RP-1 Fill & Drain System		345	1,574	0	60	Cryolab
RP-1Fill and Drain Line Assembly	1	55				Arrowhead Products
RP-1 Fill and Drain Inboard Valve	1	50				Fairchild Controls
RP-1 Fill and Drain Disconnect	1	240				Eaton Console Controls
LO2 Feed System		2,560	1,572			
502mm (19.75") Feed Line		2,232	1,572	0	0	
LO2 Tank Outlet Assembly	1	0				
LO2 POGO Suppression System	2	150				
LO2 Engine Feed Line	2	519				Arrowhead Products
LO2 Elbow	4	435				
LO2 Bellows	4	283				
LO2 Flex Joint	2	273				
25.4mm (1") Foam Insulation	2	97				
LO2 Engine Prevalve	2	388				Fairchild Controls
LO2 60mm (2.36") Circulation Line	2	66				
LO2 Circulation Valve	2	20				
LO2 Feed System Instrumentation	0	0				Pacific Scientific
LO2 Fill & Drain System		328	1,574	0	0	
LO2 Fill and Drain Line Assembly	1	38				Arrowhead Products
LO2 Fill and Drain Inboard Valve	1	50				Fairchild Controls
LO2 Fill and Drain Disconnect	1	240				Eaton Console Controls

MASS PROPERTIES AND DESIGN DETAILS

LIQUID FLYBACK BOOSTER

(April 4, 1994)

LIQUID FLYBACK BOOSTER SUBSYSTEM:	# Req.	Total Mass (lbm)		Xcg (inches)	Ycg (inches)	Zcg (inches)	COMMENTS (SOURCE, TECHNOLOGY, HERITAGE, VENDER, ETC.)
3.0 Propulsion (continued):							
RP-1 Tank Pressurization System			591	664	0	(53)	
Diffuser Assembly	1	15					
Forward He Press Line Assembly	1	20					
He Storage Bottle Assembly	1	515					
He Flow Control Valve	3	18					Eaton Console Controls
GHe Pre-pressurization Line	1	20					
GHe Pre-press Disconnect	1	2					Fairchild Controls
RP-1 Tank Press System Instrumentation		0					Pacific Scientific
LO2 Tank Pressurization System			4,936	1,608	0	(74)	
Diffuser Assembly	1	15					
Forward He Press Line Assembly	1	27					
Main He Press Line Assembly	1	275					
He Storage Bottle Assembly	6	4,579					Eaton Console Controls
He Flow Control Valve	3	18					
GHe Pre-pressurization Line	1	20					Fairchild Controls
GHe Pre-press Disconnect	1	2					Pacific Scientific
LOX Tank Press System Instrumentation.	0	0					
Pneumatic System			78	1,574	0	0	
Ground supply/fill & distribution ass.	1	25					
POGO Precharge Dist. & Control Assembly	1	0					Brunswick
Storage Bottle Assembly	1	40					Eaton Console Controls
Regulator and Control Assembly	1	8					
GHe Inject Assembly	1	5					
Pneumatic System Instrumentation	0	0					Pacific Scientific
RP-1 Tank Systems			34	175	0	0	
Tank Vent/Relief Valve	1	10					Circle Seal
Vent Line Assembly	1	12					
Vent valve actuation line & disconnect	1	7					/Fairchild
RP-1 Tank Instrumentation	1	5					Pacific Scientific
LO2 Tank Systems			43	704	0	0	
Tank Vent/Relief Valve	1	12					Circle Seal
Vent Line Assembly	1	16					
Vent valve actuation line & disconnect	1	8					/Fairchild
LO2 Tank Instrumentation	1	7					Pacific Scientific
Compartment Purge Systems	1		231	1,574	0	0	
Aft compartment purge manifold assembly		0					
Aft compartment purge disconnect ass.		0					Fairchild
Aft compartment purge flow control ass.		0					Eaton Console Controls
Aft compartment purge instrumentation		0					Pacific Scientific
Mounting & Installation (30% of above excluding engines and gimbals)			4,925	1,567			Historical Sizing (MSFC recommendation), engines & gimbals excluded

LIQUID FLYBACK BOOSTER SUBSYSTEM:	# Req.	Total Mass (lbm)	Xcg (inches)	Ycg (inches)	Zcg (inches)	COMMENTS (SOURCE, TECHNOLOGY, HERITAGE, VENDER, ETC.)
3.0 Propulsion (continued):						
Reaction Control System (RCS) (GO2/RP-1)		1423	1,621			**Sized by Joe Riccio/EP4 (JSC)**
RCS Components		1259	1,621	6	(32)	
Helium tank	1	27	1,618	0	(34)	
GO2 Propellant Tank	1	171	1,568	0	(62)	
GO2 Propellant Tanks	2	342	1,568	24	(38)	
QD - HP Gas	2	2	1,625	0	(30)	
Burst Disk/Relief	2	9	1,625	0	(30)	Marquardt, RCS
Helium Iso Valve	2	5	1,625	0	(30)	Brunswick, RCS
GO2 Iso valves	2	5	1,625	0	(30)	Eaton, RCS
TP - LP Gas	4	1	1,625	0	(30)	Fairchild, MX
Regulator	4	4	1,625	0	(30)	Rocketdyne, RCS/OMS
Check valve	1	3	1,625	0	(30)	
Manual Valve	1	2	1,625	0	(30)	Parker, RCS/OMS
Propellant tank - RP-1	1	30	1,586	(18)	(73)	
Manifold Iso Valves	9	37	1,625	0	(30)	PSI/TRW, APU
Mass Flow Controller	4	60	1,625	0	(30)	
Engines	20	440	1,684	0	(14)	Fairchild, RCS/OMS
TP - HP Gas	4	1	1,625	0	(30)	NSLD, RCS/OMS
TP - LP Liquid	2	1	1,625	0	(30)	NSLD, RCS/OMS
QD - LP Liquid	2	2	1,625	0	(30)	NSLD, RCS/OMS
QD - LP Gas	1	2	1,625	0	(30)	Fairchild, RCS/OMS
Pressure Transducer	4	2	1,625	0	(30)	Statham
Temperature Transducer	3	0	1,625	0	(30)	Rosemont
Lines (10% of above)		114	1,625	0	(30)	
RCS Mounting & Installation (20% of above - engines)		164	1,621	6	(32)	Historical Sizing

MASS PROPERTIES AND DESIGN DETAILS

LIQUID FLYBACK BOOSTER

(April 4, 1994)

LIQUID FLYBACK BOOSTER SUBSYSTEM:	# Req.	Total Mass (lbm)		Xcg (inches)	Ycg (inches)	Zcg (inches)	COMMENTS (SOURCE, TECHNOLOGY, HERITAGE, VENDER, ETC.)
4.0 Power:		**1,469**		**781**	**26**	**0**	
Generation (Rechargeable silver-zinc)		415		573			**Sized by Michael Le/EP5 (JSC)**
28 Volt System (batteries)	3		157	688	64	0	STS, Yardney Tech. Prods., Inc.
270 Volt System (batteries)	27		189	688	64	0	STS, Yardney Tech. Prods., Inc.
Mounting & Installation (20 % of above)			69	573			Historical Sizing
Battery Management & Distribution		252		688	64	0	**Sized by Michael Le/EP5 (JSC)**
28 Volt System	3		105				
270 Volt System	3		105				
Mounting & Installation (20 % of above)			42				Historical Sizing
Cabling & Connectors		802		918			**Sized by Ann Bufkin/ET2 & Michael Le/EP5 (JSC)**
Hardware			668				Based on lengths & loads (separate sheet available)
Mounting & Installation (20 % of above)			134				Historical Sizing

LIQUID FLYBACK BOOSTER SUBSYSTEM:	# Req.	Total Mass (lbm)		Xcg (inches)	Ycg (inches)	Zcg (inches)	COMMENTS (SOURCE, TECHNOLOGY, HERITAGE, VENDER, ETC.)
5.0 Control:		**6,894**		**1,285**	**0**	**(54)**	
Deployment Mechanisms		2,523		1,448			
Wing (20% of wing mass)	1		1,826	1,526	0	(119)	**Historical Sizing by Ken Wong/ES2**
Canard (20% of canard mass)	2		164	578	0	(118)	**Historical Sizing by Ken Wong/ES2**
Controllers	3		113	1,448	0	(119)	**Sized by Al Strahan/EG22 (JSC)**
Mounting & Installation			421	1,448	0	(119)	Historical Sizing
Actuation		4,371		1,192			**Sized by Al Strahan/EG22 (JSC)**
Elevators	2		500	1,216	0	(119)	
Ailerons	2		500	958	0	(118)	
Canards	2		500	645	0	(118)	
Rudder	1		125	1,694	0	(173)	
Nose Wheel Steering	1		190	716	0	86	
Brakes	4		760	1,600	0	73	
Main Gear Uplock	2		380	1,600	0	73	
Nose Gear Uplock	1		125	716	0	86	
Controllers	15		563	1,192			One for each actuator
Mounting & Installation			729	1,192			Historical Sizing

MASS PROPERTIES AND DESIGN DETAILS

LIQUID FLYBACK BOOSTER

(April 4, 1994)

LIQUID FLYBACK BOOSTER SUBSYSTEM:	# Req.	Total Mass (lbm)	Xcg (inches)	Ycg (inches)	Zcg (inches)	COMMENTS (SOURCE, TECHNOLOGY, HERITAGE, VENDER, ETC.)
6.0 Avionics:		**2,506**	**744**	**37**	**0**	**Coordinated by Sam Ankney/EK7 (JSC)**
Guidance, Navigation and Control (GNC)		1,060	545			**Sized by Al Strahan/EG22 (JSC)**
Ascent Systems		704	652	64	0	
Booster Controller Box	4	400				
Separation Controller	4	260				SRB
Ascent Rate Gyro (? need)	2	44				
Flyback Systems		260	456			
Integrated Flight Mgt. Unit (IMUs)	4	120	652	64	0	
Air Data System	4	80	15	0	0	
RCS Jet Driver	2	60	652	64	0	
Mounting & Installation (10%)		96				Historical Sizing
Communications Subsystem		62	591			**Sized by Cathy Sham/EE7 (JSC)**
S-bd STDN Transponder (15W PA)	2	33	688	64	0	Cincinnati Electronics (CE)
Diplexer (passive device)	2	2	688	64	0	CE
Signal Processor (DES, BCH, 1553 module)	2	6	688	64	0	CE
R/F Switch	1	1	688	64	0	
Antennas (including cables)	2	10	190	0	0	
Mounting & Installation (20 %)		10	591	64	0	Historical Sizing
RF Nav. Aids (Tracking)		170	395			**Sized by Ray Nuss/EE6 (JSC)**
GPS		78	688	64	0	
GPS Antenna / Pre-amplifier	6	30				
RF Cable (low loss flexible) Upper	3	23				
RF Cable (low loss flexible) Lower	3	23				
RF Combiner	3	3				
Radar Altimeter System		63	30			
Radar Altimeter Antenna	6	18				Honeywell
RF Cable low loss flexible	6	45				
Mounting & Installation		28	395			Historical Sizing
Data Management System (DMS)		854	816			**Sized by David Jih/EK74 (JSC)**
DMS Computer Unit		184	652	64	0	MIL-SPEC
Processor Board	4	8				MIL-SPEC, Lockheed Sanders
Single Channel MIL-STD 1553 Interface	4	8				MIL-SPEC, Radstone
Dual Channel MIL-STD 1553 Interface	4	8				MIL-SPEC, Radstone
Mass Storage Interface	4	5				MIL-SPEC, Lockheed Sanders
Mass Storage Device	4	30				MIL-SPEC, IBM
Chassis	4	124				MIL-SPEC, Radstone
PCMMU	2	62	652	64	0	Shuttle
MDMs		266	1,092			Shuttle
Forward MDM (1)	1	38	20			
Intertank MDMs (2)	2	76	664			
Aft MDMs (4)	4	152	1,574			
1553B Bus	12	200	652	64	0	
Mounting & Installation		142	816			Historical Sizing
Instrumentation		360	1,350			**Orbiter proportioned, Sized by Sam Ankney/EK7 (JSC)**
Hardware		300				
Mounting & Installation		60				Historical Sizing

LIQUID FLYBACK BOOSTER SUBSYSTEM:	# Req.	Total Mass (lbm)		Xcg (inches)	Ycg (inches)	Zcg (inches)	COMMENTS (SOURCE, TECHNOLOGY, HERITAGE, VENDER, ETC.)
7.0 Environment:		0			0	0	
Misc. Thermal Control Hardware		0					

LIQUID FLYBACK BOOSTER SUBSYSTEM:	# Req.	Total Mass (lbm)		Xcg (inches)	Ycg (inches)	Zcg (inches)	COMMENTS (SOURCE, TECHNOLOGY, HERITAGE, VENDER, ETC.)
8.0 Other:		**27,399**		**1,473**	**(3)**	**(119)**	
Flyback Propulsion Systems		17,320		1,613			**Sized by Ed Robertson/ET2 (JSC)**
Air-breathing Engine	1		10,726	1,639	0	(240)	GE CF6-80E1A3: 72 Klbf, TSFC = 0.339
Structural Provisions			5,727	1,628			
Air-breathing Engine Mount	1	332		1,639	0	(195)	
Air-breathing Engine Pylon (within vertical tail)	1	2,653		1,639	0	(140)	
Air-breathing Engine Nacelle	1	1,861		1,639	0	(240)	
Air-breathing Engine Firewalls & fireseals		289		1,639	0	(240)	
Air-breathing Engine Air Induction Ducts		375		1,531	0	(240)	
Air-breathing Engine Air Induction Controls		217		1,531	0	(240)	
Engine Accessories			482	1,743			
Air-breathing Engine Controls		20		1,639	0	(240)	
Air-breathing Engine Exhaust System	1	462		1,748	0	(240)	
Fuel System			385	520			
Air-breathing Engine Fuel Tank	1	340		450	0	0	
Air-breathing Engine Fuel Distribution System	1	45		1,045	0	0	
Landing System		8,736		1,298			**Sized by Jim Masciarelli/ET2 (JSC)**
Landing Gear Structure Impact			1,099	1,298			
Main Gear Assembly			5,153	1,600	0	73	
Strut	2	999					
Wheels	4	1,865					
Brakes	4	2,289					
Control		0					
Nose Gear Assembly			2,484	672	0	67	
Strut	1	596					
Wheels	2	1,888					
Control		0					
Separation System		1,343		797			Proportioned to SRB separation system mass
Forward	1		672	79	(27)	12	
Aft	1		672	1514	(79)	(37)	

MASS PROPERTIES AND DESIGN DETAILS

LIQUID FLYBACK BOOSTER

(April 4, 1994)

LIQUID FLYBACK BOOSTER SUBSYSTEM:	# Req.	Total Mass (lbm)	Xcg (inches)	Ycg (inches)	Zcg (inches)	COMMENTS (SOURCE, TECHNOLOGY, HERITAGE, VENDER, ETC.)
9.0 Growth (15%):		**21,286**	**1,235**	**0**	**(32)**	
1.0 Structure		13,397	1,101	0	(21)	Historical Sizing
2.0 Protection		409	1,120	0	(18)	Historical Sizing
3.0 Propulsion (excluding engines and gimbals)		3,349	1,680	(1)	(7)	Historical Sizing
4.0 Power		220	781	26	0	Historical Sizing
5.0 Control		1,034	1,285	0	(54)	Historical Sizing
6.0 Avionics		376	744	37	0	Historical Sizing
7.0 Environment		0	0	0	0	Historical Sizing
8.0 Other (excluding engine)		2,501	1,473	(3)	(119)	Historical Sizing
FLYBACK BOOSTER DRY MASS		**223,751**	**1,346**	**-0.1**	**(30)**	
LIQUID FLYBACK BOOSTER SUBSYSTEM:	**# Req.**	**Total Mass (lbm)**	**Xcg (inches)**	**Ycg (inches)**	**Zcg (inches)**	**COMMENTS (SOURCE, TECHNOLOGY, HERITAGE, VENDER, ETC.)**
10.0 Non-Cargo		**27,232**	**912**	**0**	**(2)**	
Reserve and Residual Fluids		27,232	912			
RP-1 Reserves & Residuals		3,161.3	1,227			**Sized by Hugh Campbell/EP22 (MSFC)**
LO2 Reserves & Residuals		8,219.0	1,572			**Sized by Hugh Campbell/EP22 (MSFC)**
RCS Reserves & Residuals		197.6	1,555	0	(73)	**Sized by Joe Riccio/EP4 (JSC)**
Air-breathing Engine JP-4 Reserves		15,010.0	450			**Sized by Ed Robertson/ET2 (JSC)**
Cruise (40 nmi)		3,530	450	0	(127)	
Loiter (30 minutes)		11,480	450	0	(127)	
Air-breathing Engine JP-4 Residuals		379	1,490	0	(127)	**Sized by Ed Robertson/ET2 (JSC)**
Pressurant (GHe)		265	1,574			**Sized by Hugh Campbell/EP22 (MSFC) & Joe Riccio/EP4 (JSC)**
LIQUID FLYBACK BOOSTER SUBSYSTEM:	**# Req.**	**Total Mass (lbm)**	**Xcg (inches)**	**Ycg (inches)**	**Zcg (inches)**	**COMMENTS (SOURCE, TECHNOLOGY, HERITAGE, VENDER, ETC.)**
11.0 Cargo		0	0	0	0	
FLYBACK BOOSTER INERT MASS		**250,983**	**1,299**	**-0.1**	**(27)**	
LIQUID FLYBACK BOOSTER SUBSYSTEM:	**# Req.**	**Total Mass (lbm)**	**Xcg (inches)**	**Ycg (inches)**	**Zcg (inches)**	**COMMENTS (SOURCE, TECHNOLOGY, HERITAGE, VENDER, ETC.)**
12.0 Non-Propellant (Consumables)		0	0	0	0	
LIQUID FLYBACK BOOSTER SUBSYSTEM:	**# Req.**	**Total Mass (lbm)**	**Xcg (inches)**	**Ycg (inches)**	**Zcg (inches)**	**COMMENTS (SOURCE, TECHNOLOGY, HERITAGE, VENDER, ETC.)**
13.0 Propellant		**1,225,208**	**898**	**0**	**(2)**	
Startup Propellant		63,276	906			
Startup Fuel		17,577	397			**Sized by Hugh Campbell/EP22 (MSFC)**
Startup Oxidizer		45,699	1,102			**Sized by Hugh Campbell/EP22 (MSFC)**
Usable Ascent Propellant		1,138,067	906			
Usable Ascent Fuel		316,130	397			**Sized by Hugh Campbell/EP22 (MSFC)**
Usable Ascent Oxidizer		821,937	1,102			**Sized by Hugh Campbell/EP22 (MSFC)**
Other Propellant		23,866	494			
Air-breathing Engine Fuel		22,930	450	0	(127)	**Sized by Ed Robertson/ET2 (JSC)**
RCS Propellant		936	1,569	14	(47)	**Sized by Joe Riccio/EP4 (JSC)**
LFBB GROSS MASS		**1,476,191**	**966**	**0**	**(7)**	

APPENDIX E - TEST & VERIFICATION PRIME WRAP FACTOR DEFINITIONS

APPENDIX E
TEST & VERIFICATION PRIME WRAP FACTOR DEFINITIONS

1. UNIT TEST HARDWARE - The Unit Test Hardware (UTH) wrap factor includes the labor and material required for mission tests that provide design and development information necessary to verify design concepts. UTH includes the design, tooling, fabrication, assembly, installation, quality assurance, and checkout of some test articles and expendables beyond the protoflight unit. Also included is prototype refurbishment. All subsystem hardware installed on the test vehicle and test fixture design/fabrication/assembly are included. Test specimens for component and subsystem development and qualification test are excluded.

2. INTEGRATION, ASSEMBLY AND CHECKOUT - The Integration, Assembly and Checkout (IACO) wrap element contains all labor and material required to physically integrate (assemble) the various subsystems into a total-vehicle system. Final assembly, including attachment, and the design and manufacture of installation hardware, final factory acceptance operations, packaging/crating, and shipment are included. IACO charged to DDT&E represents those costs incurred for the integration, assembly, and checkout of major test articles. IACO charged to the flight unit includes those same functions applied to the actual flight unit.

This item excludes the engineering effort required to establish the integration, assembly, and checkout procedures necessary for this effort. Those engineering efforts are covered under Systems Engineering and Integration.

3. SYSTEM TEST OPERATIONS - The System Test Operations (STO) wrap element includes development testing and the effort and materials required for qualification and physical integration of all test and qualification units. Also included is the design and fabrication of test fixtures.

Specifically included are tests on all UTH to determine operational characteristics and compatibility with the overall system and its intended operational parameters. Such tests include operational tests, design verification tests, and reliability tests. Also included are the tests on systems and integrated systems to verify acceptability for required mission performance. These tests are conducted on hardware that has been produced, inspected, and assembled by established methods meeting all final design requirements. Further, system compatibility tests are included, as well as, functions associated with test planning, scheduling, data reduction, and report preparation.

APPENDIX F - TEST & VERIFICATION SUBSYSTEM AND DISCIPLINE FINDINGS DETAILS

APPENDIX F
TEST & VERIFICATION SUBSYSTEM AND DISCIPLINE FINDINGS DETAILS

F.1 INTEGRATED AVIONICS AND SOFTWARE SUBSYSTEM

F.1.1 FINDINGS DISCUSSION

Flight Software T&V

The software has been costed with a factor to allow for development and independent testing. Logic is tested against software simulation of environment and hardware interface.

F.1.1.1.1 Objective - Flight software integration and verification.
F.1.1.1.2 Justification - Ensure the integrated flight software load meets all hardware and software interface and performance requirements on the target machine.
F.1.1.1.3 Risk of not conducting test - Flight software integrity is at risk. Vehicle can not fly.
F.1.1.1.4 Test Purpose and Program Phase - To certify the integrated flight software load. It shall take place between FSW development and delivery.
F.1.1.1.5 Test Hardware and Facilities - FSW development facility.
F.1.1.1.6 Estimated Cost - Cost are included in the flight software cost.

Avionics Hardware Development and Qualification

Each of the subsystems within Integrated Avionics (DMS, Instrumentation, GN&C, C&T) have included box and component testing in the DDT&E activity and cost is included in non-flight prototype and qualification units.

F.1.1.2.1 Objective - Avionics components & subsystem prototype and qualification
F.1.1.2.2 Justification - To ensure proper hardware and software interface (HSI) requirements at early phase, to qualify the hardware for flight environment.
F.1.1.2.3 Risk of not conducting test - Flight hardware failure.
F.1.1.2.4 Test Purpose and program phase - Hardware qualification test shall be performed prior to delivery. A preliminary HSI testing shall be performed at the beginning of hardware and software development to establish proper interface requirements. A formal HSI testing is needed prior to subsystem/element delivery to validate its performance.
F.1.1.2.5 Test Hardware and Facilities - Qualification test can be done at the hardware manufacturer plant. HSI can be done at the integrated avionics verification lab.
F.1.1.2.6 Estimated Cost - Cost are included in the hardware DDT&E cost.

Integrated Avionics Testing

Cost has been included to modify the existing shuttle test facilities (SAIL and ESTL) to support both boost and flyback integrated testing. Joint test involving ESTL and SAIL is planned for verification of the end-to-end data flow capability and interfaces. The flight equivalent units listed in the prototype make up the vehicle hardware for the facility operations and test execution.

F.1.1.3.1 Objective - Verify and validate LFBB integrated avionics performance through out the mission profile.
F.1.1.3.2 Justification - Required as part of certification process.
F.1.1.3.3 Risk of not conducting test - Potential Loss of mission and loss of vehicle.
F.1.1.3.4 Test Purpose and program phase - Verify integrated avionics system performance under nominal and anomalous conditions through out the mission profile. Joint test involving ESTL and SAIL is planned for verification of the end-to-end data flow capability and interfaces.
F.1.1.3.5 Test Hardware and Facilities - Modify the existing shuttle test facilities (SAIL and ESTL) to support both boost and flyback integrated avionics testing.

F.1.1.3.6 Estimated Cost - Cost has been included under the LFBB test station (LTS) costing.

Avionics-to-Main Propulsion Subsystems Testing

F.1.1.4.1 Objective - Avionics-to-Booster Engine interfaces, throttling, and gimbaling functionality.
F.1.1.4.2 Justification for Test - Ensure end-to-end thrust command/actuator polarity and response.
F.1.1.4.3 Consequence or Risk of Not Conducting Test - Engine hydraulic system will not be exercised until booster launch ignition, i.e., no engine slew test until engine ignition.
F.1.1.4.4 Test Purpose and Program Phase- TBD
F.1.1.4.5 Test Hardware and Facilities- This test should be integrated into the Main Propulsion engine test program, actual test firings.
F.1.1.4.6 Estimated Cost - None. Assume costs to be part of the Main Propulsion engine test program.

F.1.2 NON-BASELINE TESTING REQUIREMENTS - NONE

F.2 ELECTRICAL POWER SUBSYSTEM

F.2.1 FINDINGS DISCUSSION

Electrical Power System General Test Requirements

F.2.1.1.1 Objective - To verify functional and performance integrity of the battery cells and system under the projected power and energy profile, baseline environmental and mechanical evaluation, and off-nominal testing.
F.2.1.1.2 Functional Test - Verify that the cells and power system behave as designed under static and transient power profile. Testing would include repeated charge and discharge tests to fully characterize the system performance. Effects of loads on the system efficiencies (and losses) will be evaluated. Simulated LFBB loads would include avionics and EMA power and energy demands. Battery qualification and certification will customarily performed at the vendor. System (power source/distribution/loads) would be performed at JSC (similar to the Electrical Power Distribution Laboratory.
F.2.1.1.3 Environmental and Mechanical Evaluation - Ensure that the battery system can withstand routine handling, transportation and assembling operations. System will be tested for EMI/EMC, vibration, shock, bench drop test and environmental exposure (salt, fog,....).
F.2.1.1.4 Off-Nominal testing - Verify system would operate under abuse conditions including short circuit, overtemperature, overcharge and overdischarge tests.
F.2.1.1.5 Justification for Testing - Validate that the LFBB battery power system would provide power to the critical functional systems.
F.2.1.1.6 Schedule - DDT&E would span a duration of 1-3 years.
F.2.1.1.7 Test Hardware and Facility - Battery and controller would be developed and procured from a vendor. NASA could assume some qualification testing at the cell level. Integrated system test should be conducted by the prime contractor.

ElectroMechanical Actuator (EMA) Testing and Certification

The intent of an EPS/ElectroMechanical Assembly test is to verify the transient performance of the power system under loads of the avionics and EMA. It is necessary to determine the effects of the loads and its flight profile characteristics on the power and energy demands. This will be a significant subset of the Functional Test program

F.2.1.2.1 Objective - Testing and Certification of full up aerosurface EMA and power supply and distribution systems with external loads on the actuators.

F.2.1.2.2 Justification - Ensure the integrated aerosurface EMA and power supply systems meet all interface and external loading requirements.
F.2.1.2.3 Risk of not conducting test - Aerodynamic controllability of vehicle during flyback phase is at risk. Potential for lose of vehicle.
F.2.1.2.4 Test Purpose and program phase: To certify the integrated aerosurface EMA and power supply and distribution systems. It shall take place between EMA and power system component testing, and first flight test of LFBB.
F.2.1.2.5 Test Hardware and Facilities - Reactivate and modify the Flight Control Hydraulic Lab (FCHL) at Rockwell Downey (the equipment is government owned, and could be converted for EMA testing). NOTE: This facility will be excessed by the end of the Fiscal Year (effort is already starting), so if the LFBB program continues, the Level II Orbiter Office has to be convinced to retain this facility.
F.2.1.2.6 Estimated Cost - 3 Million total (This is 2 million for lab conversion and 1 million for a 1 year activity with 10 EPs).

F.2.2 NON-BASELINE TESTING REQUIREMENTS - NONE

F.3 MAIN PROPULSION SUBSYSTEM

F.3.1 FINDINGS DISCUSSION

The LFBB Main Propulsion Subsystem will conduct three classes of testing: Cold Flow Tests; Terminal Drain Tests, and full Main Propulsion Subsystem "Hot Firing" Tests. One of the principles followed in developing this test program is to get the appropriate test data in time to use it in the propulsion system design. Another principle used in developing the program is to get the data on the simplest facility and test article combination to minimize program cost. Synergistic support of Integrated Avionics and Structures Stability Subsystems in these tests is possible.

<u>Cold Flow Tests</u>

The first element of the propulsion subsystem test program is envisioned as a series of six cold flow tests. The test article would be a rough simulation of the propellant feed system with a simulated tank and tank bottom. Engines would not be required or desirable for this test program element. It could be the initial set of feed system hardware, though that would be too late to factor test results into the design program. It could be conducted on the cold flow facility in MSFC's Propulsion Laboratory west test area. From this test program, procedures would be developed to condition the propellants to assure no geysering and to assure that the propellants are at the proper conditions for engine start. Tank fill and drain procedures would also be developed using this test program as would the initial contingency planning.

<u>Terminal Drain Tests</u>

The second element would consist of a group of six terminal drain tests. The hardware for this element should be high fidelity hardware, though not necessarily flight hardware. The hardware would consist of the propellant feed systems and the propellant tanks. No engine system would be required. Through this element of the test program, the depletion sensor locations would be verified and the shutdown sequences could be developed. This element of the test program could also negate the necessity for a POGO suppression system.

<u>Main Propulsion Subsystem Tests</u>

The third element of the propulsion subsystem test program would be a series of twelve main propulsion system tests using a main propulsion test article (MPTA). The MPTA would be a high fidelity booster and could be the first booster. This test program would verify and refine the propellant tank fill and drain procedures, start and shutdown sequences, contingency procedures and would serve to verify propulsion system operation. This test element could also be used to qualify the propulsion system operation. It would require that the full compliment of booster engines be installed and hot fired.

The instrumented, flight-type vehicle, complete with all main propulsion hardware and required avionics controllers, would utilize an EPA-approved, instrumented test stand, with the testing occurring 1 to 1.5 years prior to first flight stacking at KSC (or earlier, if SW developers need data).

F.3.2 NON-BASELINE TESTING REQUIREMENTS - NONE

F.4 REACTION CONTROL SUBSYSTEM

F.4.1 FINDINGS DISCUSSION

The LFBB Reaction Control Subsystem is considered to be within the T&V baseline. The RCS will be certified using component-level verification methods and subsystem ground hot firing tests.

RCS Baseline Testing

F.4.1.1 Objective - Certify the RCS can provide adequate reaction control of the vehicle from booster separation motor shutdown to Mach 1.

F.4.1.2 Justification - Component level ATPs will be performed at the vendor (Performance, thermal, vacuum, vibration, etc.). System level performance will be performed to verify system requirements are met.

F.4.1.3 Test Purpose - Verify system level problems not screened at the component level are found:

A. System hydraulic and pneumatic manifold transients.
B. Manifold and engine level mass flow control.

F.4.1.4 Test Hardware - Same components as used to build-up protoflight vehicle:

A. Full-up subsystem build-up with proper line layout to reflect flight vehicle.
B. Protoflight vehicle components shall be reused to the greatest extent possible.
C. Only component not reused is line runs.

F.4.1.5 Project Synergism - No synergism is seen with other LFBB test activities.

F.4.2 NON-BASELINE TESTING REQUIREMENTS - NONE

If any proposed LFBB flight test covered the separation and initial return phase with some fidelity, the RCS would benefit from such a test. The flight would further demonstrate the capability of the RCS to provide adequate reaction control of the vehicle, from booster separation motor shutdown to Mach 1. However, the RCS does not singularly provide significant justification for such a flight test.

F.5 AIR-BREATHING PROPULSION SUBSYSTEM

F.5.1 FINDINGS DISCUSSION

The airframe manufacturer has the responsibility for integrating the Air-Breathing Engine (ABE) with the aircraft structure, and for developing the engine mount, nacelle and pylon structural elements. The nacelle development includes the thrust reversal deflectors and mechanisms. The cost of developing these structural elements has been estimated at 50% of the cost of the air-breathing engine, or about $5 million. An inlet fairing must also be developed for the LFBB to shield the air-breathing engine from the hypersonic ascent and reentry environments.

An off-the-shelf ABE will be certified to the flight envelope of the aircraft for which the engine has been designed. For the large commercial transport ABEs that are under consideration for the LFBB, the operational envelope extends to a maximum altitude of approximately 45 Kft and a

Mach number of 0.9. The cost of an off-the-shelf ABE in the 80 Klbf thrust range has been estimated to be in the range of $10 million.

It is expected that engine modifications will be required to adapt an off-the-shelf ABE to the LFBB vibration/acoustic, pressure and temperature environments. It should be noted that during launch and ascent, the LFBB ABE is oriented vertically while subjected to extreme vibration and acoustic loads and unusual axial accelerations. One potential strategy for addressing the vibration loads is to maintain a slow spin rate for the ABE rotating machinery during ascent and reentry. To carry the unusual axial loads during ascent, a new thrust bearing (perhaps magnetic) might be required. Modifications to the ABE lubrication system might also be necessary to handle the pressure and temperature extremes of the LFBB flight environment. A rough DDT&E cost estimate for the expected modifications for the LFBB ABE is $200 million (approximately $100 million per system), although the cost could be substantially higher. To put the $200 million estimate in context, the development cost for a new commercial transport engine is estimated to be in the range of one to two billion dollars.

The following are specific tests contributing to engine development and verification, as noted:

Vibration and Acoustic Testing

F.5.1.1.1 Test Objectives - Evaluate the impacts of the LFBB vibration and acoustic environment (launch and ascent) on the air-breathing engine and accessories. Identify design and procedural modifications required to qualify the engine for the LFBB flight environment.
F.5.1.1.2 Justification - The LFBB vibration and acoustic environment is expected to be much more severe than the operating environment for a typical aircraft. In addition, the air-breathing engine will be dormant during launch and ascent, which raises concerns for the bearing assemblies. Brinelling of bearings (flat spots) can occur when the bearings are loaded while stationary. Also, the LFBB air-breathing engine will be oriented vertically rather than horizontally, as is more typical for an aircraft application.
F.5.1.1.3 Consequences/Risk - The consequences of bearing damage could range from reduced engine life to engine failure during flyback.
F.5.1.1.4 Test Purpose and Program Phase - Development & Qualification. Concept development work can be started prior to the selection of the LFBB air-breathing engine. Detailed design and testing can begin after air-breathing engine selection is completed and the LFBB vibration and acoustic environments have been characterized (link to structures and main propulsion system development and testing).
F.5.1.1.5 Test Hardware and Facilities - Vibration and acoustic test stand. Facilities - unknown

Vacuum and Thermal Testing

F.5.1.2.1 Test Objectives - Evaluate the impacts of the LFBB pressure and thermal environment on the air-breathing engine. Identify design modifications required to qualify the engine for the LFBB ascent and reentry environments.
F.5.1.2.2 Justification - Commercial and military subsonic aircraft routinely fly at altitudes up to approximately 40,000 ft. At 40,000 ft the static pressure is approximately 20% of sea level ambient (14.7 psi) and the static absolute temperature is approximately 75% of sea level ambient (519 ^{o}R).

The apogee of the LFBB trajectory for an STS launch is approximately 260,000 ft. The current LFBB design specifies an unpressurized environment for the air-breathing engine, resulting in several minutes of exposure to near-vacuum conditions. A short-term vacuum environment is not considered to be a serious concern, however. The primary concern is the thermal environment. Sustained cold temperatures near apogee may thicken lubricants, making the engine difficult to start. Sustained high temperatures (~300 to 350 ^{o}F) may result in the precipitation of solids from some engine liquids, depending on the duration of the exposure.
F.5.1.2.3 Consequences/Risk - The consequences could range from increased engine maintenance and reduced engine life to engine failure and loss of the booster (e.g. an airstart

failure). For an STS launch trajectory the risk is considered to be relatively low since the exposure time to thermal extremes is limited.

Insulation internal to the nacelle might be needed to moderate reentry temperature extremes. Alternative fluids might also serve to reduce the thermal concerns.

F.5.1.2.4 Test Purpose and Phase - Development & Qualification. Vacuum and thermal sensitivity studies can be started prior to the selection of the LFBB air-breathing engine. Detailed testing should begin after completing any engine modifications required to handle the ascent vibration and acoustic environments.

F.5.1.2.5 Test Hardware and Facilities - Appropriate air-breathing engine (including the ascent engine fairing) and engine stand. Large vacuum/thermal chamber.

Engine Ascent Fairing Deployment and Airstart Reliability

F.5.1.3.1 Test Objectives - Test the deployment of an ascent fairing for the LFBB air-breathing engine. Evaluate the impact of the fairing deployment and airstart strategies on the airstart reliability of the air-breathing engine. Modify airstart procedures and develop hardware, as appropriate, to improve airstart reliability.

F.5.1.3.2 Justification - Commercial and military aircraft engines are subject to a rigorous development cycle which includes airstart testing. The ignition constraints for the LFBB (25,000 ft @ Mach 0.7) are within the operational envelope for existing engines. It should be noted that air-breathing engine restart is typically a contingency procedure for an engine flameout during flight, when the engine is still spinning and near standard operating temperatures.

For the LFBB, however, airstart is a standard operational procedure rather than a contingency procedure. In addition, the ease of restart is impacted by the engine conditions prior to airstart (e.g. spinning or non-spinning, engine temperature, etc.). A cold engine that is not spun up prior to fairing jettison may take several minutes to ignite and ramp up to maximum thrust. It should also be noted that high bypass turbofans, which provide the best combination of thrust and TSFC for a single engine installation, are considered to be difficult to airstart.

F.5.1.3.3 Consequences/Risk - The consequence of a failed airstart is the loss of a LFBB. The LFBB has a maximum glide range of approximately 25 nmi at maximum L/D from an initial altitude of 25,000 ft.

F.5.1.3.4 Test Purpose and Program Phase - Development & Qualification. Testbed preparation and airstart procedure development can be initiated as soon as the LFBB air-breathing engine has been selected. Airstart testing can be conducted in parallel to the thermal test sequence. Qualification of the LFBB air-breathing engine should begin after completing any engine modifications required to handle the ascent vibration and acoustic environments.

F.5.1.3.5 Test Hardware and Facilities - Appropriate air-breathing engine (including the ascent engine fairing). A wind tunnel, such as the 40x80 ft tunnel at NASA Ames, may be sufficient for the early phase of the development program. For fairing deployment and airstart tests at the flight Reynolds number, an engine and prototype fairing would be mounted on an existing aircraft testbed.

If the engine were thermally conditioned prior to the airstart tests, the results would also serve as verification for the thermal test program.

Installed Engine Performance

F.5.1.4.1 Test Objectives - Evaluate the installed thrust and TSFC performance of the air-breathing engine on the actual LFBB platform.

F.5.1.4.2 Justification - The installed thrust and airstart capability of the air-breathing engine is affected by the quality of the inlet flow. A tail-mounted engine may suffer thrust loss at high angles of attack due to fuselage interference. Wind tunnels will not be able to accommodate a full-scale LFBB test article. Subscale tests will not be able to directly measure actual engine performance, but may be suitable for extrapolation.

The proposed flight test is synergistic with aerodynamic flight test objectives.

F.5.1.4.3 Consequences/Risk - If the uninstalled thrust is lower than predicted then the LFBB cruise ceiling will be lower, resulting in a reduction in flight range. Assuming that straight-and-level flight can be achieved at a reasonable altitude, the LFBB design loiter time (endurance) will not be directly affected. However, some loiter time might be converted to flight range to compensate for a reduction in thrust performance.

F.5.1.4.4. Test Purpose and Program Phase - Qualification. This test would follow the development of major LFBB systems and would tend to occur late in the development cycle.

F.5.1.4.5 Test Hardware and Facilities - Protoflight LFBB airframe and engine. Other flight systems (avionics, actuators, etc.) could be actual flight hardware or could be adapted from existing hardware (e.g. hydraulic components) to push the flight test earlier in the development cycle. An appropriate flight test facility (Dryden?).

F.5.2 NON-BASELINE TESTING REQUIREMENTS - NONE

F.6 THERMAL PROTECTION/INSULATION SUBSYSTEM

F.6.1 FINDINGS DISCUSSION

The LFBB Thermal Protection Subsystem/Insulation Test Program will encompass both the Shuttle Orbiter TPS Certification Process and Shuttle TPS flight experience, including: Vehicle Damage Tolerances/Impact Resistance, Inspection, Repairs and Maintainability. The Orbiter TPS Certification Process covered:

A. Testing
- Thermal performance
- Aerodynamic flow
- Acoustic fatigue
- Strength integrity
- Material properties

B. Analysis
- Natural environments
- Induced environments
- Miscellaneous

C. Similarity

The LFBB TPS Insulation will encompass:

A. The heat sink structure (forward of Lox tank)
- Aluminum
- Titanium

B. The Lox tank
- TABI blanket
- Rohacell foam

Resources required for the LFBB TCS/Insulation Verification activities include

A. Laboratories
- Materials and processes
- Analytical
- Mechanical/thermal properties
- Cryogenic
- Thermal vacuum
- Vibroacoustics
- Vibration

B. Facilities
- Plasma Arc at JSC and Ames
- Wind tunnels, e.g., LaRC High temperature Structures Tunnel
- Rain/salt spray/humidity
- Debris impact
- Vibroacoustics at JSC
- Thermal vacuum/radiant heater at JSC

C. Aircraft Flight Testing of Components.

LFBB TPS/Insulation Panel Test

TPS/Insulation Panel testing at the Dryden aircraft facilities is an integral part of the overall development and verification activities and is anticipated to be within the T&V baseline.

F.6.1.1 Test Objective - Demonstrate TPS/Insulation concept to natural environment, using aircraft flight tests.
F.6.1.2 Justification for Test - To obtain environmental effects (i.e., rain, ice, debris) on the proposed TPS/insulation concept representative of flight environment.
F.6.1.3 Consequence or Risk of Not Conducting Test - Reuse/refurbishment requirements will not be understood.
F.6.1.4 Test Purpose and Program Phase - Development Test in Phase B/C.
F.6.1.5 Test Hardware and Facilities - Test panels for mounting to various locations on aircraft to simulate different environments; DFRC aircraft.

F.6.2 NON-BASELINE TESTING REQUIREMENTS - NONE

F.7 STRUCTURES SUBSYSTEM

F.7.1 FINDINGS DISCUSSION

The LFBB Structures Subsystem T&V development, qualification, and acceptance test requirements are within the T&V baseline envelope.

A comparison of STS experience with today's technology shows:

A. Analytical methods are faster than those of the 1970s, but accuracy is still about the same.

B. Structural testing and data acquisition are more automated today.

C. Risk at LFBB first launch vs STS-1 is dependent on the accuracy of the design loads and the amount of testing and model correlation completed by that date. If the loads are off - structural margins are off.

The LFBB Structural Testing is as follows:

Development Testing

F.7.1.1 Panel Development
F.7.1.1.1 Objective - Obtain panel buckling loads (allowables).
F.7.1.1.2 Justification - Needed to design stiffened panels loaded in compression.
F.7.1.1.3 Purpose - Development
F.7.1.1.4 Test Hardware - Panel sections representative of LFBB geometry, material, & fabrication.
F.7.1.1.5 Synergism with other tests - Acoustic panel testing.

F.7.1.2 Weld Development
F.7.1.2.1 Objective - Develop weld procedure and obtain weld strength.
F.7.1.2.2 Justification - Needed to design and fabricate welded structure.
F.7.1.2.3 Purpose - Development
F.7.1.2.4 Test Hardware - Representative panel sections of LFBB material and geometry.
F.7.1.2.5 Synergism with other tests - None (External Tank experience may reduce extent of effort).

F.7.1.3 Aft Skirt Development (aft skirt/wing pivot/thrust structure/main landing gear/pad tie down)
F.7.1.3.1 Objective - Demonstrate design feasibility and performance.
F.7.1.3.2 Justification - Unique aft skirt and thrust structure that must support the wing pivot, tail structure, main landing gear, engine thrust, and the entire stack weight and moments.

F.7.1.3.3 Purpose - Development
F.7.1.3.4 Test Hardware - Full-scale aft skirt, thrust structure, and wing pivot.
F.7.1.3.5 Synergism with other tests - Pad release development, wing pivot mechanical system development, & possible use as qualification test article for fatigue and ultimate strength test if final design is similar.

F.7.1.4 Nested Fuel Tank Development
F.7.1.4.1 Objective - Demonstrate design feasibility and performance.
F.7.1.4.2 Justification - Unique nested tank configuration.
F.7.1.4.3 Purpose - Development
F.7.1.4.4 Test Hardware - Full-scale JP fuel tank and RP fuel tank.
F.7.1.4.5 Synergism with other tests - Propulsion system development & possible use as qualification test article for fatigue and ultimate strength test if final design is similar.

F.7.1.5 Launch Pad Release Development
F.7.1.5.1 Objective - Demonstrate design feasibility and performance.
F.7.1.5.2 Justification - Will influence launch dynamics that affect booster & ET.
F.7.1.5.3 Purpose - Development
F.7.1.5.4 Test Hardware - Same aft skirt development hardware and launch pad i/f structure.
F.7.1.5.5 Synergism with other tests - Loads & Dynamics testing.

Qualification Testing

F.7.2.1 Fatigue Life
F.7.2.1.1 Objective - Verify hardware life.
F.7.2.1.2 Justification - Required for structural certification for flight.
F.7.2.1.3 Purpose - Qualification
F.7.2.1.4 Test Hardware - Dedicated structural LFBB assembly (entire primary structure).
F.7.2.1.5 Synergism with other tests - Mechanical systems tests.

F.7.2.2 Ultimate Structural Strength
F.7.2.2.1 Objective - Verify the ultimate strength all primary structure.
F.7.2.2.2 Justification - Required for structural certification for flight.
F.7.2.2.3 Purpose - Qualification
F.7.2.2.4 Test Hardware - Dedicated structural LFBB assembly (entire primary structure).
F.7.2.2.5 Synergism with other tests - Mechanical systems tests.

Acceptance Testing

F.7.3.1 Tank Proof Pressure
F.7.3.1.1 Objective - Verify workmanship and material.
F.7.3.1.2 Justification - Establish that tanks were manufactured the same as the qualification tanks.
F.7.3.1.3 Purpose - Acceptance
F.7.3.1.4 Test Hardware - All flight LFBB tanks.
F.7.3.1.5 Synergism with other tests - none.

F.7.3.2 Tank Leak
F.7.3.2.1 Objective - Demonstrate hardware readiness.
F.7.3.2.2 Justification - Establish that hardware does not leak before use.
F.7.3.2.3 Purpose - Acceptance
F.7.3.2.4 Test Hardware - All flight tanks.
F.7.3.2.5 Synergism with other tests - Propulsion system tests.

F.7.4 NON-BASELINE TESTING REQUIREMENTS - NONE

A significant point must be made - the extent and duration of the structures test program is dependent on the testing approach - incorporating a dedicated Structural Test Article (STA) vs protoflight unit and structures component tests. Within this Subsystem, using an STA is advocated, in lieu of the test H/W available in protoflight T&V, based on:

A. Shorter test program duration and less manpower,

B. Less hardware, facilities and fixtures,

C. Test results reducing uncertainty associated with analysis, i.e., lessen conservatism in design needed to deal with uncertainties,

D. Less model correlation.

Given the above , the Structures Subsystem recommends inclusion of an integrated vehicle STA in the LFBB T&V baseline.

F.8 MECHANICAL SYSTEMS SUBSYSTEM

F.8.1 FINDINGS DISCUSSION

The Mechanical Systems Subsystem T&V philosophy is to follow, on the large number of LFBB assemblies, the STS experience of using ground testing to verify system function and flight DTOs to verify operational loads. This approach is complicated somewhat by the use of ElectroMechanical Assemblies and DC power, with the partial loss of commonalty with the STS subsystems models. Comparison of the STS experience and today's technology shows:

A. Kinematic and dynamic analysis tools could be used to supplement some development testing.

B. Maintainability requirements for LFBB may require more extensive life testing than STS systems.

C. Use of EMAs and DC power will require significant development testing, but should not require additional tests at the integrated system level.

These points, along with major mechanical systems unique to the LFBB (wing and canard deployment and fairings jettison), will require significant testing, but below the LFBB Integrated System level. The subsystem/component costing should, however, cover the projected testing requirements.

F.8.2 NON-BASELINE TESTING REQUIREMENTS - NONE

F.9 LOADS/DYNAMICS/STABILITY TECHNICAL DISCIPLINE

F.9.1 FINDINGS DISCUSSION

F.9.1.1 LOADS

LFBB Loads pertain to the following phases of the mission: 1) Transportation, 2) Prelaunch, 3) Liftoff, 4) First Stage Ascent, 5) Separation, 6) Early Descent, 7) Flyback, and 8) Landing. Loads verification is comprised of model verification and selected predicted loads verification:

- Without a "boilerplate" vehicle, most loads are analytically derived rather than flight derived, thus verification of models and some operational vehicle loads is the method used to manage risk. (Don't need dedicated DFI.)
- Analytical prediction has saved large costs, but remaining risk is addressed by test.
- Loads model verification consists of stiffness verification and mass distribution verification, performed by influence coefficient tests, and modal tests.
- These tests occur on full and subscale test articles, and at segment and integrated assembly fidelity.

These tests were used to anchor Apollo and Shuttle flight readiness statements (Apollo also had boilerplate vehicle experience). The end result is that all critical design conditions are verified.

Specific tests for loads model verification are:

A. Prelaunch dynamics test to set booster liftoff timing
B. Stiffness verification of booster shell prior to modal survey for liftoff loads
C. Liftoff configuration (booster only) modal survey for liftoff loads
D. Stiffness tests of interfaces to other elements (MLP, Forward and aft ET)
E. Landing configuration modal survey for landing loads
F. Vehicle landing loads tests
G. Landing gear loads tests

Specific tests for external forces verification

A. Booster thrust loads (sponsored by propulsion)
B. Distributed pressure loads (sponsored by aerodynamics
C. Air-breather thrust loads (sponsored by propulsion)
D. Cryo-shrinkage induced loads (sponsored by loads

F.9.1.2 DYNAMICS

Within the Dynamics discipline, design and verification are concerned about: 1) Liftoff, 2) Ascent, and 3) Early Descent acoustics and vibrations. Acoustics and vibrations verification considers the following:

- Booster ignition acoustics must be verified by subscale hot-fire test and by full scale launch pad firing.
- Vibrations resulting from acoustics must be verified by measurement of full scale response at critical locations, e.g., instrumented vehicle the first time it flies.
- Ascent acoustics must be verified by wind tunnel test (piggy-back on aero tests).
- Vibrations resulting from acoustics must be verified by measurement on the flight vehicle, especially the early flights.

F.9.1.3 STABILITY

Engine/Structure Stability (POGO)

POGO, i.e., structure interaction with the booster, requires:

- Single engine testing with pulsing to acquire engine dynamic transfer functions (thrust divided by pressure versus frequency and npsp).
- Cluster engine testing with pulsing as above.
- Full scale integrated vehicle verification by data acquisition (possibly pulsing).

Aerodynamic/Structure Stability (Flutter)

Flutter (structures interaction with the flight aerodynamic environment) testing requirements include:

- Dedicated wind tunnel test to descent vehicle wings and tail flutter verification.
- Descent flight test with data acquisition and flutter pulsing excitation.

Landing Braking System Stability (Anti-Skid System)

Landing Brake System stability could be verified through full scale landing gear test with pulsing, possibly piggy-back with brake performance testing.

F.9.1.4 FLIGHT TESTING

Several tests are required to verify launch vehicle safety that cannot be satisfied by a single booster flight:

- Aerodynamic pressure loads

- Booster modal test for loads and integrated shuttle flight control stability
- Flutter tests (ascent portion)
- Cryogenic shrinkage induced loads

Many other tests can be rolled up into a single booster flight test if potential schedule impacts from late technical surprises are found are acceptable:

- Launch, ascent, and early descent acoustics tests
- Propulsion tests (thrust and stability)
- Flutter tests (descent portion)
- Potentially, landing gear tests (loads and stability)

F.9.2 NON-BASELINE TESTING REQUIREMENTS - NONE

F.10 AERODYNAMICS AND AEROTHERMODYNAMICS TECHNICAL DISCIPLINE

F.10.1 FINDINGS DISCUSSION

The LFBB represents a substantial change to the Shuttle ascent configuration and, as such, will significantly impact the ascent aerodynamic and aerothermodynamic environments of the Orbiter and ET elements. These impacts must be quantified by testing. Therefore, for the Shuttle Launch Vehicle w/LFBBs, increments to current ET & ORB certification databases must be developed, including producing new database for LFBB components, and deltas to ET & ORB DBs early enough to support necessary modifications.

For re-entry and flyback, an LFBB is more like an Orbiter than an SRB in configuration, flight envelope, subsystems and operations. LFBB aerodynamic/aerothermodynamic characteristics and loads must be quantified by testing. Thus, for the LFBB entry vehicle, consider the Orbiter testing requirements as a baseline and develop LFBB databases from scratch.

For the LFBB testing and verification requirements to be within the Shuttle experience envelope, certain assumptions must be made:

A. Assume that the outer mold lines are frozen by PDR - no 'late' changes - with detailed WTT done early in program to support design.
B. Launch Vehicle WT testing will be able to utilize existing WT models for the ET & ORB elements, with LFBB model design and fabrication necessary.
C. Launch Vehicle WT testing must provide "typical" database information to the existing elements (Orbiter & ET) to support baselined certification requirements.
D. LFBB control systems (RCS, BSM, etc.) are defined in detail by PDR.

Given the above, the Aerodynamics Discipline testing requirements can be summarized as follows:

1. All indicated ascent aerodynamic testing are typical of Shuttle program requirements and are necessary because of the geometric differences between the SRB and LFBB.
2. The similarity of the LFBB to the Orbiter justifies the indicated aerodynamic (entry) testing to be typical of Orbiter program requirements and necessary because of the unique LFBB entry configuration.
3. The potential exists for reducing (but not eliminating) necessary wind tunnel testing through utilization of advanced Computational Fluid Dynamics (CFD) analysis: JSC/ARC launch vehicle application & LaRC entry vehicle application.
4. CFD analysis can further assist in quantifying limitations of ground test facilities and therefore enhance (over STS-1) pre-flight database accuracies.

5. The ability of the LFBB to fly significantly lower dynamic pressure ascent trajectories could reduce the amount or accuracy required of aero loads test data necessary to maintain the current Shuttle vehicle margins.

6. Flight tests of the LFBB could serve as preliminary verification of the aerodynamic characteristics but do not reduce ground test requirements.

Summarizing Aerothermodynamics:

1. All indicated aerothermodynamic testing are typical of Shuttle requirements and necessary because of the geometric differences between the SRB and LFBB as well as the unique entry configuration of the vehicle.

2. First stage testing of the LFBB integrated vehicle cannot, at this time, be reduced or replaced through analytical means. Entry configuration testing requirements may be decreased using current wind tunnel testing and computational technologies.

3. There are no other means to reduce or minimize the amount or types of testing indicated in order for an accurate aerothermodynamic analysis to be conducted.

4. Flight tests of the LFBB could serve as preliminary verification of the aerothermodynamic environments but do not reduce ground test requirements.

INTEGRATED LAUNCH VEHICLE TESTING

First Stage F&M Wind Tunnel Test Series

F.10.1.1.1 Objective - Obtain aerodynamic force and moment characteristics of launch vehicle and individual element interface loads (M=0.5 to 3.5). Several tests required to cover Mach range, provide repeatability.
F.10.1.1.2 Justification - LFBB represents a significant aerodynamic configuration change to the launch vehicle resulting in necessary updates to operational aerodynamic database in support of flight performance, flight design, structural design & structural margins assessment.
F.10.1.1.3 Risk - Unacceptable definition of aero loads environment resulting in overly conservative design and/or restrictive launch constraints.
F.10.1.1.4 Test Purpose and Program Phase - Development & Verification in Phase B/C.
F.10.1.1.5 Test Hardware and Facilities - High Fidelity F&M model w/4 internal balances (e.g. 0.02 scale model - 89-OTS) in transonic/supersonic wind tunnels (e.g. AEDC PWT 16'T & 16'S, ARC Unitary Plan 9'x7'S or 8'x7'S).
F.10.1.1.6 Estimated Cost (in baseline) - $0.5-1.5M per test.

First Stage Aero Loads & Acoustics Test Series

F.10.1.2.1 Objective - Obtain external static pressure distribution over entire launch vehicle for Mach 0.5-2.5. Define acoustic environment due transonic (Mach 0.8-1.55) shocks.
F.10.1.2.2 Justification - LFBB represents a significant aerodynamic configuration change to the launch vehicle resulting in necessary updates to operational aerodynamic database in support of structural design, structural margins assessment and aerothermal analysis.
F.10.1.2.3 Risk - Unacceptable definition of aero loads environment.
F.10.1.2.4 Test Purpose and Program Phase - Design & Verification in Phases B/C.
F.10.1.2.5 Test Hardware and Facilities - High fidelity aero pressure model [>1500 taps], (e.g., 0.03 scale model - 47 - OTS), in transonic/supersonic wind tunnels (e.g., AEDC PWT 16'T & 16'S, ARC Unitary Plan 9'x7' or 8'x7'S).
F.10.1.2.6 Estimated Cost (in baseline) - $1.5-2.0M per test.

Ground Winds Effects

F.10.1.3.1 Objective - Define wind induced dynamic response/loads between SLV & tower.
F.10.1.3.2 Justification - Establish dynamic stability of launch vehicle on pad. Inputs to determining allowable pad dwell time.
F.10.1.3.3 Risk - Unacceptable definition of interface loads between SLV & launch tower.
F.10.1.3.4 Test Purpose and Program Phase - Design & Verification in Phase C.

F.10.1.3.5 Test Hardware and Facilities - Structural dynamics model & instrumentation (e.g. 0.046 scale model - 100) in transonic dynamics wind tunnel (e.g. LaRC 16'T Transonic Dynamics Tunnel).
F.10.1.3.6 Estimated cost (in baseline) - $0.25-0.5M.

Ascent Flutter (Vehicle Interaction + LFBB VT)

F.10.1.4.1 Objective - Define structural dynamics stability. Includes both integrated launch vehicle testing and component (LFBB VT) level testing.
F.10.1.4.2 Justification - LFBB represents a significant aerodynamic configuration change to the launch vehicle requiring updates to certification environments of the ORB & ET. The LFBB VT must also be evaluated for flutter sensitivity.
F.10.1.4.3 Risk - Inadequate design to account for flutter sensitivity.
F.10.1.4.4 Test Purpose and Program Phase - Design & Verification in Phase B/C.
F.10.1.4.5 Test Hardware and Facilities - Structural dynamics model & instrumentation in transonic dynamics wind tunnel (e.g. LaRC Transonic Dynamics WT).

SLV/LFBB Separation (Proximity + BSM plume interaction effects)

F.10.1.5.1 Objective - Obtain proximity and BSM plume interaction aerodynamic effects during LFBB separation sequence for stability and control evaluation.
F.10.1.5.2 Justification - Recontact of LFBB with SLV is unacceptable. SSME plume impingement on LFBB most likely unacceptable. Design and verification of this sequence/trajectory requires aerodynamic force & moment data.
F.10.1.5.3 Risk - Undefined separation environment characteristics - risk to vehicle stability and control.
F.10.1.5.4 Test Purpose and Program Phase - Design & Verification in Phase B/C.
F.10.1.5.5 Test Hardware and Facilities - High fidelity launch vehicle WT model with separation simulation (CTS) and BSM simulation capabilities. (e.g. 0.01 scale model - 32-OTS or 52-OTS) in supersonic/hypersonic wind tunnel (e.g. AEDC VKF Tunnel A & B).
F.10.1.5.6 Estimated Cost (in baseline) - $0.5-1.0M.

First Stage Aerodynamic Convective Heating

F.10.1.6.1 Objective - To measure heating rates and distributions on the LFBB, ET, and Orbiter in the first stage configuration.
F.10.1.6.2 Justification - The inherent geometry differences between the current SRB and the LFBB will result in different undisturbed heating rates, distributions, protuberance heating, and shock interference heating on the Orbiter, ET, and LFBB. Current analytical techniques are not efficient and accurate enough to obtain quantitative information on the above phenomena.
F.10.1.6.3 Risk - Overly conservative heating rates and distributions which could result in over designed TPS (increased weight) on the LFBB and TPS redesigns on the ET and possibly the Orbiter.
F.10.1.6.4 Test Purpose and Program Phase - Development in Phase C/D.
F.10.1.6.5 Test Hardware and Facilities - Refabricated STS integrated heating model and new thin skinned T/C LFBB models (both left & right) built to similar scale (e.g. 0.0175 scale model - 60-OTS) in Mach 3 - 6 hypersonic wind tunnel facility (e.g. AEDC VKF Tunnel A, LaRC Mach 6 Hypersonic Tunnel).
F.10.1.6.6 Estimated Cost (in baseline) - $0.5-1.0M.

Plume Radiation and Convective Heating Testing

F.10.1.7.1 Objective - Plume radiative and convective heating measurements during stand testing of RD-170 engines.
F.10.1.7.2 Justification - To obtain or confirm radiative and convective heating data for RD-170 engines for inputs to radiative and plume recirculation heating models for the Orbiter base, ET base and LFBB base and aft skirt.

F.10.1.7.3 Risk - Overly conservative radiative heating rates and distributions which could result in over designed TPS (weight increase) on LFBB and possible TPS redesigns on ET & ORB.
F.10.1.7.4 Test Purpose and Program Phase - Development in Phase B/C.
F.10.1.7.5 Test Hardware and Facilities - Radiometers, calorimeters, gas temperature probes and associated data acquisition equipment. This would be an add-on test objective to scheduled testing of the RD-170s.
F.10.1.7.6 Estimated Cost (in baseline) - $200K per test.

Hot Gas First Stage Test

F.10.1.8.1 Objective - Obtain plume recirculation convective heating data on the integrated vehicle with LFBB.
F.10.1.8.2 Justification - Base configuration of the integrated vehicle with LFBBs is substantially different from the current configuration with SRBs. Data of this type will help reduce uncertainties of heating models developed for the base region which includes the ET base and LFBB base and aft skirt.
F.10.1.8.3 Risk - Overly conservative heating rates and distributions which could result in over designed TPS (weight) on the LFBB and TPS redesigns on the ET.
F.10.1.8.4 Test Purpose and Program Phase - Development in Phase B/C.
F.10.1.8.5 Test Hardware and Facilities - Instrumented first stage vehicle configuration with hot gas firing capability in a pressurized hypersonic wind tunnel facility capable of running with hot gas firings.
F.10.1.8.6 Estimated Cost (in baseline)- $1.0-2.0 M.

RE-ENTRY LFBB VEHICLE TESTING

Aerodynamics (F&M + C.S. Effectiveness) Test Series (M=6.0 to landing)

F.10.1.9.1 Objective - Define LFBB aerodynamic characteristics and control surface effectiveness across flight regime. Several tests required to cover Mach range and provide sufficient repeatability.
F.10.1.9.2 Justification - Required to define vehicle flight performance, stability & control and design flight control system.
F.10.1.9.3 Risk - Unacceptable aerodynamic characteristics and flight control definition.
F.10.1.9.4 Test Purpose and Program Phase - Development & Verification in Phase B/C.
F.10.1.9.5 Test Hardware and Facilities - Several Wind Tunnel Models [0.02->0.05 scale] (e.g. Orbiter had on the order of 10 tests in various facilities - 3 models) in hypersonic/supersonic/transonic/subsonic WT (e.g. AEDC VKF Tunnel A&B, LaRC Transonic WT, ARC Unitary Plan WT).
F.10.1.9.6 Estimated Cost (in baseline) - $0.5-1.0M per test.

Aero Loads Testing (M=3.5 ---> landing)

F.10.1.10.1 Objective - Define external pressure distribution of re-entry configurations for use in structural design and margins assessment.
F.10.1.10.2 Justification - Unacceptable definition of aero loads environment resulting in over designed vehicle structure.
F.10.1.10.3 Risk - Unacceptable weight growth, structural integrity.
F.10.1.10.4 Test Purpose and Program Phase - Development & Verification in Phase B/C.
F.10.1.10.5 Test Hardware and Facilities - High fidelity aero pressure model (>1000 taps) in supersonic/transonic/subsonic wind tunnels.
F.10.1.10.6 Estimated Cost (in baseline) - $0.5-1.5M.

Descent Flutter (Lifting Surfaces)

F.10.1.11.1 Objective - Define structural dynamics stability; component level testing.
F.10.1.11.2 Justification - LFBB lifting surfaces must be evaluated for flutter sensitivity.
F.10.1.11.3 Risk - Improper design to account for flutter sensitivity.
F.10.1.11.4 Test Purpose and Program Phase - Development in Phase B/C.
F.10.1.11.5 Test Hardware and Facilities - Structural dynamics component (i.e. wing) model in transonic dynamics wind tunnel.

RCS Plume Interaction Effects

F.10.1.12.1 Objective - Develop RCS plume interaction aerodynamics.
F.10.1.12.2 Justification - RCS plume interaction aerodynamics can amplify or adversely effect intended control authority and must be factored in to the design of the flight control system.
F.10.1.12.3 Risk - Unacceptable flight control system design input.
F.10.1.12.4 Test Purpose and Program Phase - Development & Verification in Phase B/C.
F.10.1.12.5 Test Hardware and Facilities - Hi-Fidelity LFBB WT model (w/RCS capability) in supersonic/hypersonic wind tunnel (e.g. AEDC VKF Tunnel A&B, LaRC 31-in Hypersonic).
F.10.1.12.6 Estimated Cost (in baseline) - $0.5-1.0 M.

Aerothermodynamic - Convective Heating (Mach 6.0->3.0)

F.10.1.13.1 Objective - Obtain convective heating rates and distributions on the entry configuration of the LFBB between 65 and 20 angle of attack, Mach 3-6.
F.10.1.13.2 Justification - The unique geometry of the LFBB will require some ground testing to obtain accurate heating rates and distributions at a variety of conditions. This data will be used to validate and build confidence in analytical techniques which will also be used in the development.
F.10.1.13.3 Risk - Overly conservative heating rates and distributions which could result in over designed TPS (increased weight) on the LFBB.
F.10.1.13.4 Test Purpose and Program Phase - Development in Phase B/C/D.
F.10.1.13.5 Test Hardware and Facilities - Mecor machined model of the LFBB in flyback mode in Mach 6 hypersonic wind tunnel. This model can be coated with thermographic phosphor to obtain quantitative heating data. Engineers at LaRC have developed this technique.
F.10.1.13.6 Estimated Cost (in baseline) - $100K/model, $0.5M per test.

F.10.2 NON-BASELINE TESTING REQUIREMENTS - NONE

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13. ABSTRACT *(Maximum 200 words)*

The concept of a flyback booster has been around since early in the Shuttle program. The original two-stage Shuttle concepts used a manned flyback booster. These boosters were eliminated from the program for funding and size reasons. The current Shuttle uses two Redesigned Solid Rocket Motors (RSRMs), which are recovered and refurbished after each flight; this is one of the major cost factors of the program. Replacement options have been studied over the past ten years. The conclusion reached by the most recent study is that the liquid flyback booster (LFBB) is the only competitive option from a life-cycle cost perspective.

The purpose of this study was to assess the feasibility and practicality of LFBBs. The study provides an expansion of the recommendations made during the aforementioned study. The primary benefits are the potential for enhanced reusability and a reduction of recurring costs. The potential savings in vehicle turnaround could offset the up-front costs. Development of LFBBs requires a commitment to the Shuttle program for 20 to 30 years. LFBBs also offer enhanced safety and abort capabilities. Currently, any failure of an RSRM can be considered catastrophic, since there are no intact abort capabilities during the burn of the RSRMs. The performance goal of the LFBBs was to lift a fully loaded Orbiter under optimal conditions, so as not to be the limiting factor of the performance capability of the Shuttle. In addition, a final benefit is the availability of growth paths for applications other than Shuttle.

Participants included JSC, KSC, and MSFC. If it is determined that a more detailed study is warranted, a new study would be initiated to obtain baseline requirements, which would lead the way for detailed vehicle designs and a reference concept with bottoms-up cost.

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