The Shuttle: A Balancing of Design and Politics

by Dale D. Myers

When Apollo was started, and even deep into the program, NASA had very little integrated planning. No one tried to balance efforts between aeronautics and space, or even manned versus unmanned activities. Jim Webb seemed to want to keep his options open until the last minute, and a long range plan would be a deterrent to that idea. Planning groups were set up, but no lasting results emerged. Even the planning of the science experiments for Apollo, worked almost entirely between Manned Space Flight and the Office of Space Science and Applications, was late getting into the system. When it came to real post-Apollo planning, even though there were pockets of studies and interest, no overall plan emerged until 1969. Detailed specifications from the Congress and their staffs were not a major problem. Congress would want to be kept informed about our planning (no surprises) but in general, their role was supportive.

In 1969, the Space Council, under Vice President Agnew, ran a post-Apollo study, with most of the inputs coming from NASA through Dr. Tom Paine, who, as Deputy Administrator, was a member of the task force. Dr. George Mueller, then Associate Administrator for Manned Space Flight, made some strong inputs to the study. NASA's budget had peaked in 1966, but extrapolations based on the strong support of the public led to a very ambitious outlook. As usual, NASA saw the budget reduction as a temporary thing, failing to understand the growing Vietnam budget, and leaders of the Congress and the administration increasingly fearing a failure in space.

The results of the post-Apollo study were:

- First, we must reduce the cost per pound to orbit by a factor of ten. This would be done with a reusable launch vehicle.
- A reusable Space Tug was needed to reduce the costs from low Earth orbit to geostationary orbit.
- We must have a large, Saturn V-launched space station.
- With the Space Station as a base, we must place a permanent colony on the moon.
- Then, we must explore Mars with people.

The 1969 task force study also had some ambitious projections for the near future of American spaceflight: NASA planned to complete the Apollo program by 1972 with the Apollo 18 mission, and Skylab A was to be completed by 1974.

As Associate Administrator for Manned Space Flight, I had some projections of my own in 1970. Skylab B was also planned for early 1976, the first flight of the Space Shuttle in 1976, a large Space Station by 1980, and the beginning of construction on a lunar base by 1985.

In the meantime, after 1967, the NASA budget started falling at about 14 percent per year. Manned Space Flight's budget was cut in half from 1966 to 1971. Part of that decline was because Congress and the administration were beginning to have misgivings about the continued risk of lunar flights. So were some in NASA. By 1970, it was obvious that the decline would continue, and drastic action had to be taken in planning NASA's future.

First, all studies and technologies associated with Mars were stopped. We canceled Skylab B. Then Apollo 18 was canceled (under pressure from Congress). Finally, the lunar base and the large Space Station were deferred, with the final launch of Saturn V then pegged to Skylab A.

As budget pressures continued, we held discussions with European nations to consider their roles in space exploration. We discussed their providing parts for the Space Shuttle, the whole Space Tug and finally settled on Spacelab as an appropriate item for European interests. Many painful diplomatic discussions were held in that series of negotiations. Space Tug was dropped.

The order of priority for the cutback was based on a conviction that if we could just reduce the cost of transportation to low Earth orbit dramatically, the future would fall back in place.

In 1970, we already had underway a Phase A study of the fully recoverable, two-stage Shuttle. Budget pressures from the administration were continuing, and although no numbers had been developed, it was evident that a program above $10 billion would not fly. Industry saw the problem, too, and began to come up with partially recoverable systems. In 1971, the administration began to talk about $5 billion for the development program, and it was clear that we now had to look very seriously at partially recoverable systems. Consequently, many new configurations were studied, leading to a number of possibilities, fully costed and ready for use in cost trade studies.

At about the same time, and after a long debate with the Office of Management and Budget, NASA agreed to demonstrate the cost effectiveness of a reusable shuttle system. This decision had an enormous impact on the design decisions for the program.

We hired Mathematicians, with Dr. Klaus P. Heiss as the project leader, to run a total cost versus total savings study for a 20-year period. The key cost data for this study was the development costs, the cost per flight, the number of flights per year, and Shuttle effects on the cost of payloads.

The Development Costs

A two-stage, fully recoverable launch vehicle was our starting point. We looked at Max Hunter's single stage to orbit model, but decided that the structure weight left us with no reserves. We recognized that with the Saturn V production line being closed down, the vehicle should have a large diameter payload bay to accommodate a future Space Station. We had an agreement with the administration that NASA would pay for development of the Shuttle, and that the Air Force could use it if they paid launch costs. When we made that offer to the Air Force, they agreed, but wanted a cross range capability to return to base during polar launches from Vandenburg AFB. We agreed, because it was becoming obvious that to meet the cost effectiveness criteria, we would need all the launches we could get. As noted above, European space interests had agreed to build Spacelab, thereby adding reusable payloads.

Cost Per Flight

Launch costs were badly underestimated. Almost all our emphasis was put into pushing down the development costs to get under the administration's bogey. Although President Nixon was a space buff, I am convinced that he and OMB were in lockstep in demanding a less costly Shuttle. Unfortunately, we relied too heavily on airline-supplied data on what this airplane-like device could cost per flight if we followed airline maintenance and on-line checkout rules. NASA's lack of an operations voice at or near the top of the agency caused us to naively believe (or hopefully believe?) that these very low costs per flight could be met. In retrospect, I have become convinced that *some* of the projected launch costs reductions could have been obtained, had the entire design team concentrated on operations as strongly as they concentrated on development.

Number of Flights Per Year

I believe our final cost effectiveness study was based on 50 or 60 flights per year. After all, we were going to have drastic reductions in cost per flight, particularly at high flight rates. With the airline industry's advice that we could check the Shuttle out like a commercial transport, our projections of manpower at the Cape were much smaller than for the Saturn program. We had a large projection of Air Force payloads, the promise of European payloads in addition to Space

Spacelab, and a plan to build relatively cheap scientific payloads that could be modified between flights and flown over and over. Finally, we expected to carry a large number of commercial payloads, most of which would be communications satellites.

The Cost of Payloads

With the Shuttle's capability to carry bulky, heavy payloads, the concept developed that we could build heavy, simple "I-beam" structures for a space bus system, load them with instruments, and fly them over and over, with a different, or upgraded instrument package. We could leave them in space, and then recover them, modify them, and redeliver them to space. With low costs per launch, and many launches, this projected reduction in payload cost contributed to the cost effectiveness of the system.

The Results

Even with these aggressively cost-effective numbers, the study results showed, that to be fully cost effective we had to go with one of the lowest development cost systems. OMB, I'm sure, expected that result, and Congress liked it because of other budget pressures. Whatever the outcome of the study, the administration had decided that NASA could have any kind of Shuttle it wanted, as long as the development costs were equal to or lower than $5.5 billion. In January 1972, when the Shuttle go-ahead was given by President Nixon, Jim Fletcher got a handshake agreement for an additional 20 percent reserve over my 15 percent reserve (mine was included in the $5.5 billion). That 20 percent reserve, had we applied it to reducing operational costs, could have made a big difference. Unfortunately, the reserve was essentially removed by the administration when a leak occurred and the Wall Street Journal reported that the cost could run as high as $6.6 billion.

Design Considerations

While the cost effectiveness study was going on, some important trade studies continued throughout the Phase A, Phase B, and Phase B+ studies carried out by industry. Decisions were made at the top level of NASA on items that affected the Program Authorization Document. These included the studies that led to a blended delta wing rather than a straight wing, the choice of parallel boosters rather than a series booster, solid strap-ons rather than liquid, the payload bay size (length and width), payload weight, and cross range.

A report written by Charles Donlan in 1972 (following this article) summarized the wide ranging configuration studies done between 1970 and the end of 1971. It is important to note that in many cases, decisions were made which reduced the development cost at the expense of operating costs. The choice of solid boosters is a case in point. NASA had extensive experience with liquid boosters, but there was overwhelming evidence that solids would be over a billion dollars less expensive to develop than liquids.

There was also a 100 percent reliability record for large solids at that time. In the final review concerning choice of solids or liquids, we were presented evidence that we could cancel the solid motor thrust in flight, and even abort from them. Later, we found that we could not escape from the solids, but would be better off riding them out. But, at the time, we had concluded that we had very low development cost, very high reliability, an abort capability, and a means of reducing the cost per flight by recovering and reusing the solids.

Postscript

NASA did well in meeting the development cost set out for the program. They missed it by about 5 to 10 percent in 1971 dollars.

They missed badly on operational costs. First, the airline idea of designing with triple redundancy, but flying with a system out, was naively accepted at the time, but was never possible in manned flight. The risk, and the relatively undeveloped systems, could not be compared to commercial aircraft's 30 years of evolutionary development. Second, with NASA's approach to checking all critical circuits and understanding the personality of all components used for our manned flights, there was no way we could come.

come close to the number of 50 to 60 flights per year used in the study (and flights per year is the dominant factor in cost per flight).

A rough estimate of how well we did in operations costs can be reached by correcting our 1971 figures for the increase in cost per flight resulting from flying 12 per year rather than 50, and then comparing those costs to those corrected estimates from 1971 (in real dollars). We still missed our costs per flight by a factor of two or three. Lost over the years, however, was the fact that the original costs per flight were based on accounting only for the "additive costs," over and above the personnel who would be in place if we did not have a Shuttle.

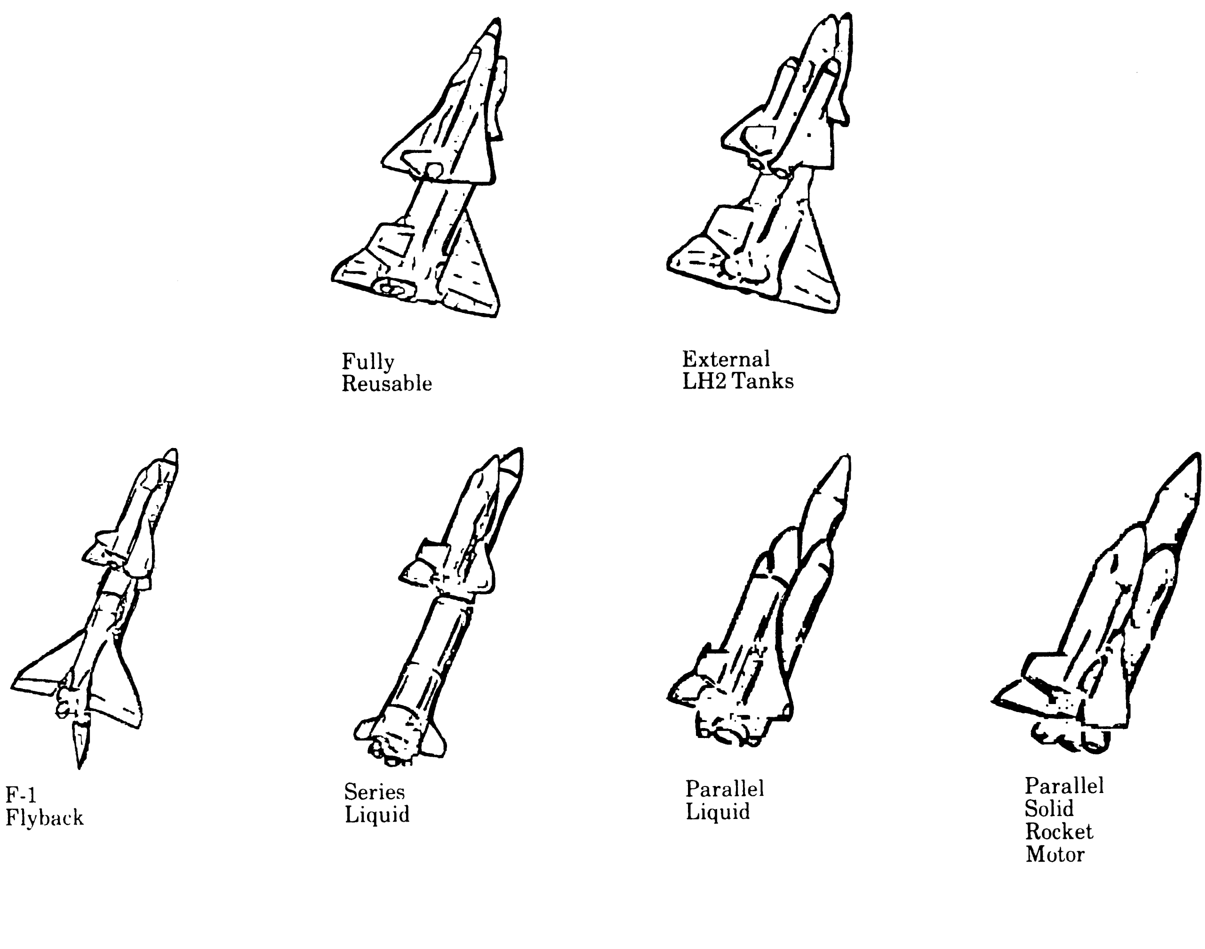
There have been a few ruggedly designed payloads, but there was never a NASA directive to have any. There have been a few payloads recovered, and a few fixed in orbit, but the bookkeeping doesn't show a reduction in transportation cost to give credit to the transportation system.

All things considered, I judge the Shuttle to be a resounding success. It has done everything in space that we set out to do. Perhaps, considering the 1970 budget setting, there was no other way to get a program going than through the somewhat ethereal cost effectiveness approach that was taken.

The configuration of the Shuttle has been superb. To fly from Mach 25 to a perfect landing is a major step forward in aeronautics, but to do it with the configuration that was defined at the end of phase B is a tribute to the team of NASA and industry personnel who defined it.

Finally, the Program Authorization Document system worked. That relatively limited set of requirements, approved by the Administrator or the Deputy, brought stability to the program. No change to those few top specifications could be made without convincing the Administrator of the need. That was priceless in holding down changes during the development program.

Shuttle Comparison



Space Shuttle Systems Definition Evolution

by Charles J. Donlan
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The initial studies, begun in 1969-70, addressed a fully reusable shuttle system which emphasized minimum refurbishment, autonomous on-board checkout, minimum turnaround time, and the lowest operational cost of any system studied. The operational cost, about $4 million per flight, is about the same as for the Thor Delta launch vehicle—the most widely used launch vehicle in the United States. The development costs of the fully reusable system, however, approach $10 billion and reflect the extensive research and development activity associated with developing two large piloted vehicles that possess both the features of a rocket launch vehicle and a hypersonic aircraft.

Further studies yielded a system with a smaller, more efficient orbiter by the use of expendable hydrogen tanks, rather than propellant tanks located in the orbiter. The booster staging velocity was lowered from 11,000 feet per second for the fully reusable system to 7,000 feet per second. This allowed use of a heat sink booster so that the development costs were lowered to $8 billion. The expendable tankage, of course, meant somewhat higher operational costs of $4 million per flight. The high risk and high peak annual funding associated with developing two piloted vehicles still existed and studies for lower cost systems continued.

Eventually, by removing both the liquid oxygen and liquid hydrogen from within the orbiter, NASA was able to devise a much smaller, lower cost orbiter with a single expendable combined propellant tank. The size of the orbiter and its development costs were dramatically reduced while retaining equal performance capability by utilizing this expendable tank for both liquid propellants. The selected orbiter is a delta wing aircraft, powered by high pressure hydrogen-oxygen engines.

Time phasing some of the orbiter subsystems received considerable study effort. This was known as the Mark I/Mark II shuttle system. The Mark I orbiter was to use available ablative thermal protection, a J-2S engine developed as a extension of the existing Saturn J-2 engine, and other state-of-the-art components such as existing avionics. Improved subsystems such as fully reusable thermal protection and the new high pressure engine would be phased into later orbiters to achieve the operational system (Mark II). This time-phasing reduced expenditures early in the development cycle, but the Mark I system had reduced payload and cross range capability as well as an increased turnaround time of one month. This represented a severe loss in operational capability. Furthermore, the total development costs to achieve the full Mark II system actually increased.

Additional studies indicated that further reductions in orbiter development costs could only be achieved at the expense of compromising the objectives of providing the required flexible orbital capability at low operational costs. The possibility was considered of reducing total systems costs through reducing the size of the payload bay in the orbiter from 4.6 × 18 meters (15 × 60 feet) to 4.3 × 14 meters (14 × 45 feet) and reducing the payload capability for a due east launch from 29,500 kilograms (65,000 pounds) to 20,400 kilograms (45,000 pounds). The additional cost savings were estimated to be only about $70 million in the development program. Furthermore, the orbiter with the smaller payload compartment was unable to accommodate about 10 percent of the projected civil missions and about 37 percent of the projected military missions for a typical mission model for the period 1979 - 1990. Therefore, the smaller shuttle would have required retention of large expendable boosters in the U.S. launch vehicle inventory to handle the larger payloads, thus incurring higher costs than were achievable with the baseline shuttle system.

The Mark I/Mark II concept would have used Saturn F-1 engines but nevertheless would have been a costly and relatively high-risk undertaking since, again, two manned returnable vehicles were required to be developed. Its development cost was estimated at between $6 and $7 billion with a cost per flight of approximately $7 million. In a further attempt to reduce the development cost, studies were initiated to examine a shuttle configuration utilizing an unmanned ballistic booster.

Evolution to the Current Shuttle Configuration

The introduction of the external tank orbiter had a major impact on the booster element of the shuttle system. Since the orbiter became much more efficient, it became possible to let it take even more of the burden of propelling the shuttle into orbit. Staging could therefore occur at about 5,000 feet per second. An important advantage from the use of the external tank orbiter was the opportunity to utilize ballistic liquid boosters or solid rocket motor boosters that are efficient at the lower staging velocities. Their use promised the greatest reduction in development costs.

The ballistic unmanned booster studied included both pressure-fed and pump-fed liquid propellant boosters and solid propellant boosters. The two liquids compared as follows:

In the pressure-fed system, the engine would have been a major new development. In the pump-fed system, it would have been a modified F-1 engine (the engines used in the Saturn V booster).

New manufacturing techniques would be required for the pressure-fed booster; conventional techniques developed for Saturn would be used for the pump-fed.

Major modification of facilities would be required for the pressure-fed booster; to a large extent, existing facilities could be used for the pump-fed booster with minor modifications.

The stiff, thick walls of the pressure-fed booster could withstand a moderately high impact velocity, and thus it lent itself to booster recovery. Recovery of the thin-walled pump-fed booster appeared to be of much higher risk.

It was concluded that the pump-fed system had cost advantages and lower technical risk in all aspects except the recovery risk, which appeared large. Of the two liquids, the pump-fed concept was deemed more advantageous in spite of the need to develop complex recovery systems.

After we examined the liquid booster class, a comparison was then made against solid rocket motor configuration. Conventional expendable pump-fed systems currently exist in the series burn configuration where the orbiter engines are ignited after booster shutdown and separation. However, a parallel burn configuration where both booster and orbiter engines are ignited at liftoff takes maximum advantage of the high performance orbiter engines. This parallel burn configuration is particularly attractive for the solids where it is desirable to stage at a low velocity and to minimize the size of solids for operational cost reasons. The pump-fed liquid booster in the series configuration was therefore compared with the parallel burn solid rocket motor booster.

Due to the high cost for each pump-fed booster, recovery refurbishment and reusability are essential, while for the SRM this is not so critical. Essentially, the net cost of losing a liquid booster would be much greater than losing a solid, jeopardizing the ability of the shuttle to attain the low costs of recurrent operations. In addition, providing recovery would entail major developmental risks for the liquid but would be simpler for the solids.

Development costs of the solid booster are estimated to be about $700 million fewer than those of the liquid booster. Environmental effects for both liquid and solid systems were about the same with one exception—propellants and their exhaust products. The liquid booster would use RP, a kerosene-like rocket propellant, and liquid oxygen, and its exhaust products would be chiefly carbon monoxide, water vapor, and carbon dioxide, along with smaller quantities of hydrocarbons and ammonia. The chief emissions from the solid rocket motors are hydrogen chloride, carbon monoxide, water vapor, and aluminum oxide.

It was finally determined that, of the unmanned ballistic boosters, the solid booster recoverable system with parallel orbiter burn would give the lowest development cost ($5.15 billion), least capital risk per flight, and lowest technical risk of development. In addition, economic studies have shown that this system will provide the highest rate of return on investment. Environmental effects would be minor, although it would be necessary to impose additional but acceptable constraints on launches associated with the likelihood of rain.

Summary

Preliminary design studies of the initial two-stage fully reusable concept showed that the size of the system and its development cost could be greatly reduced through the use of an external expendable liquid-hydrogen tank for the orbiter, with a small increase in operating costs per launch. Further study showed that additional cost savings and technical advantages in the development program would accrue if both the liquid-oxygen and liquid-hydrogen for the orbiter were carried in an external tank jettisoned from orbit. This change permitted the orbiter vehicle to be significantly smaller and more efficient, thereby simplifying the booster development and reducing substantially the development and procurement costs at the expense of some additional increase in the recurring cost per flight. Consideration of all factors led to the selection of the solid rocket motor booster, parallel burn system for the Space Shuttle. All configuration comparative issues have been studied in great detail both in and outside of NASA, to evolve this most cost-effective space transportation system.