Appendixes

Appendix A
Benefits and Drawbacks of Liquid Rocket Boosters for the Space Shuttle

Potential Benefits

Safer Abort Modes

Figure A-1 and table A-1 give abort mode comparisons for different Shuttle/booster configurations. The Liquid Rocket Boosters (LRBs) allow a variety of safe abort modes, that is, several engines could fail on lift-off and still not cause a catastrophic mission failure.[1] A Solid Rocket Booster (SRB) or Advanced Solid Rocket Motor (ASRM) failure, however, is generally catastrophic because solids cannot be turned off after they are ignited. The LRB configuration consists of two boosters, each with four liquid-fueled engines. The ASRM and SRB configurations each consist of two solid booster rockets. All configurations rely on three Space Shuttle Main Engines (SSMEs) on the orbiter.

Long History, Potentially Greater Mission Reliability

All major launch systems use liquid engines for part or all of the first stage; there is an extensive data base on their performance and use and fuel handling needs. LRBs can be test fired before launch. If the engine monitoring instruments indicate a problem, the engines can be shut down and the flight aborted on the pad. This is presently done with the SSMEs for a very short period before the solids are ignited.[3] Once a solid rocket is ignited it cannot be shut off-it burns through all of its fuel.[4]

The LRBs can also be tightly monitored during flight and can be shutdown if a problem arises-perhaps before a catastrophic engine failure occurs. If the system were designed with sufficient margin, the thrust of the remaining engines could be increased to compensate for the shut-down engine, and the mission completed without requiring an abort mode.

Shutting down a liquid engine would present some problems of vehicle control in part because the control system would have to balance the thrust of a the remaining engines. Because the remaining engines can be throttled (unlike solids) it is possible to compensate for changed moments of force about the vehicle's center of gravity to reduce airframe stress and prevent cartwheeling. The failure of more than one engine would be even more difficult to compensate for. Control of these types of potential failures have not been thoroughly investigated.

Increased Lift Capability

The LRB performance improvement for the Shuttle could be an additional 20,000 pounds[5] to low-Earth orbit as shown in figures 3-7 and A-2.

Mission Profiles Can Be Changed Relatively Easily

As noted above, LRBs can be throttled while solid boosters cannot. Once a solid is poured to a predetermined configuration, its burn and hence thrust characteristics are set, fixing the direction and speed of the Shuttle on ascent. (Some flexibility is allowed by throttling the three SSMEs but this entails several potential problems and is avoided if possible.) These solid booster thrust characteristics sometimes change unpredictably when the solids age. In contrast, throttling LRBs within reasonable thrust ranges is relatively easy and can be used to compensate for different payloads, atmospheric conditions, desired trajectories or orbits, etc. This can lead to more "efficient" launches and perhaps slightly heavier payloads.

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[1] All of these assume that a single engine (or motor) failure does not affect the operation of arty other engine (or motor). A catastrophic failure Of one engine (Or motor) could of course destroy the Shuttle (no abort mode).

[2] The reliability of liquid engines versus solid rockets is the subject of heated debate and increasing study. NASA is creating a database that covers every U.S. launch and full -scale engine test—over 1,300 liquid or solid propulsion events. It will include date, vehicle, engine type, top three anomalies (if there were problems) with corrective action taken, comments, documentation, and location of documentation. This database should be available soon. NASA intends to keep it updated with future launches and engine tests. Study of this database could help resolve some of the present uncertainty in liquid v. solids reliability statistics. (The Aerospace Corp. also has a significant database on engine successes and failures and the American Institute of Aeronautics and Astronautics has working groups analyzing these solids v. liquids reliability issues).

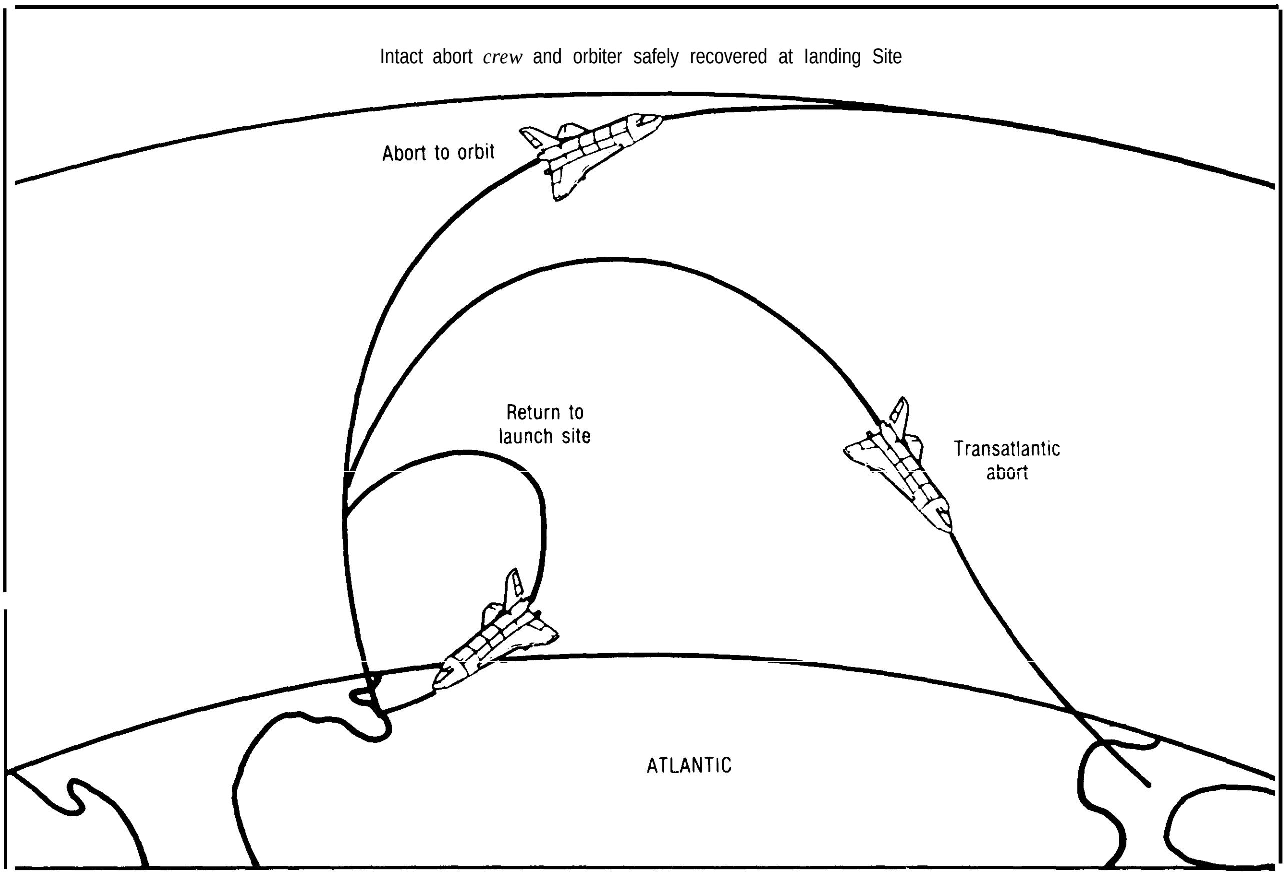
Some LRB proponents feel that arguing about solid versus liquid engine reliability is not german e; they believe that the probability of mission success, or the ability to abort a mission safely, are the critical points. They argue that even if a given LRB engine were slightly less reliable than a given solid rocket motor, because of the ability to shut down the liquid engine in flight, the mission reliability for the vehicle using LRBs would be higher than than for a vehicle using solid rocket motors.

[3] On one Shuttle mission, one of the three SSME's was shut down after the Shuttle was already well into its flight, and the mission was not affected. Shutting down an SSME takes about 30 seconds. The proposed LRBs are simpler enginea and can be shut down essentially instantaneously ("immediate fuel cutoff) thus making catastrophic engine failure easier to avoid "in case engine monitors detect an anomaly.

[4] In theory, if ● solid is already ignited, one could provide a means to blow out the opposite end of the motor and ignite it also, yielding essentially zero thrust. However, the *other solid* (even if functioning properly) would also havelobe''shutdown" in the same manner in order [o prevent vehicle cartwheeling. With both solids essentially shut-down the Shuttle would have to be well into its trajectory to affect any reasonable ● bort. The joha to the Shuttle system and connec t points would also be revere and the Shuttle would probably break ● part. Thus this is not ● viable option.

[5] This performance increase, which is nearly double that planned for the ASRMs, would be possible in part because the LRBs would be longer and of greater diameter than the ASRMs. NASA held the diameter and length of the ASRM design to dimensions that would necessitate little or no alteration of the mobile launch platform. Because liquid engines would require fuel tanks that are *larger than the* ASRM dimensions to reach even 12,000 pounds additional thrust, NASA relaxed the geome trical constraints in the LRB design.

Figure A-1-Intact Abort Modes for Space Shuttle Missions



A Shuttle orbiter is not expected to survive a ditching at sea, although the crew might escape and survive if controlled gliding flight is established before ditching.
SOURCE: General Dynamics.

Safer Shuttle Processing Flow

LRBs are fueled just before launch. SRMs, on the other hand, carry explosive fuel at all times and must be handled carefully. Safety considerations are a critical, and expensive, part of SRM use—from manufacture, to transport, to launch vehicle mating, to liftoff. At some points in the Shuttle processing flow, entire buildings must be evacuated while a handful of people cater to the solid rockets.[6] Liquid cryogenic fuels are well understood and have a good safety record.[7]

Lighter Structure Would Allow Horizontal Assembly

Empty LRB tanks are lighter than assembled solid rocket segments, which are stacked vertically, For example, the Soviet *Energia* heavy-lift launch vehicle is assembled horizontally and then raised to the vertical only shortly before launch. Horizontal assembly and transport is much easier than vertical processing.

[6]Five or more days are lost during this procedure. Twenty to thirty people are idled.

[7]Hypergolics are dangerous and potentially detrimental to the environment, but these are not being proposed for LRBs. LRBs would use some form of liquid oxygen/liquid hydrogen fuels or perhaps liquid oxygen/hydrocubon fuels. Hydrocarbons such as methane or kerosene arc relatively benign environmentally.

[8]The hut of the exhaust of any of these rockets may produce small amounts of nitric and nitrous oxide from the nitrogen in the air, just as automotive and jet engines do.

LRBs Are More Environmentally Sound

The exhaust of an LRB fueled by liquid hydrogen would consist solely of steam. The exhaust of an LRB fueled by RP-1 (kerosene) or some other hydrocarbon would contain both steam and carbon dioxide, along with small amounts of other gases. In contrast, the exhaust of atypical solid-propellant rocket contains large amounts of hydrochloric acid.[8]

Synergisms With Other Programs

The proposed ALS launcher could use the same engines developed for the LRB, or vice-versa. The LRB, if developed, could be used as a stand-alone launch vehicle.

Potential Drawbacks

Technical Uncertainties

The engine technology is known but the engines do not yet exist. Other uncertainties exist as to whether LRBs should be pump-fed or pressure-fed,[9] what fuel combinations (LOX/LOH, LOX/HC)[10] to use and for which stages or even whether to look at different cycle concepts.11 Earlier, NASA expressed a concern that the larger LRBs would place unacceptable loads on the Shuttle wings. Subsequent wind tunnel tests have shown that the wing loads are acceptable.

Long Development Times

NASA has estimated that if an LRB program started today, liquid boosters might not be available until at least 1997.[12] This long time period results from the stringent development and testing requirements inherent for a new engine, particularly one that must be "crew-rated." ASRMs themselves could not be on-line until 1994, and they represent less development risk than do the LRBs.

High Initial Cost

NASA estimates that LRBs would cost $3 billion. Pad modifications would cost about $0.5 billion. A new flight dynamics data base would also have to be generated. By comparison, the cost for the ASRMs is estimated at $1 billion DDT&E and $300 million for construction of facilities. At this point it is hard to know how accurate these estimates really are. Rocketdyne Corp. has suggested that it would be possible to build a much cheaper engine, based on its engine used on the Atlas 11 and Delta II expendable launchers.[13] If LRBs cost significantly more to develop than ASRMs, they could strain an already tight NASA budget.[14] However, developing LRBs in consort with ALS propulsion needs could actually be a cost-effective path and could help both the Shuttle and ALS programs.

Table A-1—Abort Mode Comparison of Shuttle/ Booster Configurations

Engine failure[a]		Abort mode		
Booster	SSME	SRB	ASRM	LRB
0	1	RTLS	RTLS	TAL
0	2	Split-S or ditch	Split-S or ditch	Loft-return
0	3	Split-S or ditch	Split-S or ditch	Loft-return
1	0	None	None	ATO
1		None	None	RTLS
1	2	None	None	Loft-return
	3	None	None	Loft-return
2	0	None	None	TAL
2		None	None	RTLS
2	2	None	None	Loft-return
2	3	None	None	Loft-return

[a]Assumes engines fail at liftoff.

KEY: ASRM=advanced solid rocket motor; ATO=abort to orbit; LRB=liquid rocket booster; RTLS=Return to launch she; Split-S=aircraft landing maneuver involving a reverse of direction and rapid baa of attitude; SRB=solid rocket booster; SSME=Space Shuttle main engine; TAL=transatlantic abort.

SOURCE: General Dynamics.

Unique Operational Requirements

The same pad could in theory accommodate both solids and liquids, but as a practical matter NASA would need to dedicate a unique pad to each during the transition from solids to liquids because fuel handling, launch tower needs, component logistics, etc. would differ from those on the current Shuttle system.[15] It may be too expensive to keep both forever just to increase resiliency-but this could be explored. For example, Pad B at KSC could

[9]Pump-fed appears to have the advantage since, for one thing, pressure-fed would take 5 years longer to develop than pump-fed,

[10]Liquid Oxygen/Liquid *Hydrogen* or Liquid Oxygen/Hydrocarbon

[11]Such as the Pratt and Whitney split-expander cycle.

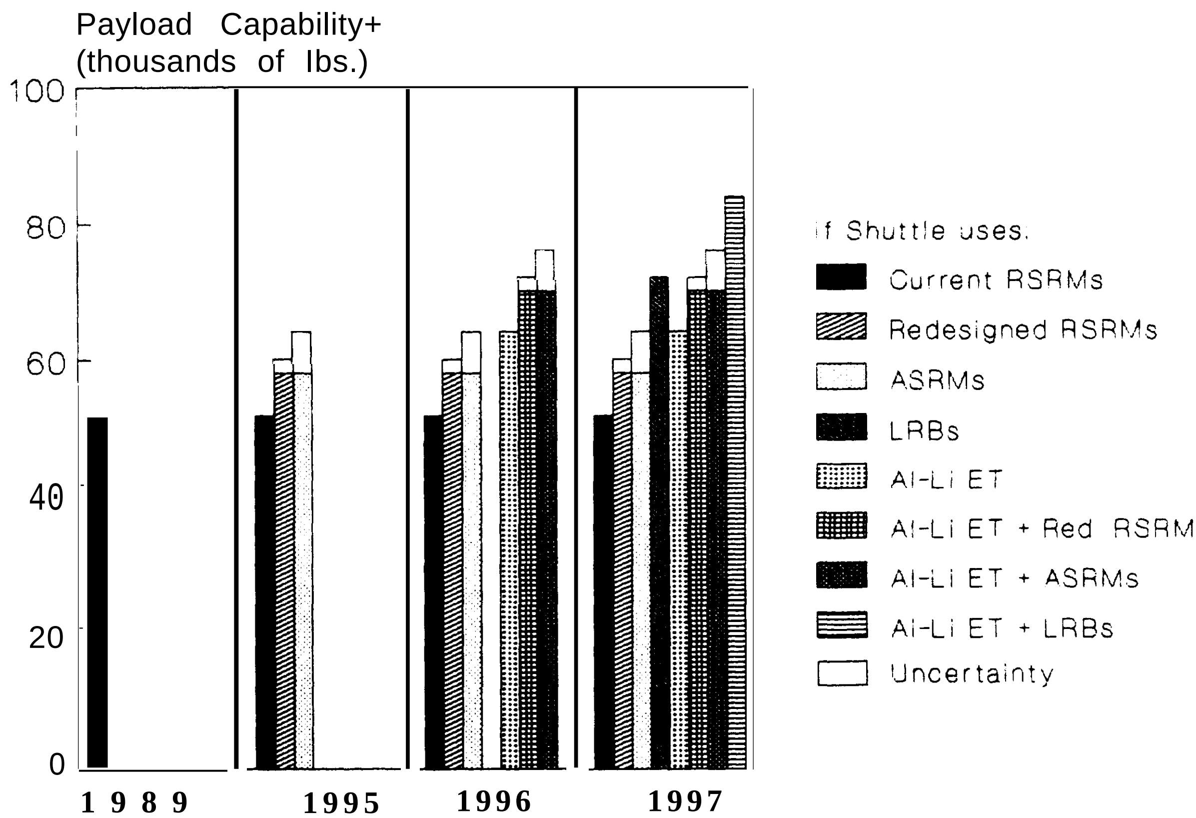
[12]If Phase B started in 1990 with several contractors competing, one winner could be chosen in 1991 for full-scale development. The LRBs would be ready for flight in 1997. However, in the Rocketdyne concept, the engines could be available earlier since much hardware already exists and is proven.

[13]Rocketdyne briefing to OTA, May 1989.

[14]This extra cost would seem small, however, if a solid rocket again destroyed a Shuttle. Loss of the *Challenger* cost the Nation between $7 billion and $13.5 billion, depending on how the accounting is done for the cost of failure, Yet, a new engine, like that needed for an LRB, would have ita own significant risks of failure.

[15]Lockheed recently completed a study of operational c@ which would be required at KSC in order to use LRB's *on* the Shuttle. "Liquid Rocket Booster integration Study," Final Report, Vets. 1-5, Lockheed Space Operations Company report to NASA-KSC Advanced Projects and Technology Office, LSO-000-286- 1410, NAS 10-11475, November 1988.

Figure A-2--Options for Increasing Shuttle Payload Capability v. Date of Availability



* To 110 n.mi. 28.5-degree orbit,

KEY: Al-Li ET = Aluminum-lithium external tank; ASRMs = Advanced Solid Rocket Motors; LRBs = Liquid Rocket Boosters; RSRM = Redesigned Solid Rocket Motor; RRSRMs = Redesigned RSRMs.

SOURCE: Office of Technology Assessment, 1989.

remain a solids facility while the presently unused Pad A could be converted to accommodate LRBs. One operational advantage is that processing in the vehicle assembly building (VAB) would be faster and less dangerous with liquid boosters.[16]

[16]However, Shuttle turnaround time is constrained by orbiter processing, hence fester VAB processing does not necessarily mean faster STS turnaround times.