Big Dumb Boosters: A Low-Cost Space Transportation Option?

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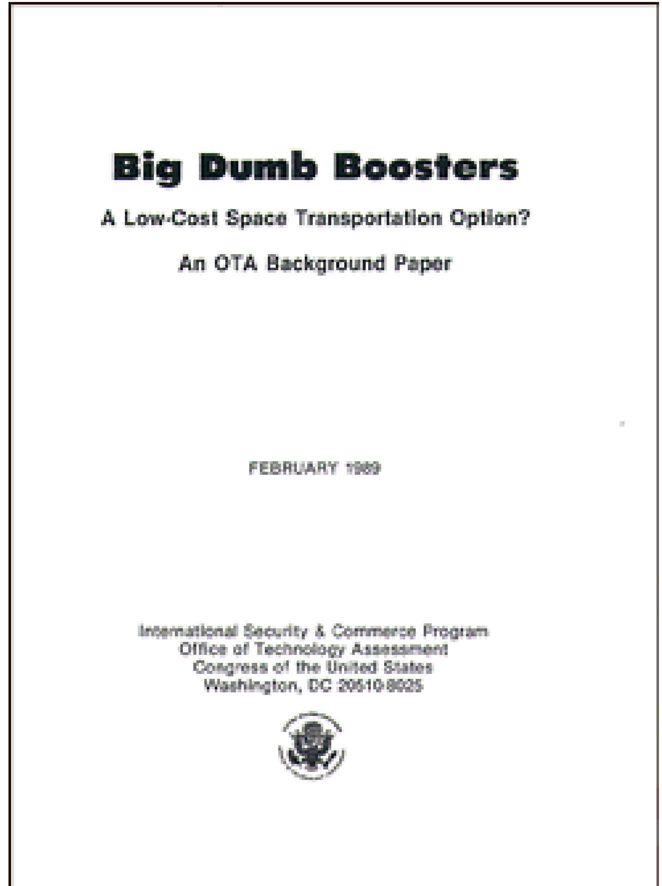

Big Dumb Boosters

A Low-Cost Space Transportation Option?

An OTA Background Paper

FEBRUARY 1989

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Office of Technology Assessment
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Washington, DC 20510-8025

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SUMMARY

This background paper describes and examines a launch vehicle concept commonly known as the "Big Dumb Booster,"[1] a concept that derives from efforts first made in the 1960s to minimize costs of space launch systems.[2] Some launch system analysts believe that the use of this concept, when applied to existing technology, could markedly reduce space transportation costs. Other analysts disagree.

Low-cost space transportation is one of the keys to more effective exploration and exploitation of outer space. If space transportation costs were much lower, government agencies and firms with good ideas for using the space environment might be more willing to risk their investment capital. In this era of increased budget stringency, the high cost of space transportation has prompted analysts to examine a wide variety of ideas to reduce these costs.

This paper derives from a "Big Dumb Booster" workshop OTA conducted in December 1987, which was held to examine the Big Dumb Booster concept. It summarizes the findings of the workshop composed of a panel of industry and government aerospace experts, augmented by staff research and reviewers' comments on earlier drafts. The paper is part of a broad assessment of space transportation technologies requested by the House Committee on Science, Space, and Technology, and the Senate Committee on Commerce, Science, and Transportation.

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1 The term Big Dumb Booster has been applied to a wide variety of concepts for low-cost launch vehicles, especially those that would use "low technology" approaches to engines and propellant tanks in the booster stage. As used in this paper, it refers to the criterion of designing launch systems for minimum cost by using simplified subsystems where appropriate.

2 For example, Arthur Schnitt and F. Kniss, "Proposed Minimum Cost Space Launch Vehicle System," Aerospace Corporation, TOR-0158(3415)-1, July 18, 1966.

Previous publications in this assessment examined a variety of future launch options,[3] and possible reductions in the costs of launch operations.[4] Future publications will treat crew-carrying launch systems and payload design.

Origins of Today's Launch Vehicles

Current U.S. expendable launch vehicles (ELVs) were designed to meet stringent performance specifications. As a result, launch system designers gave relatively little priority to reducing launch costs. U.S. ELVs are derived from 1960s intercontinental ballistic missile designs that used high-performance engines and lightweight structures in order to minimize launch vehicle weight and maximize payload and range. Military requirements for storability in submarines or silos and the ability to be launched quickly drove their designs. These considerations, for example, led to the development of the Atlas rocket, with lightweight fuel tanks that taper in thickness to nearly a hundredth of an inch thick. Not only are such tanks expensive to manufacture, but they must be kept under pressure, like a balloon, to keep them from collapsing under their own weight.

Budgetary limitations during development as well as unforeseen technological challenges prevented Shuttle designers from building a system that minimized recurring launch costs. As a result, the Shuttle is extremely expensive to maintain and launch.[5] As the United States looks toward possible future launch systems, reducing space transportation costs would be a critical positive step in increasing the use of space resources.

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3 U.S. Congress, Office of Technology Assessment, OTA-ISC-383, *Launch Options for the Future: A Buyer's Guide* (Washington, DC: U.S. Government Printing Office, July 1988).

4 U.S. Congress, Office of Technology Assessment, OTA-TM-ISC-28, *Reducing Launch Operations Costs: New Technologies and Practices* (Washington, DC: U.S. Government Printing Office, September 1988).

5 U.S. Congress, Office of Technology Assessment, *Reducing Launch Operations Costs: New Technologies and Practices,* op.cit. The Shuttle program consumes approximately one-third of NASA's yearly budget. See U.S. Congress, Congressional Budget Office, *The NASA Program in the 1990s and Beyond* (Washington, DC: Congressional Budget Office, May 1988), p. 20.

A New Design Criterion

A 1966 Aerospace Corporation study first suggested that launch vehicles could be designed explicitly to minimize manufacturing and operational costs.[6] The new criterion, “Design for Minimum Cost” (DFMC), was based upon the understanding that in rocket design, minimum weight, maximum performance, and high reliability, taken together, are achieved only at high cost. Instead, these criteria must be examined with respect to one another and various technical design parameters traded off to produce a vehicle with the desired characteristics at minimum cost. Instead of pushing launch vehicle performance, the DFMC design criterion would accept lower performance in order to reduce the overall cost of the launch system.

Launch vehicles designed to achieve sharply reduced costs would be very different from today’s launch vehicles. For example, according to the study, the first stages of a rocket should be relatively unsophisticated. It suggested that heavier hardware produced at lower unit costs by relaxing manufacturing tolerances should replace expensive, state-of-the-art, lightweight hardware. The former director of that study has explained the intuitive appeal of the concept: “[At the time] . . . we were designing every stage as if it went into space. For the top stage, which is small and extremely valuable, minimum-weight design made sense. For the lower stages it was nonsense. Why spend millions on high-efficiency engines when you could substitute a less efficient engine and simply make it bigger?"[7]

This concept assumes that the vehicle weight and fuel added by using heavier materials and less efficient designs would be more than offset by cost savings that accrued from the use of simpler, less costly technologies. One workshop participant drew an analogy to trucks and high-performance sports cars: despite the truck’s heavy engine, fuel tank, and frame, it hauls cargo less expensively than a high-performance sports car. Although the fundamental technologies of both are the same, the greater manufacturing tolerances allowed on most trucks

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6 Arthur Schnitt and F. Kniss, “Proposed Minimum Cost Space Launch Vehicle System,” op. cit.

7 Arthur Schnitt, quoted by Gregg Easterbrook, “Big Dumb Rockets,” *Newsweek*, Aug. 17, 1987, p. 48.

make them much less expensive per pound than sports cars. Engineering analyses suggested, for example, that relatively simple pressure-fed engines would be suitable for such a booster, replacing more complicated and expensive pump-fed engines.

Further Studies and Hardware Developments

In the late 1960s, several aerospace companies performed system studies on minimum-cost launch vehicles, and the Government conducted some demonstration projects on Big Dumb Booster engines. The Air Force supported 120 ground tests of pressure-fed engines with up to 250,000 pounds of thrust. These studies and hardware developments prompted the Air Force in 1968 to start an R&D program for a minimum cost launch vehicle. However, the program was cancelled before a thorough analysis of the overall life-cycle costs[8] of such a booster could be performed. Most Big Dumb Booster research was officially abandoned in 1972 when President Nixon decided to develop the partially reusable Space Shuttle.

Continued Controversy

The Big Dumb Booster concept remains controversial. Supporters of the concept argue that it still has considerable merit and that it is not too late for the United States to adopt this rocket design philosophy. Opponents maintain that time and improved technology have passed it by. They further argue that technology choices that reduce cost in one area, such as engines and tanks, may drive up costs elsewhere. For example, larger, heavier tanks require larger launch pads and facilities. Supporters counter that in minimizing costs over a whole system, cost increases in one area, such as launch facilities, would be more than offset by decreases gained in operational simplicity, and that the concept merits further investigation. Further, some point out that boosters using pressure-fed engines would not necessarily be much larger than pump-fed vehicles if existing composite tank technology and advanced pressurization systems, or stage-mounted low pressure, commercial-type turbo pumps were used.

8 Life-cycle costs include not only the costs of manufacturing the launch vehicle, but also the costs of ground operations and launch facilities, developing and testing. It also includes the discounting of all these costs to reflect opportunity costs and inflation.

Big Dumb Booster design's primary uncertainty is whether pressure-fed engines, which are relatively inexpensive to manufacture, can be made extremely large. The largest pressure-fed engine ever tested produced 250,000 pounds of thrust. A Big Dumb Booster might need an engine with at least six times that thrust, or six 250,000 pound thrust engines. OTA workshop participants generally agreed that the task presented no obvious obstacles, but still remained to be accomplished.[9] By contrast, pump-fed engines and cryogenic fuels are now mature technologies with a considerable experience base, though they are expensive.

Some tout the large Soviet boosters, *Proton* and *Energia*, as examples of Big Dumb Booster designs because of their apparent simplicity and use of heavy steel structures. Furthermore, Soviet rocket assembly lines bear a closer resemblance to automobile factories than do their U.S. counterparts, which look more like operating rooms. On the other hand, large Soviet boosters do not use simple pressure-fed engines; they do use multiple combustion chambers (typically four), which are fed from a single turbopump. In addition, their new *Energia* heavy-lift launch system has many advanced features reminiscent of U.S. launch systems.[10] In any event, cost comparisons with U.S. boosters are extremely difficult to make because we have no objective measures of the true cost of Soviet launch vehicles.[11]

Payloads

Big Dumb Booster proponents claim that a high-capacity launcher that drastically reduced the cost of launching a pound of payload would generate a large synergistic cost saving by making cheaper spacecraft possible. However, one workshop participant with experience in developing communications satellites suggested that even if weight were not a constraint on payloads, satellite builders would probably use any added weight margins to continue to add

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9 Nevertheless, the technology would still have to be thoroughly tested, as combustion stability and any unexpected problems would need to be addressed.

10 These include large, high chamber pressure, reusable, pump-fed, hydrocarbon-fuel booster engines; and fault-tolerant, advanced avionics.

11 One reviewer averred that using Soviet designs built and operated in the United States would be expensive and that, in any event, Soviet designs are not as simple as some of the low-cost Big Dumb Booster concepts.

capacity, redundancy, and lifetime at high cost, rather than attempting to apply Big Dumb Booster principles to satellite design. As some critics of current payload design practices point out, avoiding the temptation to add performance margins to payloads instead would require considerable management discipline.

Big Dumb Booster approaches are certain to meet pointed questioning from satellite owners and payload managers. Payload designers expect launch vehicles to provide services for the payload, including power, air conditioning, and fueling, along with custom-made interconnections. In order to meet goals of substantially reducing launch costs, Big Dumb Booster designers would wish to eliminate some of these services and custom-fittings, but payload managers are highly skeptical about designs that seek to reduce launch costs by placing greater requirements on the payload. Spacecraft owners must be convinced that if Big Dumb Boosters shift launch vehicle costs to the payload, they will be compensated by a greater reduction in launch costs, and acceptable reliability.

Conclusions

The Big Dumb Booster appears to be an attractive option in part because it seems intuitively obvious-- make the first stage of a launcher simple to build and operate, large, and cheap, retaining any necessary complexity in the lighter upper stages. However, the technical community, which was divided over the soundness of the concept when it was first proposed in the 1960s, is still divided today. Nevertheless, attempting to determine who was "right" and who was "wrong" in a debate that occurred twenty years ago is beyond the scope of this paper. Nor would such an exercise contribute to an evacuation of the Big Dumb Booster concept in today's space program. Specific designs that might have been the minimum-cost solution two decades ago are certainly not today's minimum-cost design. Technology has advanced since the early Big Dumb Booster studies, significantly altering potential trade-offs among costs and technologies.

The critical issue is not whether the launch vehicle design is "dumb" or "smart," but whether the use of the minimum-cost criterion is capable of reducing launch vehicle costs--i. e., a 'Big Cheap Booster." Objective evaluation of the Big Dumb Booster concept would require systematic analysis, with attention to engineering details and costs. It would also involve some hardware development and testing. If a Big Dumb Booster study is done, it should be carried out as a systems study that integrates specific hardware choices with the entire system, including the launch facilities, and logistics and support required to place payloads in orbit. It should also include estimates of the demand expected for such a booster, as future demand would have a marked effect on program life cycle costs. Such a study might also include consideration of recovery and reuse. For example, the Naval Research Laboratory is now exploring a reusable sea-launched booster that would use a pressurized liquid propellant. A Big Dumb Booster concept study might cost between $5 and $10 million, depending on its scope.

ALTERNATIVE APPROACHES

If Congress decides that the Big Dumb Booster requires more focused evaluation, it could task NASA or the Air Force to carry out such studies. For example, the joint Air Force/NASA Advanced Launch System (ALS) study and NASA's Liquid Rocket Booster (LRB) study are already examining issues and technology closely related to the Big Dumb Booster Concept.

Congress could:

1) Task NASA to investigate the Big Dumb Booster concept as an extension of its Liquid Rocket Booster (LRB) Study. NASA's Marshall Space Flight Center is studying the use of liquid fuel boosters to replace the solid rocket boosters on the Shuttle, and is investigating pressure-fed engines. Although the NASA studies show that pump-fed boosters are the clear choice for the Shuttle LRBs, they do not rule out using pressure-fed propulsion systems as the the basis for a new, low-cost expendable "Big Dumb" booster. Adding such tasks to the LRB studies, to which NASA has already committed about $14 million, would require some redirection of the program and additional funding of $2 to $5 million for a detailed concept study, based on the Shuttle LRB. Validating some of the hardware necessary for a launch vehicle, based on a criterion of minimum-cost, could cost much more.

2) Task the Air Force and NASA to investigate the Big Dumb Booster concept as part of the Advanced Launch System (ALS) program. This program is studying systems that contain features of Big Dumb Booster design, such as reduced complexity and design for minimum cost. ALS program managers are examining the entire launch system in order

to achieve cost reductions of a factor of ten in recurring launch costs. If this goal remains the priority, ALS would be the first U.S. launch vehicle designed for minimum cost.[12] Although it is not specifically investigating such concepts as Pressure-fed boosters, the ALS program does provide the systems approach that would be needed to carry out an adequate Big Dumb Booster study. In fact, some ALS contractors' proposals contain features of earlier Big Dumb Booster designs.[13] However, as noted for the previous option, such a course of action would require additional funding for the ALS program.

(3) Fund the Air Force and NASA to investigate technologies related to the Big Dumb Booster concept in other programs. For example, the NASA Civil Space Technology Initiative Booster Technology program is investigating combustion issues related to performance, stability, heat transfer, cooling, and combustor fabrication techniques. This program hopes to resolve some of the problems related to low pressure combustion in very large combustors, as well as tank pressurization concepts for minimizing weight.[14] It might not prove cost-effective for boosters designed to carry large cargos, but might be appropriate for smaller boosters. Various programs within the Air Force and NASA are investigating technologies related to Big Dumb Booster.

12 One reviewer noted that the Congressional restriction requiring the ALS program to pursue a cost goal of $300 per pound in *recurring costs*, may unnecessarily limit the ALS program. Designing for minimum *life cycle cost could* lead to a less costly launch system.

13 For example, as part of the Phase I ALS studies, McDonnell Douglas investigated a modern version of a Big Dumb Booster, in which the boosters strapped on to the core stage used a pressure-fed engine and liquid hydrogen/liquid oxygen as fuel. The design used low-pressure ratio boost pumps to offset the high pressures normally associated with pressure-fed designs, which also reduced the weight penalty incurred with pressurized tanks.

14 Program managers hope to assemble a pressure-fed liquid booster test bed that would integrate the combustor and gas generator hardware from the technology program with oxidizer and fuel tankage and feed systems, in order to assess and model feed system and combustion system dynamic interactions. This technology base would be applicable to Big Dumb Booster applications, as well as Shuttle LRBs. NASA OAST Program Office, November 1987.

(4) Conduct an independent competition between proponents of the Big Dumb Booster and proponents of alternative launch system designs. The Government could fund two contractors, one a proponent of the Big Dumb Booster, the other a proponent of a more traditional approach, to design an optimized launch system according to the same mission rules (i.e., payload capability, flight rate, and destination). An independent organization, such as the National Academy of Engineering could serve as a study monitor. Although this approach does not guarantee resolution of the debate, it would give proponents of the Big Dumb Booster concept an opportunity to be judged on an equal footing with the traditional design approach.

(5) Remove barriers to adoption of low-cost launch strategies by commercial launch firms. The development of reduced-cost commercially-developed launch systems incorporating elements of the Big Dumb Booster strategy could be achieved by adopting purchase criteria based entirely on performance, i.e., delivery of a specified payload to a specified orbit. Using this strategy would encourage the private sector to arrive at competitive designs and prices to meet government performance specifications. The Reagan Administration Space Policy of February 1988 moved a step in this direction by mandating purchase of launch services for civilian payloads and encouraging such purchases for national security payloads.[15]

Several entrepreneurial launch vehicle firms[16] are developing new launch systems for small or medium-size payloads. These projects present opportunities to incorporate low-cost approaches at little cost to the Government. However, launch firms still complain that the cost of continued excessive government oversight unnecessarily raises the costs of launch services. They argue that government oversight far exceeds the actual risk of a failed mission. The government role, vital during the development and demonstration phases of a new, high technology, becomes counterproductive when the basic technology

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15 The White House, Office of the Press Secretary, “The President’s Space Policy and Commercial Space Initiative to Begin the Next Century,” *Fact Sheet,* Feb. 11, 1988, p. 3.

16 For example, American Rocket Company, Orbital Sciences Corporation, and Space Services, Inc.

has been successfully acquired, and is needed for ongoing operations. Then, matters of cost and reliability become paramount. However, Government users may fear that boosters not built to government specifications might be too unreliable. Dozens of successful launches would be required to prove high reliability with high statistical confidence. For example, if launch vehicle reliability were actually 95 percent, about 60 launch attempts would be needed to provide 90 percent statistical confidence in a vehicle reliability of at least 90 percent.

(6) Provide no extra funding to investigate Big Dumb Booster. Congress could simply trust that those in charge of making the technical decisions within the Air Force and NASA are carrying out their analytical duties adequately. Proponents of such an option point out that both Air Force and NASA already face extremely strong pressures to reduce launch costs, and argue that directing these organizations to focus specific attention on the Big Dumb Booster would be wasteful micromanagement. The Big Dumb Booster is only one of several means to achieve low-cost access to space. Emphasizing this approach at the expense of others might waste valuable resources.

BIG DUMB BOOSTER TECHNOLOGIES

This section examines representative technologies that have been proposed for use in a Big Dumb Booster. Although these technologies may contribute to low-cost design, minimizing the costs of a launch system requires comparing different approaches in detail, and making choices among such technologies depending on their effects on overall launcher design.

Engines

Rocket engines and tanks provide obvious targets for cost-cutting by relaxing weight constraints. The Aerospace Corporation's analysis[17] suggested that relatively simple pressure-fed engines would be suitable for a Big Dumb Booster's first stage, instead of more complex pump-fed engines like the Space Shuttle main engines (SSMEs) and the engines on all current ELVs. A turbopump increases the pressure of the propellants fed into the rocket engine, and thus permits much lower tank pressures than required by pressure-fed engines; besides the savings in tank weights, higher chamber pressures result in slightly higher propulsion efficiencies. However, a turbopump is complex, made of hundreds of rapidly moving parts under considerable stress. The pump typically accounts for about 20 percent of the cost of a pump-fed engine.

A major uncertainty is whether pressure-fed engines can be made large enough[18] to power a first stage. The largest pressure-fed engine ever tested produced 250,000 pounds of thrust. A Big Dumb Booster might need an engine with at least six times that thrust, or six engines of 250,000 pounds thrust.[19] A workshop participant noted that only the manufacture and demonstration of full-scale hardware can eliminate this and other uncertainties related to

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17 Arthur Schnitt, "Design for Minimum Cost--A Review," Aerospace Corporation, F04695-67-C-0158.

18 Pressure-fed booster engines tend to be larger than traditional pump-fed engines for the same thrust level because the former typically operate at lower pressures. Higher engine pressures result in higher overall engine performance.

19 Using multiple engines could have other advantages: increased production volume, and better operating reliability (i.e., possible "engine-out" capability).

very large pressure-fed engines. “In my mind the largest of these uncertainties are the complexities of the pressurization system and the unknowns associated with combustion performance and stability,” he added. Another participant noted that the perceived technical risk of scaling up pressure-fed liquid engines was a major reason that NASA chose solid boosters for the Shuttle.[20]

Tests performed on pressurization systems in 1969 did raise questions about the feasibility of scaling up pressurized tanks. A 2000 cubic foot tank was pressurized with rocket fuel and the fuel allowed to flow out. A workshop participant whose company conducted the test said, “a large [negative] shift in performance from previous small tank tests noted.”

The workshop participants generally agreed that scaling up large pressure-fed engines presented no obvious insurmountable obstacles, but still remained unproven. By contrast, pump-fed engines and cryogenic fuels are now mature technologies with a considerable experience base.. However, several ALS design studies are investigating the possibility of using clusters of smaller engines to achieve the necessary booster thrust. A pressure-fed booster might also be able to use such a strategy, rather than scaling-up the engine. Engine clusters are particularly attractive for adding an extra margin of safety. If one fails non-catastrophically, the remaining engines can be throttled up to compensate. Although engine-out capability is currently being studied as a goal for clusters of pump-fed liquid engines, the principle can be applied in part to pressure-fed systems by including multiple (clustered) pressurization sources in addition to the clustered combustors.[21]

Engine cooling is another area where weight might be added in exchange for lower costs. Current engines are cooled by complex, mechanical systems that allow engines to operate at higher pressures, making them more efficient. Lower-performance engines might use heavier, but simpler, ablative protection, similar to the heat shield on the Apollo capsule. Ablative coatings would protect the engine nozzle by gradually burning away as the engine heats up during firing.

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20 The cost of risk played an important role. Designers had the experience of the large solid rocket motors on the Titan 111 on which to build.

21 All ALS contractors have ranked the capability for engine-out high on their list for enhancing launcher reliability.

Two engines in the 10,000 pound thrust class, the Lunar Excursion Module Descent Engine and the Transtage engine on the Titan III, used ablative materials for their thrust chambers and both were pressure-fed. The Transtage engine is still used to power the third stage of the Delta II and Titan III.

Propellant Tanks

Early Big Dumb Booster studies also proposed that low-cost fuel tanks could be made of welded steel instead of titanium or beryllium/aluminum. These studies reasoned that welded steel tanks might reduce fabrication costs by eliminating the precision manufacturing needed to produce the thin, lightweight, expensive structures now used.

Although welding tanks and structures made of steel is less capital- and labor-intensive than manufacturing techniques now used for these components, inspection costs would remain high because every weld would have to be inspected for quality control.[22] Furthermore, the United States no longer manufactures the HY140 and HY150 steels proposed for use in Big Dumb Boosters, introducing an additional uncertainty in using these materials.

More important, technologies that have appeared since the early Big Dumb Booster studies could significantly change the analysis of this launch concept. For example, one workshop participant presented a rough analysis of the cost of various tank materials and suggested that graphite-epoxy could be used for about the same cost as HY140 steel.[23] Yet, graphite-epoxy is considerably lighter: a graphite-epoxy tank for one Big Dumb Booster design would weigh 38,000 pounds compared to 213,000 pounds for HY140. That would free up 175,000 pounds for other purposes, such as adding extra fuel or additional payload.

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22 One way to avoid costly inspections is to control the output of the manufacturing processes more effectively. The Air Force Reliability and Maintainability 2000 program has developed the variability reduction process to do that.

23 Graphite-epoxy technology has grown rapidly in the last decade (U.S. Congress, Office of Technology Assessment, *Advanced Materials By Design, OTA-E-351* (Washington, DC: U.S. Government Printing Office) p. 142.). It has been developed experimentally for application to Shuttle solid rocket booster casings. Yet, because the material has not been certified for use with cryogenic liquids, its use for cryogenic fuel tanks must remain speculative until more research is done.

This may indicate that the best approach to launch systems would be to design for minimum cost using proven, off-the-shelf "appropriate technology." Such an approach would use the Big Dumb Booster maxim of designing to minimum cost, but not necessarily rely on "boiler-plate" technology components often associated with it.

Propellants

Some conventional rockets use liquid hydrogen, a high-performance cryogenic fuel that requires insulated fuel tanks to maintain it at temperatures of 423 degrees below zero, Fahrenheit. Big Dumb Booster designs often call for use of lower-performance Nitrogen Tetroxide (N_2O_4) and Unsymmetrical Dimethyl Hydrazine (UDMH) as propellants because these fuels can be stored at room temperature in simple, welded-steel tanks. These high density fuels also require smaller tanks than liquid hydrogen, for example. The Titan family of vehicles uses these fuels, which ignite spontaneously when mixed.

However, these fuels can pose safety and environmental hazards, and they are relatively expensive. N_2O_4 is corrosive and UDMH is carcinogenic. Both propellants and others like them require special handling. Their transport by rail and truck is strictly regulated. Safety rules at Vandenberg Air Force Base limit the amount of such fuels that can be handled at one time so that a gas cloud from an accidental spill will not endanger neighboring communities. Titan launch operations at Vandenberg already approach the limit allowed by the rule. A much larger rocket would need an expanded safety zone, possibly requiring the development of offshore launching facilities.[24] Such marine launch pads could present their own fuel handling problems.

Pressure-fed engines can also be designed to burn other fuels, such as methane, propane, or kerosene, which do not require extraordinary handling and pose less environmental hazard. It may also be possible to use liquid hydrogen and liquid oxygen, although no engine tests have yet been made using these propellants.

24 Offshore facilities may be developed for other reasons as well. See the discussion in *Reducing Launch Operations Costs: New Technologies and Practices, op.* cit., p.64.

Avionics

One area where today's technology is clearly superior to 1960s technology is avionics. Advances in electronics can greatly reduce the weight and cost of avionics equipment while also improving its performance. General Dynamics recently upgraded the 1960s vintage electronic components of the Atlas-Centaur rocket with new integrated circuits. As a result, the cost of the on-board computer fell fivefold; the weight of the inertial guidance system went from 150 pounds to 50 pounds; and performance improved by a factor of ten.

Launcher Reliability

Workshop participants disagreed on the reliability of low-cost designs. Proponents of simplified designs argue that reducing the number of moving parts and using heavier materials with conservative design margins decreases the possibility of malfunctions. They note that a pump-fed engine may have 15,000 parts compared with fewer than 100 in a pressure-fed engine. Simple designs, that decrease possibilities for human error and reduce special handling, would not only increase reliability, but also simplify trouble-shooting. "When a pump-fed engine fails you have a research project on your hands," said one workshop participant. In the words of the Shakers, "Tis a gift to be simple."

Another workshop participant pointed to the Shuttle's complexity and the Challenger accident: "you can't be in a position where when you have a failure you have to reconstitute the design team to figure out what went wrong."[25] Others disputed the view that simplicity equals reliability y. They argued that commercial jet aircraft are made reliable by their very sophistication. Still others drew attention to the high reliability of the pump-fed engine used on the **Atlas** Centaur, the RL-10, which has suffered no failures in over 150 flights and hundreds of ground tests since its first test flight in 1962.

The workshop participants generally agreed that while simplicity is a virtue in any design, it does not guarantee high reliability. Another path to reliability is through robust, redundant, autonomous subsystems with wide performance margins, capable of performing in

25 Yet, in fact, the Challenger's problem was with one of the simplest systems on the Shuttle, the O-rings on the solid rocket boosters, not with the complex pump-fed engines as experts first speculated.

excess of normal demands. If a more complex design is better able to tolerate human errors and anomalous operating conditions, then the net reliability can be higher and lead to lower life cycle costs than in a simpler design.

BIG DUMB BOOSTER STUDIES

Although several corporations and the Government have conducted analytical studies and tests of the Big Dumb Booster concept, the results of one study often contradict the findings of another. This section briefly summarizes the results of these analyses.

Favorable Studies

The first stage engine of the original Aerospace Corporation Big Dumb Booster was to have 1.5 million pounds of thrust, the same as the Saturn V. Because of the Big Dumb Booster's greater weight, its payload capacity was only 43,000 pounds, compared to the Saturn V's 250,000 pounds. Yet the study concluded that this rocket would cost 25 times less than the Saturn V, yielding a cost per pound to low earth orbit five times lower than the Saturn V.

In the late 1960s, several aerospace companies performed system studies on minimum-cost launch vehicles. One study done for NASA proposed a family of three rockets. The largest would have employed two 3 million pound thrust engines in the first stage, giving it a payload capacity of 120,000 pounds, half that of the Saturn V.[26] This booster would have been the same height as the Saturn V and weighed twice as much, but would have been able to place a pound in orbit for one-quarter the cost of the Saturn V.[27]

McDonnell Douglas proposed building a 22-foot diameter solid booster coupled with a Saturn IVB second stage to deliver 100,000 pounds to low-earth orbit for a cost of $270 per pound (in 1967 dollars), less than half the cost of a Saturn V.[28]

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26 National Aeronautics and Space Administration, Transportation Systems Division, "Low Cost Launch Vehicle Study," contractor report NASW-1792, June 23, 1969, p. 1.8; see also G.W. Elverum, Jr., "Scale Up to Keep Mission Costs Down," 24th International Astronautical Congress, October 1973.

27 However, in order to launch the Saturn V payload, such an approach would require a total thrust of 8.7 million pounds.

28 National Aeronautics and Space Administration, Marshall Space Flight Center, "Use of Large Solid Motors in Booster Applications," contractor report NAS-8-21051, Aug. 30, 1967.

The Government conducted some demonstration projects on Big Dumb Booster engines. In the late 1960s the Air Force supported 120 ground tests of pressure-fed engines scaled up to 250,000 pounds of thrust. Also in the 1960s, NASA Lewis Research Center managed the 260-inch diameter solid rocket program, which utilized a motor designed by Aerojet. Three successful firings were completed for thrust levels from 3.0 to 7.5 million pounds.

These hardware developments and systems studies prompted the Air Force to start an R&D program for a minimum-cost launch vehicle in 1968. However, the program was cancelled before a thorough analysis of the overall life-cycle costs of such a booster could be established. Most of the Big Dumb Booster research was officially abandoned in 1972 when President Nixon chose to pursue the piloted, reusable Space Shuttle instead of continuing development of ELVs. Reusability of the expensive Shuttle orbiter appeared to provide substantial cost reductions over expendable systems.

A 1982 study for NASA reintroduced the concept as a proposed “Low Cost Shuttle Surrogate Booster” that could be used to carry cargo in place of the Shuttle.[29] This study reached many of the same conclusions as earlier studies. It envisioned a booster having roughly the same height and take-off weight as the Saturn V, but carrying a Shuttle-sized payload of 65,000 pounds, or one-fourth that of the Saturn V. The additional weight of this design resulted primarily from its heavier half-inch thick steel tanks.

Unfavorable Studies

Although favorable studies have reported up to five-fold cost reductions with Big Dumb Boosters, other studies have concluded that these designs would not reduce costs at all. One workshop participant, whose company examined the idea in the late 1960s, said, “We were one of the earliest supporters of the ‘low-cost’ approach, but the more we studied it the more it cost."

29 “Study of a Cost-Optimized Pressure-Fed Liquid Rocket Launch Vehicle,” D.E. Fritz and R.L. Sackheim, paper No. AIAA-82-1108, AIAA 18th Joint Propulsion Conference, June 1982.

A 1969 McDonnell Douglas study for NASA compared 32 low-cost launch vehicle designs.[30] configurations with pressure-fed engines were judged to be more costly than conventional boosters with pump-fed engines.

In 1985 Martin Marietta and General Dynamics were asked by the Air Force to analyze Big Dumb Boosters because of the "intuitive attractiveness" of the design.[31] The studies concluded that total launch system costs per flight would be 40 to 50 percent more for a pressure-fed Big Dumb Booster than for a comparable pump-fed booster. They found that cost savings achieved by simpler engines were offset by the greatly increased weight of the vehicle.[32]

Critique

None of these studies is definitive, as each was pursued only at the conceptual design level. Big Dumb Booster proponents argue that the unfavorable studies fall into the trap of analyzing the concept according to models that assume costs are proportional to weight.[33] This unfairly penalizes Big Dumb Booster approaches, and "woefully underestimates the development, fabrication, and testing costs resulting from the complexity of today's minimum weight launch

30 "Integral Launch and Reentry Vehicle Study--Parametric Vehicle Comparison," NASA contract 9-9204, March 1969.

31 Dr. Richard Weiss, Chief Scientist, Air Force Astronautics Laboratory, personal communication, Dec. 1, 1987.

32 However, one reviewer noted that, "The flaw in these studies was to overemphasize the cost of propellant and materials and underestimate the increase in personnel resulting from using more complex hardware with complicated interfaces."

33 One reviewer noted that any good cost estimation considers truly analogous data and appropriate adjustments for complexity, rather than merely comparing weights. At the current state of the art, it is easier to compare the materials and manufacturing costs of proposed vehicles than it is to compare operations costs.

vehicle design." Indeed, it may be futile to draw inferences about "what can be" based on "what has been." As one workshop member noted, historical data may be innocently biased by company experience. In some cases, the data are two decades old.[34]

Part of the disagreement on Big Dumb Booster costs may be the result of different accounting assumptions. Big Dumb Booster opponents maintain that technology choices that reduce cost in one area, such as engines and tanks, may drive up costs elsewhere, for example by requiring larger launch pads and facilities. A number of panel members criticized the early, optimistic studies for not adequately considering ground operations costs.

Reducing operations costs is critical to reduced life-cycle costs.[35] Operations costs may account for more than half of the total life cycle costs of a launch system.[36] Big Dumb Booster supporters on the workshop agreed that a credible study of the Big Dumb Booster would have to include detailed estimates of operations costs.

Variations in study assumptions or ground rules will profoundly affect the outcome of cost comparisons. For example, flight rates assumed in one study are often very different from the flight rates assumed in other studies. Most studies assume major increases in demand. Because assumed future launch rate is a major driver of estimated life-cycle cost, a study that based its cost projections on an expectation of many future launches would be biased because that system would have a high number of flights over which to amortize its development costs.

Another significant factor that can perturb straightforward cost-reduction concepts, such as the Big Dumb Booster, is the application of principles of recovery and reuse. Proponents of reusable systems point out that the use of costly, high-performance components is justified if they can be reused often enough. However, the potential cost savings of reusable or

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34 See *Reducing Launch Operations Costs: New Technologies and Practices,* op. cit., Appendix A for a discussion of the uncertainties and subjectivity in current space transportation cost-estimating models.

35 *Reducing Launch Operations Costs: New Technologies and Practices,* op. cit.

36 For the Shuttle, one analysis estimated that costs for launch and mission operations will account for 86 percent of the total life cycle costs. National Aeronautics and Space Administration, "Shuttle Ground Operations Efficiencies/Technologies Study," Kennedy Space Center, NAS10-11344, May 4, 1987.

partially reusable systems are not well understood, nor sufficiently demonstrated. The Naval Research Laboratory (NRL) has just started a small program to develop a pressure-fed, recoverable, launch vehicle that could be launched from the ocean.[37] This sea-launch concept could apply to a wide variety of launcher sizes. If recovery and reuse prove successful, the concept could provide a basis for providing reduced-cost launches. Although NRL's initial analysis appears promising for small launchers, several years of development and testing would be required to prove the concept, especially for large launchers.

The NASA LRB study has analyzed the costs for system design, development, testing and evaluation (DDT&E), unit manufacture, and operations for both pressure-fed and pump-fed Shuttle LRBs. The study indicates essentially equal DDT&E costs for both, but lower unit costs for the pump-fed concept.[38] The pump-fed concept therefore appears the technology ‘f choice for Shuttle liquid rocket boosters. Assumed flight rates varied between nine and 14 per year.

37 Naval Research Laboratory briefing to OTA, Dec. 27, 1988.

38 NASA briefing to OTA, September 1988.

INSTITUTIONAL OBSTACLES

Bias Against Low Technology

One of the Big Dumb Booster's toughest obstacles may have been an inherent bias against industrial-grade technology within the aerospace community. According to Everett Welmers, a former Aerospace Corporation executive:

> As an organization, Aerospace Corporation was often more interested in the technical grandeur of a program than in doing it in a cost-effective way. The people there came from defense contractors and knew they would go back. There was no status attached to working on something simple. Big Dumb Booster was more like an industrial boiler than a spaceship, and the people at Aerospace definitely did not want to reassociated with boilers.[39]

These sentiments were echoed by Gerard Elverum, a TRW vice president who worked on a Big Dumb Booster project. "It's really frustrating to be told, 'Yes, this is a great idea, but it doesn't advance the technology.' Reactions to the idea of low-cost rockets are usually inked to who has a vested interest in expensive boosters."[40]

Resistance from Satellite Owners

Big Dumb Booster proponents claim that a Big Dumb Booster that drastically reduced launch costs and freed up weight for payloads would generate a large synergistic cost saving through reduced payload costs. However, current spacecraft designs may cost $5,000 to $250,000 per pound, depending on their complexity,[41] which dilutes the significance of any small savings in launch vehicle costs, because typical satellites cost three to ten times as much as their launch vehicles. One workshop participant said that "By working on the booster, we're working on the short end of the stick: 10 to 20 percent of the total mission cost. Where's the

39 Cited in "Big Dumb Rockets," op.cit.

40 Cited in "Big Dumb Rockets," op. cit.

41 These estimates include program costs, but not the additional costs required to operate the payloads once on orbit.

Big Dumb Satellite?" One workshop participant with experience in communications satellite development pointed out that even if weight were not a constraint on payloads, satellite builders would probably use added weight margins to add capacity, redundancy, and lifetime, rather than decreasing fabrication costs by applying Big Dumb Booster principles to satellite design. OTA's own analysis[42] suggests that if a new launch system were able to launch much larger payloads for much less per pound, spacecraft costs are likely to decrease only slightly on the average.

One thing is certain however: satellite owners and payload managers have little enthusiasm for the Big Dumb Booster. Payload designers expect launch vehicles to provide services for the payload, including power, air conditioning, and fueling, along with custom-made interconnections. They fear that Big Dumb Boosters would eliminate these services and custom fittings to cut costs. Payload managers are skeptical about designs that seek to reduce launch costs by placing greater requirements on the payload and replacing custom interfaces with standard interfaces. Satellite buyers must be convinced that Big Dumb Boosters will not merely shift launch vehicle costs to their payload.

Referring to the considerable experience we have with the current ELVs, one workshop participant noted, "It is sometimes difficult to dislodge an incumbent." The technology is proven, with a success rate of 94 percent in over 300 launches. New approaches are bound to meet resistance from satellite owners and payload managers. Nevertheless, dramatic change would be required for costs to come down significantly.

Lack of Incentives to Cut Costs

Many workshop participants argued that launch vehicle design is not the most significant factor in determining overall launch costs. Reformers must consider the entire system, from management through vehicle design, facilities and operations.

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42 U.S. Congress, Office of Technology Assessment, *Alternative Approaches to Spacecraft Design*, Staff Paper, in preparation.

The group argued that a major barrier to reducing cost was the government procurement system, which they believed is cumbersome and requires unnecessary paperwork and excessive quality control tests. One workshop participant said, “There are so many specifications that half of them conflict with each other. Unless we do something to change that, I don’t care whether it’s a pressure-fed booster or a pump-fed booster--you’re not going to get low costs."[43]

Workshop participants criticized the lack of cost-reducing incentives in government contracts and argued that industry has little incentive to pursue new designs on its own.” Furthermore, according to several workshop participants, government payload managers would be reluctant to launch their payloads on a vehicle over which they had little control.[45]

The detailed vehicle specifications, military specification requirements, and cost documentation requirements present formidable barriers to entry of new, non-aerospace firms, reducing competition in the launch industry. They also constitute an effective barrier to the adoption of low-cost strategies by existing firms, because existing specification requirements effectively negate the benefits of such approaches, and because the existing contract system removes the financial incentives for trying them.

Most participants agreed that costs could be lowered through reducing the thousands of pages of contract specifications, which cover items down to the finish on bolt heads. Yet some of the paperwork documenting each part allows investigators to identify causes of failure, and inspectors to reduce the variability of manufactured parts. Modern computer-based systems allow substantially cheaper ways to record, retain, and access part and subsystem information. However, the overall system of documentation could still be streamlined to great benefit.

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43 One reviewer pointed out that “the concept/design phase determines about 75 percent of the ultimate cost of a system. Simple systems have simple paperwork.”

44 *Reducing Launch Operations Costs: New Technologies and Practices,* op. cit.

45 One reviewer complained that such attitudes constitute most of the problem and asserted that because launch technology is relatively mature, the purchase of launch services, in which the seller agrees to place a payload in a specified orbit for a specified price, with agreed-upon penalties, ought to suffice for most applications.

The low rate at which launch vehicle components are produced also drives up costs and reduces government and private sector incentives to invest in cost-saving measures. One workshop participant noted that the Centaur's relatively simple RL-10 engines cost about $2.5 million each. Gas turbine helicopter engines contain approximately the same number of parts and are of the same complexity, but are made on assembly lines at a rate of several thousand a year. Those engines sell for $80,000. "When you're building in lots of tens, you're basically hand-building these engines and they're bound to be very expensive."