RIGHT for FLIGHT

The Structural and Architectural Design of Machines That Fly

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I - INTRODUCTION

It may be presumptuous to undertake the task of explaining structural design in a book like this, but this one was started because the author has, in the course of a 44-year design career, had the luck to stumble on significant information that doesn't seem to be generally known. At least, if it were common knowledge, one would expect aerospace structures to look much different than they do.

So this book is about structural design - not the analysis of structure which has been the subject of many books by many authors. While analysis cannot be ignored, design involves more than that; it is the art of starting out with a clean sheet to accomplish some objective. The starting point is usually some similarity or analogy to the present task, springing from a background of related experience. For a beginner, the background is usually furnished by someone else.

In design for aerospace programs, usually dealing with a government agency, there is little guidance from the feedback provided by free commercial markets. As a result, many unwarranted habits have crept into general usage unnoticed, practices which must be questioned. That is what this treatise attempts to do, basing the questions on disturbing evidence which has cast doubt on the assumed "rightness" of accepted folklore - some of it mythical.

While not a textbook, this book may work quite well with one. It probably means more to experienced structural structural designers than to most other people, but is not intended for their use alone. It is partly intended to show designers of other systems what they have reason to expect from structural design. There is also the hope that it will be for newcomers to the design business a substitute for the experience they have not yet acquired.

The occasional use of a mathematical formula to explain some phenomenon more simply than it can be done in English should not deter even a casual reader if he is willing to accept a mathematically proven statement without looking at the numbers. In short, the mathematically timid need not be intimidated.

Structural design is seldom seen as a disciplinary foundation for the practice of "systems" engineering. In fact, hardly anyone employed in that "discipline" is more than passingly acquainted with the subject. This is strange because if there is one common bond between all the

subsystems in a vehicle it is the structure; everything attaches to it. It is also noticeable that the creators of vehicle configurations in preliminary design organizations often come from a structural design background, having a store of experience which makes them familiar with the size, shape, and arrangement of whole vehicles. This is usually career limiting because their formative years were spent making engineering drawings. Drawings, since they convey instructions to the manufacturing side of the corporate business, are rarely seen by "top management" and seldom influential.

Stress analysis is concerned with how strong (or stiff, or whatever) a piece of hardware is, analyzing its suitability for service and starting with a concept backed up by accurate physical descriptions. Structural design, like all design, must consider many other functions such as the architectural subdivision of spaces, leak tightness in pressurized or fluid containment volumes, provision for stowage of and access to the components of other systems, fabrication and assembly methods, and all the compromises which inevitably go into making a balanced flying machine - or, for that matter, any other kind of machine. All of this should be done with a minimum of fuss, feathers, and dollars (or whatever measure of expenditure is appropriate) in a manner consistent with production quantity. And that's where the real problem arises in the aerospace business. That's how this writer became involved with the relatively unexplored subject of the effect of design on aerospace costs and developed the philosophy of design which follows.

This project began to take shape in 1967 when unusual requirements for the Skylab program generated a novel structural concept. The program started with the simple plan of keeping an upper boost stage in orbit and later boarding it to set up a space habitat, much like more recent moves to represent the Space Shuttle's expendable tanks as habitable modules. When first introduced, the idea seemed simple, but a boost stage hydrogen tank contains few of the comforts of home.

Adding even the simplest of living provisions to a fuel tank can interfere with feeding fuel to the engine. The structure must drain the fuel without trappping it. The design must assure a minimum of chip-catching and dirt-trapping joints and fasteners; otherwise, screens can clog and pumps can be damaged. Besides, the crew needs a few amenities - lights, electrical power, sanitary provisions, partitions for occasional privacy and logical subdivision of spaces, mobility aids like handrails, restraints to compensate for gravity loss, and much more. The list grows. Eventually, using a Saturn S-IVB as a boost stage stopped making sense, and the Orbital Workshop portion of Skylab simply used the basic shell of the S-IVB, shedding all the propulsion elements and

the propellants with them. Fortunately, the tank structure was adaptable.

Before reality intruded, the idea of occupying an emptied hydrogen tank persisted for some time, so the bare living structure was built of the largest single pieces of structural planking that could be brought in through a 40-inch opening in the end dome. The planks were machine-perforated into an array of bars forming equilateral triangles. Splices were made only at nodes in the pattern which also contained attachment holes for later installation of equipment. This standard "pegboard" pattern was matched in a unit called the Multiple Docking Adapter (MDA) on top of the Airlock, assuring that equipment carried there during launch would fit the location designated for it when the boarding crew carried it in. It would also fit the pattern everywhere else on the floors and partitions of the living quarters. The construction was the first hardware application of "isogrid", so called because of its uniform elastic response in all directions to applied structural loads. Its form, as originally applied on Skylab, is shown in Figure I-1.

Though it may not have been recognized at the time, this pattern was physically integrating all the subsystems that found their way into the Orbital Workshop. Not only that, but the manufacturing method, machining, was roundly criticized as an expensive way of doing business, a remarkable criticism when one considers how little effort was made anywhere else to economize on that program.

Justifying the choice of "expensive" machining led to some illuminating discoveries about the real costs of making aerospace structure, including the revelation that an assembly of individually simple and inexpensive parts can still cost much more than a large, fully machined unit which incorporates them all.

The investigation helped to confirm, as suspected, that the cost of structure, or any other manufactured product, is greatly influenced by the number of parts in it. In low production quantities, those typical for aerospace contracts, this is particularly the case. The phenomenon seems quite independent of the manufacturing process. One of the main effects of reducing part-count is similar reduction of coordination effort, confusion (with its adverse effect on learning), and, most importantly, documentation. The evidence that integral construction (single units incorporating many parts) is economical has usually been uncovered when this manufacturing method was selected for some technical reason like the leak tightness required for a hydrogen tank. The Lockheed Corporation found it to work well for the "wet" wings of later model Constellation transports. Too often, even in such cases, the evidence of cost reduction has not been revealed because nobody asked

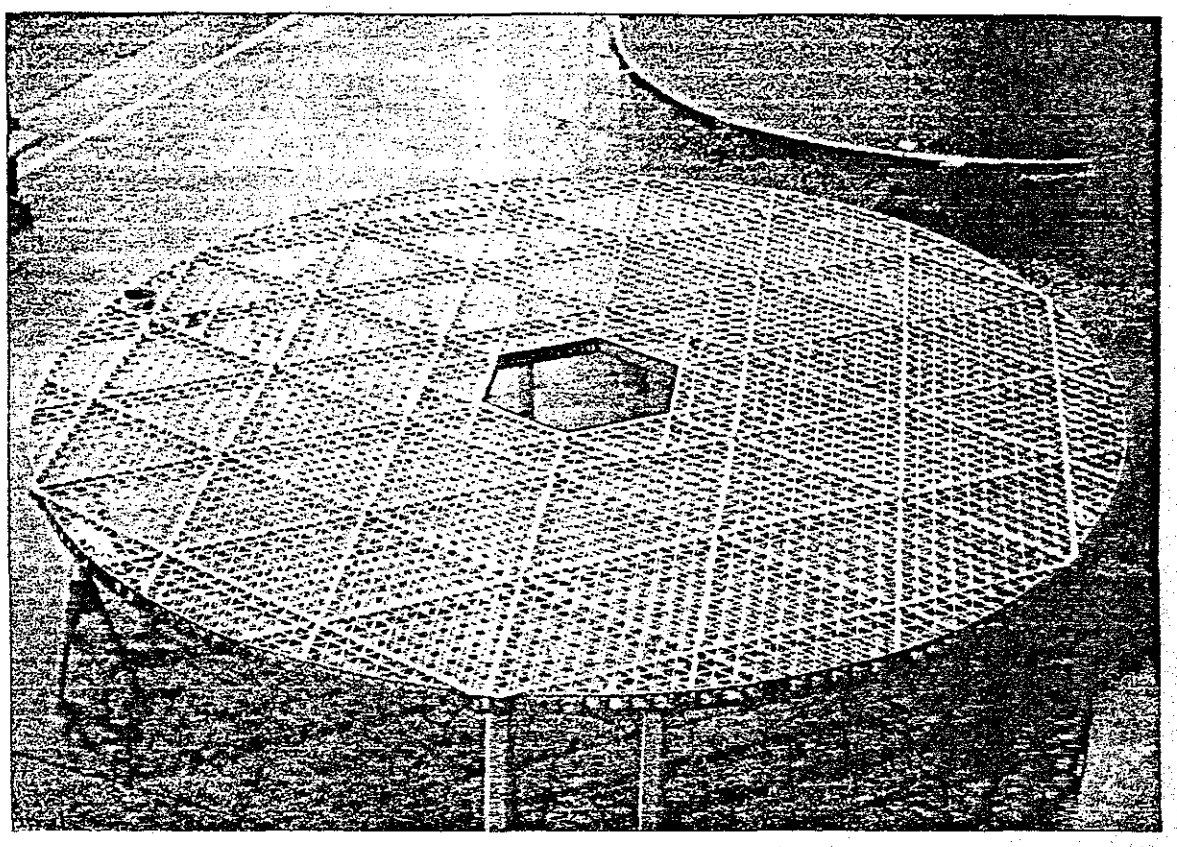


FIGURE I-1 - Open isogric lattice applied to Skylab - photo of a 21-foot diameter floor assembly

for it. Just the improvement in performance is thought to justify assumed higher cost.

In customary practice for aerospace projects, the structure is designed and the drawings describing it released first, the background for other subsystems needing to be revealed before their definition can really begin. The type of construction has generally been selected on the basis of "trade study" results - that is, the lowest calculated weight of structure needed to carry the imposed structural loads without regard to accommodation of other subsystems. The next procedure is to negotiate changes in the structure as subsystems are defined. The inevitable consequence of these changes is a proliferation of additional parts. Local reinforcement must be provided where equipment components are installed. Holes must be cut between components where they must communicate with each other - for wire harnesses, control cables, plumbing runs, and the like. Obstructive structural members must be

removed or relocated to make space for installations or for access to them. It is clear that structure must be significantly mangled before the airplane or space craft is ready for use, the standard for structural design long having been the creation of obstructions. What is more, the structure envisioned when original choices were made bears little resemblance to the final result, negating the validity of "trade studies". Obviously, the penalties inflicted on other affected systems are not negligible, either, the outcome possibly as far from original intent, and the economic effects as little known.

The adjustment just described passes for "design integration", an activity always involving structure. "Integration", however, is the wrong term. It is actually the patchwork created by forgetting or deferring ***real integration*** at the beginning. Such integration must **start** with the structure.

Examples of this approach to structural design in the pages which follow are intended to emphasize the point that ***integration*** and ***adaptability*** are of primary importance in the effective initial design of structure. In fact, it can be stated that ***adaptation*** is that which must be done when ***adaptability*** is missing.

The presence of ***adapters*** is one of the more notable symptoms of this affliction - adapters in the form of clips, doublers, intercostals, cut-outs, and other such reworks. It seems reasonable to claim that when the accommodation functions are effectively incorporated in the initial design of structure, efficiency and economy will be much easier to achieve. Miracle materials are not likely to overcome the adverse effects of design practices which ignore these needs, but they can add a lot of expense

What follows is an attempt to make a good case for these assertions, including meager but rarely offered evidence.

EMPLOYMENT IN AEROSPACE

In 1946, employment opportunities having run dry at the shop of my original employer, the Douglas Aircraft Company, I found a job with North American Aviation. Holding contracts to build and deliver about six different models of airplane, this company was at that time about the busiest in the industry.

Just the same, within about 5 or 6 weeks of my arrival, the rumors of impending layoffs started. Even though this didn't make much sense with the prevailing work load, I had come to respect the validity of rumors.

So I approached my new supervisor about it, saying, "I've been hearing there may be a reduction in the Engineering department, something I'm sure you're not allowed to confirm until somebody in a higher position makes it official. But I'm about the most recent hire in this group and probably should make plans to look elsewhere. Let me put it this way, 'Would you advise me to investigate the possibilities?'"

He looked at me with what seemed like genuine astonishment. "Lay-off?" he said, "Hell, I don't know you well enough to lay you off!"

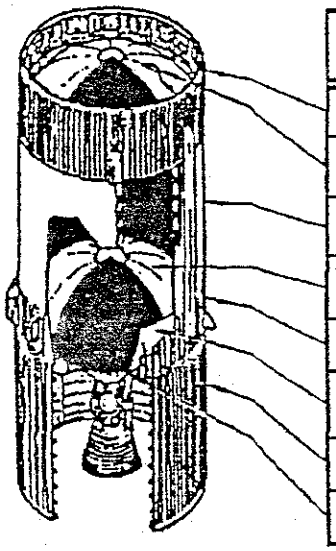
We later became better acquainted.

II - DESIGNING FLIGHT STRUCTURE TO MINIMIZE COST

Although the evidence may strongly indicate otherwise, those involved in aerospace vehicle production claim to be aiming for economy. It is sometimes conceded that this goal must be forsaken to improve performance, it being assumed that superior performance means extra expense. For the structural frame this notion implies that lightness can only be achieved at high cost while **heavy** structure must cost less. That is, the warm feeling of economy is only attained when the structure is crude and cumbersome. Actually, the key action for lowering cost is reducing the number of parts. This, in turn, reduces splice weight penalties. Hence, low cost and light structure are not necessarily incompatible, especially when the production method and material are conducive to effective arrangement.

Keep in mind that ***really*** low cost is achieved only with high production rates and quantities. The term "low cost" is used here in a relative sense. ***All*** aerospace costs are high, even at comparatively high aircraft and missile production quantities. Thousands of articles still cost more per copy than the millions associated with consumer products. In addition, the light and efficient structure needed for flight must be made from light and strong, relatively costly, materials - not the cheap low carbon steels found in auto bodies, appliance cases, and construction girders.

In 1967, McDonnell Douglas Astronautics Company in California (MDAC-West), justifying the selection of "costly" fully machined grid for Skylab interior floors and walls, turned to an examination of costs associated with the then-current Saturn S-IVB boost stage. Each major structural subassembly was built in a distinctive style, thus facilitating comparison. The unexpected result of the investigation is shown in Figure II-1. The numbers are not manufacturing man-hours per pound but ***ratios*** of this parameter. The reference value of 1.0 is assigned to the lowest cost assembly, the hydrogen tank cylinder. It was made of large, fully machined slabs welded together to assure leak tightness, whatever the cost. In areas where leakage of hydrogen was not a problem - the skirts, for instance - it was decided, for economic reasons , to fall back on the familiar "inexpensive" sheet metal skin-stringer-frame construction. That's why the reversed results were



SUBASSEMBLY	TYPE OF CONSTRUCTION	COST RATIO (MFG HRS / LB)
FORWARD SKIRT	SKIN, STRINGER & FRAMES	3.8
FORWARD DOME	WELDED, FORMED, & CHEM-MILLED GORES	1.8
TANK CYLINDER	WELDED MACHINED WAFFLE PANELS	1.0
COMMON BULKHD	HONEYCOMB SANDWICH WELDED GORE FACES	3.3
AFT SKIRT	SKIN, STRINGER & FRAMES	4.3
LOX TANK DOME	WELDED, FORMED, & CHEM-MILLED GORES	1.8
INTERSTAGE	SKIN, STRINGER & FRAMES	1.4
THRUST STRUCTURE	SKIN, STRINGER & FRAMES	4.9

FIGURE II-1 - Relative costs (ratios of manufacturing man-hours per pound) for S-IVB major subassemblies with different styles of design. Costs of material, tooling, and fixed costs like engineering are not included.

surprising. How could anyone in the design profession so completely miss the target? The answer, of course, is that with enough ignorance anything is possible.

To be sure that this information was not an aberration peculiar to the S-IVB, other evidence was examined - with similar results. The findings for the Thor/Delta program were much the same, as indicated in Figure II-2. Here the costs are expressed as ratios of dollars per square foot of surface area, rather than per pound, including material cost as well, but the S-IVB findings were generally confirmed. As in the previous case, the cost analysts cautioned that the numbers were incomplete, covering only limited costs in actual factory production and not covering such activities as Engineering, Tooling, Planning, and Procurement. Just the same, there was reason to be uneasy about the state of cost knowledge.

To examine the effect of parts reduction, the suspected culprit at this point, a detailed study of S-IVB forward skirt structure variations was conducted; it produced the results shown in Figure II-3. This study

is somewhat suspect because, in the first place, it was just a study, involving no real hardware. Also, the hardware description was simplified to make the cost analysis more manageable.

All the operations to fabricate parts were identified and analyzed in paralyzing detail. However, assembly time, much more difficult to define, was estimated as a percentage of fabrication time, though sensible thinking suggests that the efficiency of assembly for 527 parts (or 103) is noticeably less than for 10. Likewise, the interaction with other subsystems and associated changes were ignored for convenience, though this cost, as the original investigation suggests, would adversely influence a real program. In any case, the study, for all its simplifications and shortcomings, was one of the better efforts along this line and managed to confirm the adverse effect of higher part count.

Concurrent with this exercise, a contracted study of a graphite-epoxy bonded assembly designed to the same specifications was completed. Slightly heavier than the 10-part aluminum isogrid design (1000 pounds to 980, a toss-up for selection purposes), its estimated

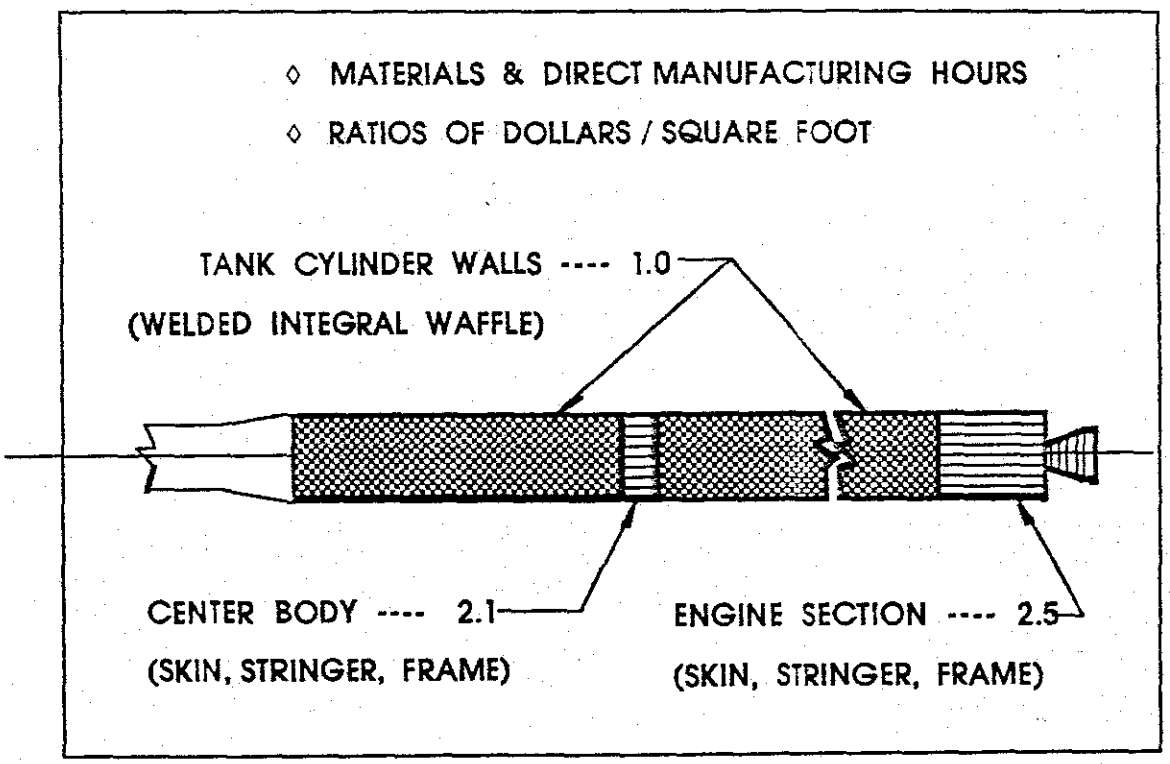


FIGURE II-2 - Cost ratios for the Thor/Delta booster, dollars per square foot instead of man-hours per pound. In general agreement with the S-IVB feedback.

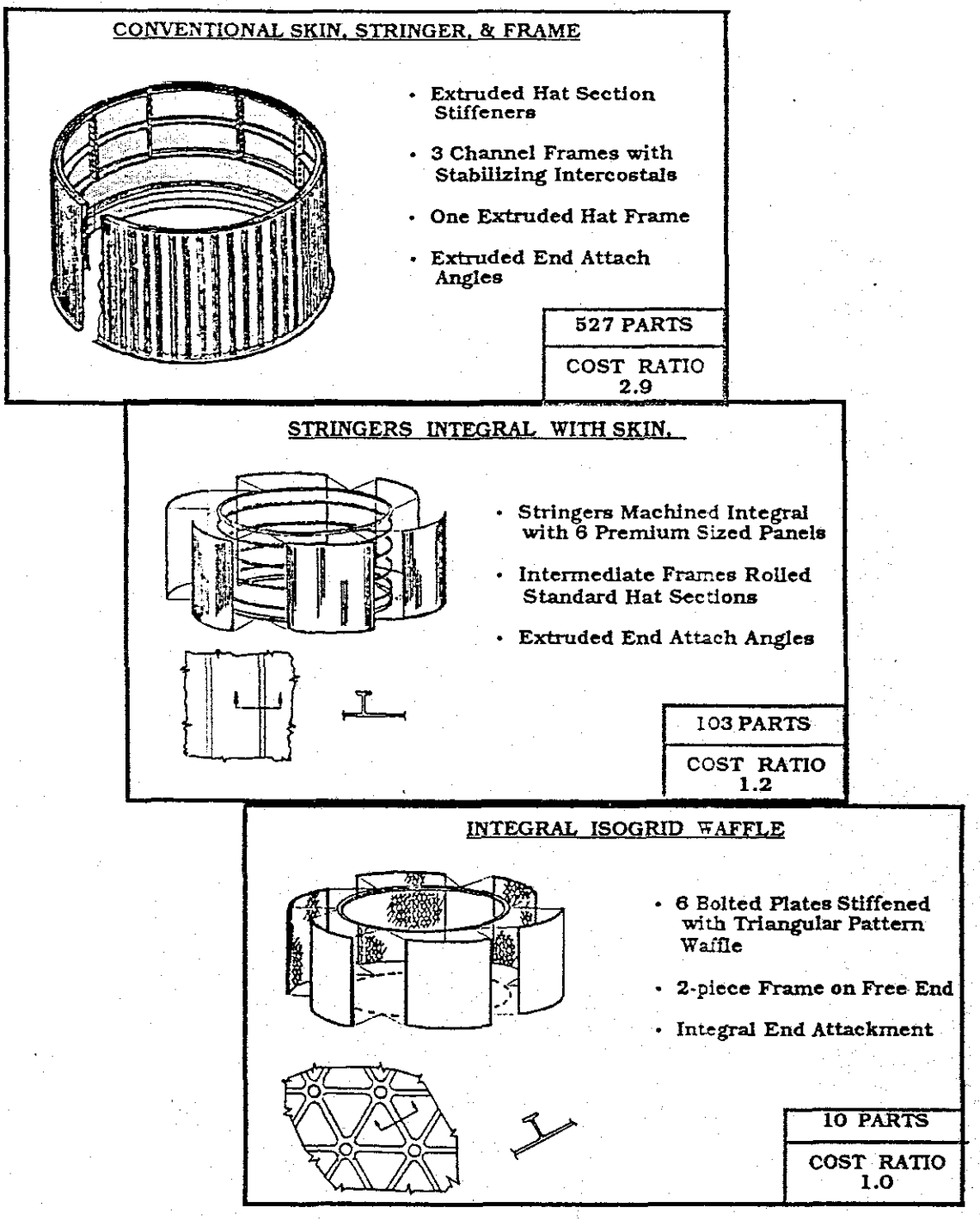


FIGURE II-3 - Results of an S-IVB cost study of a simplified forward skirt assembly, showing the cost reducing effect of part count reduction.

cost ratio on the same baseline was 9.3 - not a very good investment for no performance gain, (another mysterious anomaly).

In retrospect, these findings should not have been so surprising because earlier (in the early 1950's) another division of the same company, the El Segundo Division of the Douglas Aircraft Company, had been detecting some of the same phenomena. A careful review of production costs for the A-1 Skyraider airplane (then known as the AD-1) had revealed that the least expensive pieces of structure in the machine were the wing spar caps, long, fully- machined, relatively large parts. From the labors of the Engineering Cost Analysis Group, a unit formed to provide design support, enough verification of the value of part-count reduction was accumulated to affect the design of the A-4 Skyhawk wing. In this wing, the spars were single machined pieces from tip to tip - no separate spar caps, spar webs, and stiffeners. All were combined into a single part. After rough overall machining close to final dimensions, the parts were finished with template-guided hand-fed power routers. Similarly, the upper and lower wing skins were made from single rolled sheets 25 feet long, while all the full-span stringers were made from extrusions of the same length. The fact that the A-4 was a small craft helped, but parts 25 feet long were rare in 1953 (except, perhaps, for wing spar caps).

In another case whose details have become dim with the passage of time, a study was conducted to define appropriate construction of a large fuselage bulkhead for different production quantities - prototype, early introduction, and full service. This major structural element was located at the rear spar of a swept wing for a fighter which eventually was cancelled before being built. It was called the F3D-3 for as long as it lasted.

A prototype design had been laid out at the start of the study, a typical sheet metal assembly with extruded internal stiffeners and edge flanges, and with machined fittings and load-spreading doublers at concentrated load points - wing root attachments, landing gear supports, and fuselage longeron clips. There were also large flange-reinforced holes where the bulkhead was pierced for two engine inlet ducts. Alternative designs were sketched and roughly sized for a single-piece unit machined from one side out of a 2-inch aluminum plate (sort of a substitute for a forging) and a similar design made from a very large press forged blank.

As previously stated, the details are hazy, but the conclusions of the study were significant. As it turned out, the sheet metal prototype design was uneconomical from the start. Even for unit number one, the part machined from plate stock was more economical and remained the

best choice up to about unit 250. At this crossover point, reduced chip production started to favor the forging. Subsequent developments in production capability, such as numerically-controlled large machining centers, along with escalated cost for forging dies, would probably favor the machined plate version for the first thousand units or more today.

Returning to an interpretation of the S-IVB subassembly costs:

- The assembly with fewest parts per unit of weight costs least, even when machined all over. The average weight of hydrogen tank cylinder parts (40 pounds) is 55 times as great as the average weight of parts in the aft skirt (.73 pound) for a unit cost ratio of 4.3.

- The ***average*** cost of structure (the basis of cost estimates) varies over a wide range - about 5 to 1 for the assemblies shown. Even the weighted average is about 2.2 times as great as the reference cost (of the tank cylinder). This means that a 54 per cent cost reduction would be achievable if the entire vehicle were built like the tank cylinder. As will be shown, greater reductions than this are possible.

- The aft skirt and the interstage were made in the same structural style - internal ring frames and external longerons - yet the aft skirt structure cost about 3 times as much per pound. The most obvious difference is that the interstage was simply a throw-away structural spacer between the S-IVB and the stage below, while the skirt was filled with installed S-IVB system components. Out of a 1200-pound total, there were 160 pounds of doublers, intercostals, clips, etc., added to adapt the skirt primary structure for the component mountings in an unstandardized fashion(Figure II-4).

If the unit cost of the remaining 1040 pounds were the same as the interstage, while the modifications tripled the average, it means that the new pieces required about 16 times as many man-hours per pound as the rest of the skirt. At that rate, the basic structure cost was only 28 per cent of the total, the 160 pounds of modifications accounting for 72 per cent - about 3 times as much.

Clearly, there is economic benefit when installation provisions can be incorporated into primary structure in some consistent and predictable manner. It appears to be about 3 times as significant a consideration as carrying applied structural loads.

The question of how to anticipate the installation requirements was later answered in Skylab, a different application of the same vehicle. The

low-cost integrally stiffened tank shell (Figure II-5) accidentally offered over 2000 regularly spaced attachment opportunities at the intersections of the waffle stiffening ribs. The Skylab interior floors and partitions (all 38,000 pounds, including furnishings) were supported on appropriately located studs occupying tapped holes in these intersections (Figure II-6). This was a standard situation which only had to be explained once and repeated where indicated on a "road map". It certainly was not as complex and unstandardized as the reworks in the aft skirt. The cost increase may have been10 per cent or less. Nobody will ever know, but it surely wasn't tripled. Incidentally, if every one of the intersection nodes held a stud - a situation which did not occur - the weight increase would have been no more than 7 per cent, not the 15 per cent found in the skirt.

While the costs revealed cover manufacturing labor hours only, it is not difficult to see that the effect of part-count complexity is likely to be an increase in the cost of Engineering, Tooling, Planning, Material

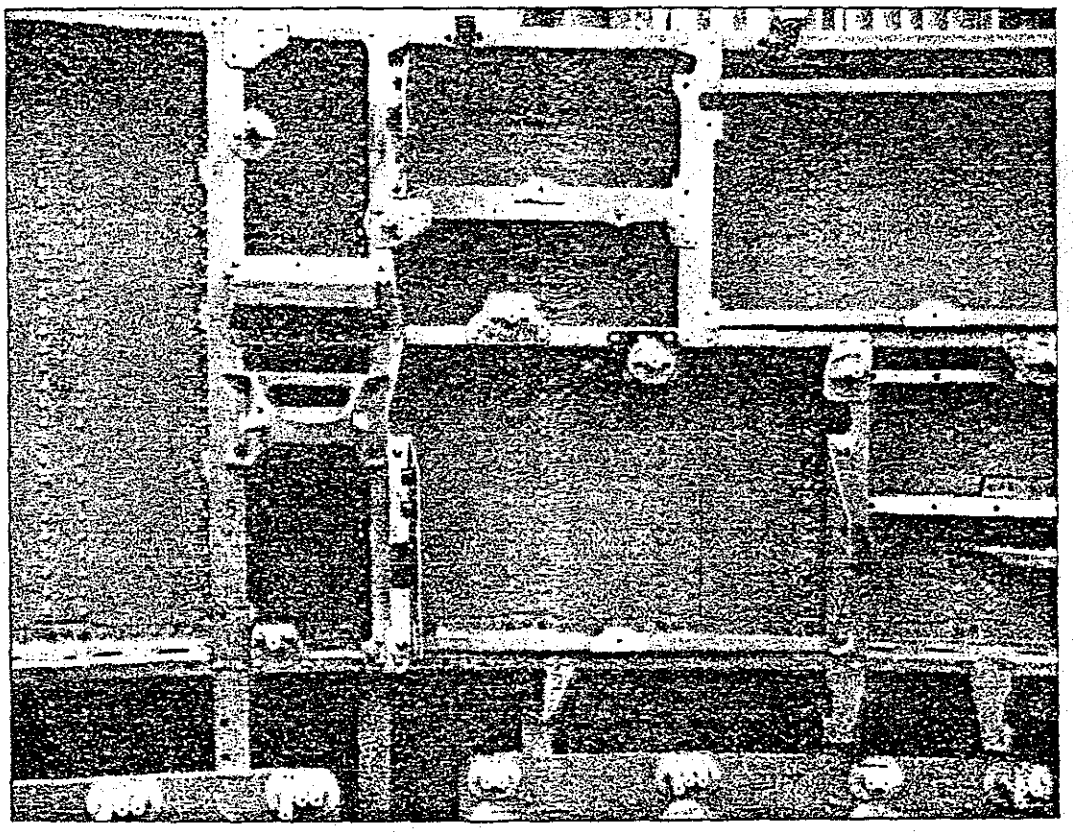


FIGURE II-4 - Photo of part of an S-IVB aft skirt, showing the lack of standardization for equipment mounting. Double rivet lines are the attachments for external stringers on the far side.

Procurement, Receiving, and other production activities. This is at least partially confirmed by examining features of the assembly drawings for the S-IVB hydrogen tank cylinder and the aft skirt (Figure II-7). All the parameters measured and counted offer ample reason to believe that the engineering time spent on the aft skirt was at least consistent with the

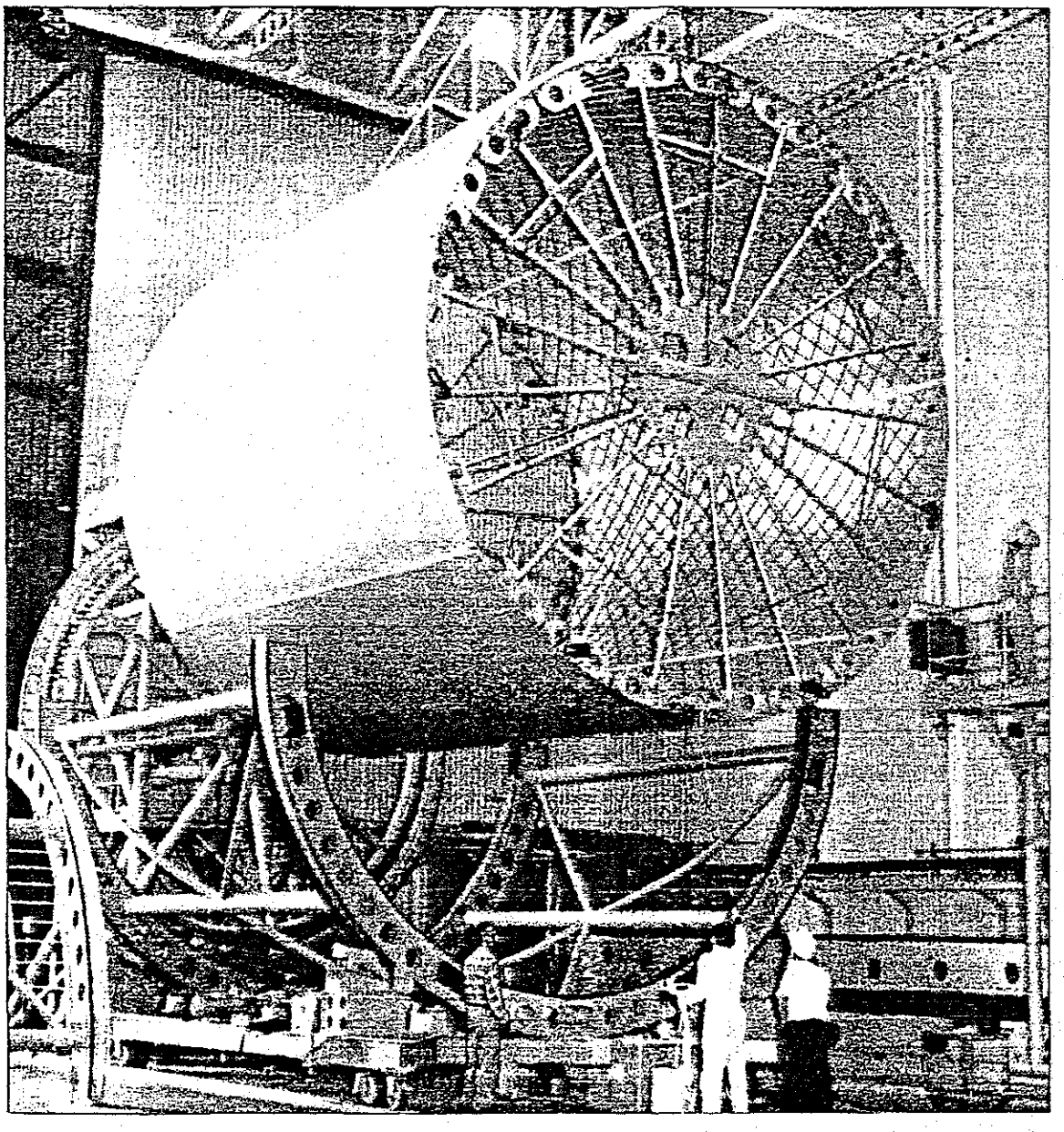


FIGURE II-5 - The S-IVB hydrogen tank cylinder being hoisted into the welding fixture where the end flanges were mated to it. The internal 45-degree square waffle pattern offered about 2000 nodal strong points which were not originally exploited for attachment. That function was introduced later on Skylab.

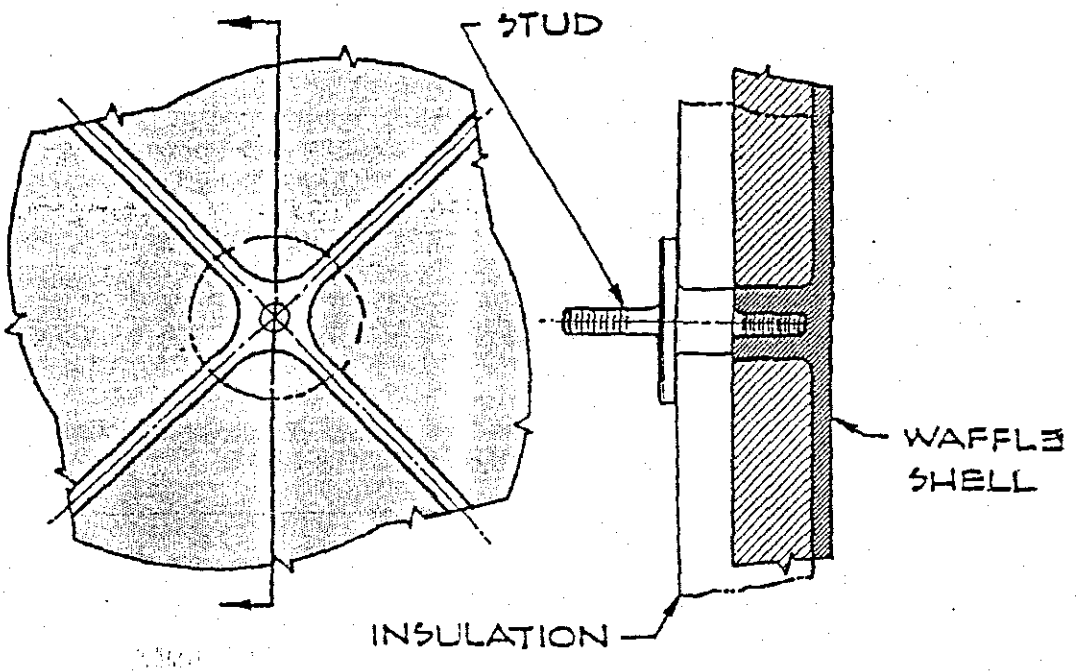


FIGURE II-6 - The standard stud at a typical S-IVB tank waffle node. It was installed where required to support the internal structure which converted an S-IVB into the Orbital Workshop of Skylab.

manufacturing cost ratio. Other activities must have been similarly affected. Note, particularly, the large number of changes needed to modify the skirt to accept equipment.

The tank didn't get by unmodified either, although much of this can be explained by the fact that the handy opportunities previously mentioned were originally ignored. All installations were accommodated by special machining and welding adaptations which made the local structure heavier, weaker, and more costly.

In one S-IVB bean-counting exercise (Figure II-8), the traffic in drawing changes was shown to be about 3 times as great as new drawing releases. This is somewhat understated because changes usually create new drawings as well as alterations to old ones. However, what it implies is that large structural assemblies, even relatively simple ones like the hydrogen tank, bear a disproportionate share of change traffic. It stems from the custom of releasing the structural drawings first, defining for subsystem installers the background of their tasks. From initial release until the program dies, the structure is continuously altered to create the typical entanglement which makes further change increasingly difficult - and later updating or modernizing economically impossible.

Such lack of foresight is usually accepted as inevitable, although it doesn't have to be. Figure II-9 shows how the physical integration of subsystems was accomplished on Skylab where all the components were attached at the nodal intersections of a regular grid lattice. It is evident

	MANUFACTURING COST RATIO	1.0	4.3
		TANK CYL	AFT SKIRT
DRAWING LENGTH, FEET		37	132
NUMBER OF PARTS		86	1,625
NO. OF PART NUMBERS		11	325
DRAWING CHANGES		46	122
AUXILIARY VIEWS		21	155

FIGURE II-7 - A comparison of various features indicative of cost between the drawings describing the S-IVB aft skirt and the hydrogen tank cylinder. The skirt cost averaged 4.3 times as many man-hours per pound as the cost of the tank.

that any of the units could be removed and replaced by any others designed to fit the standard pattern. This can only happen, of course, if the standard pattern is established early and made known to all concerned. This suggests, in turn, the adoption of some long overdue structural design practices.

To sum it up, the structure physically integrates (or unintegrates) all the other subsystems because they are all attached to it. Without forethought, as in the case of the S-IVB skirts and most typical structural systems, structural cost penalties are high. Extra costs for subsystems have not been recorded and are probably unmeasurable, but there is no reason to expect them to be low, either. Even accidental inclusion of a standard pattern, as happened in the case of the S-IVB tank wall, can, if recognized, offer substantial benefits. Better yet, the standards can be incorporated intentionally and early, as they were in Skylab - and haven't been since.

Not all the cost information confirming the economy of parts reduction comes from a single source. Figure II-10 gives an example of the advantage of a single-piece cast frame for an aircraft canopy over a built-up counterpart. Note that the outlay for "material" (in one case, the casting) is five times as high for the more economical design. Note also that expended man-hours are proportional to the number of parts.It would seem that if man-hours (by far, the major constituent of cost in low aerospace production) are exactly proportional to numbers of parts, the handiest way to estimate the cost of a hardware assembly is to estimate the number of parts it will contain. This is exactly what the Vertol (helicopter-building) Division of the Boeing Company concluded, as shown in Figure II-11. In effect, their study revealed that it is more accurate to estimate the cost of assemblies at a rate of 0.68 man-hours per part than at 0.78 man-hours per pound. (These figures must mean unburdened and unfactored costs, being exceptionally low for aerospace). The application of this finding in a design-to-cost method

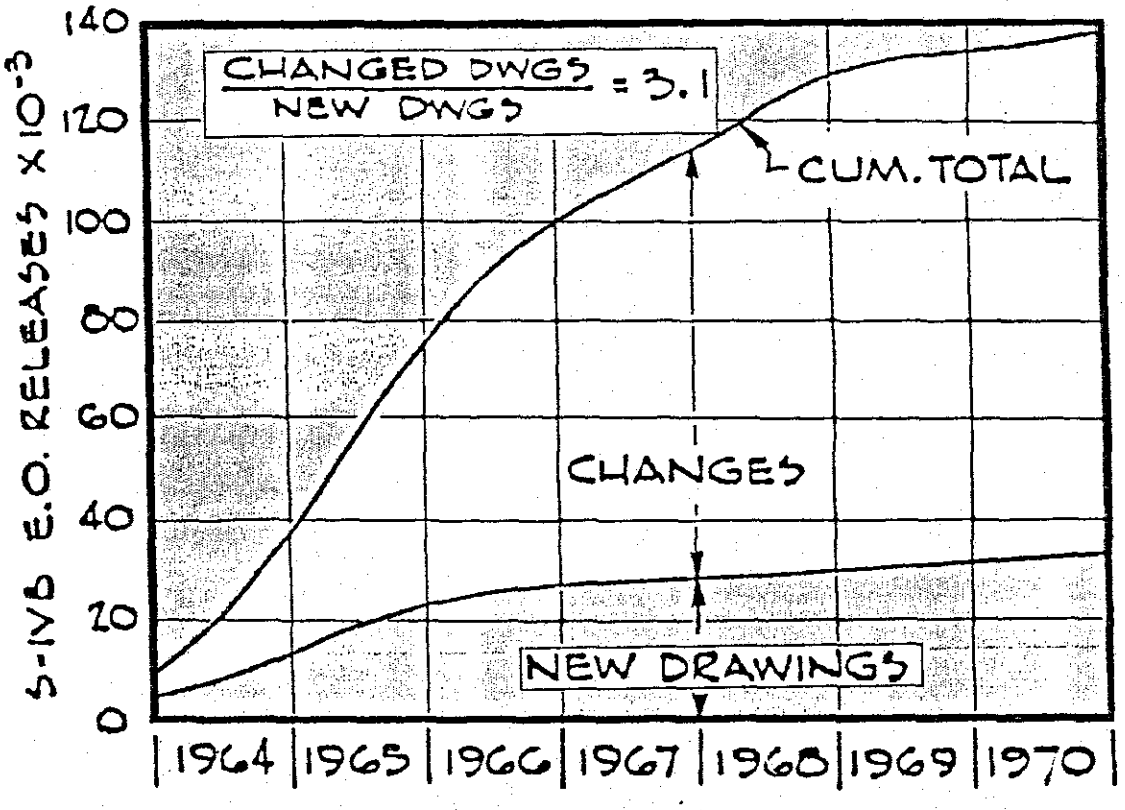


FIGURE II-8 - A plotted record of Saturn S-IVB drawing releases over a 7 year period. showing that changes were over 3 times as numerous as new drawings on the avercge. Probably greater, because many changes must have caused the creation of new drawings.

was to set for each designer the tangible goal of designing his particular assembly with one-third as many parts as had been counted in similar assemblies on previous projects. It really takes more change in habitual practice than this to accomplish significant results, but, as with most engineers and estimators, mental bias probably identified machining with high cost - thus precluding this method of combining parts.

To digress slightly at this point, the tangible goal mentioned above brings to mind a pronouncement made many years ago by a high level

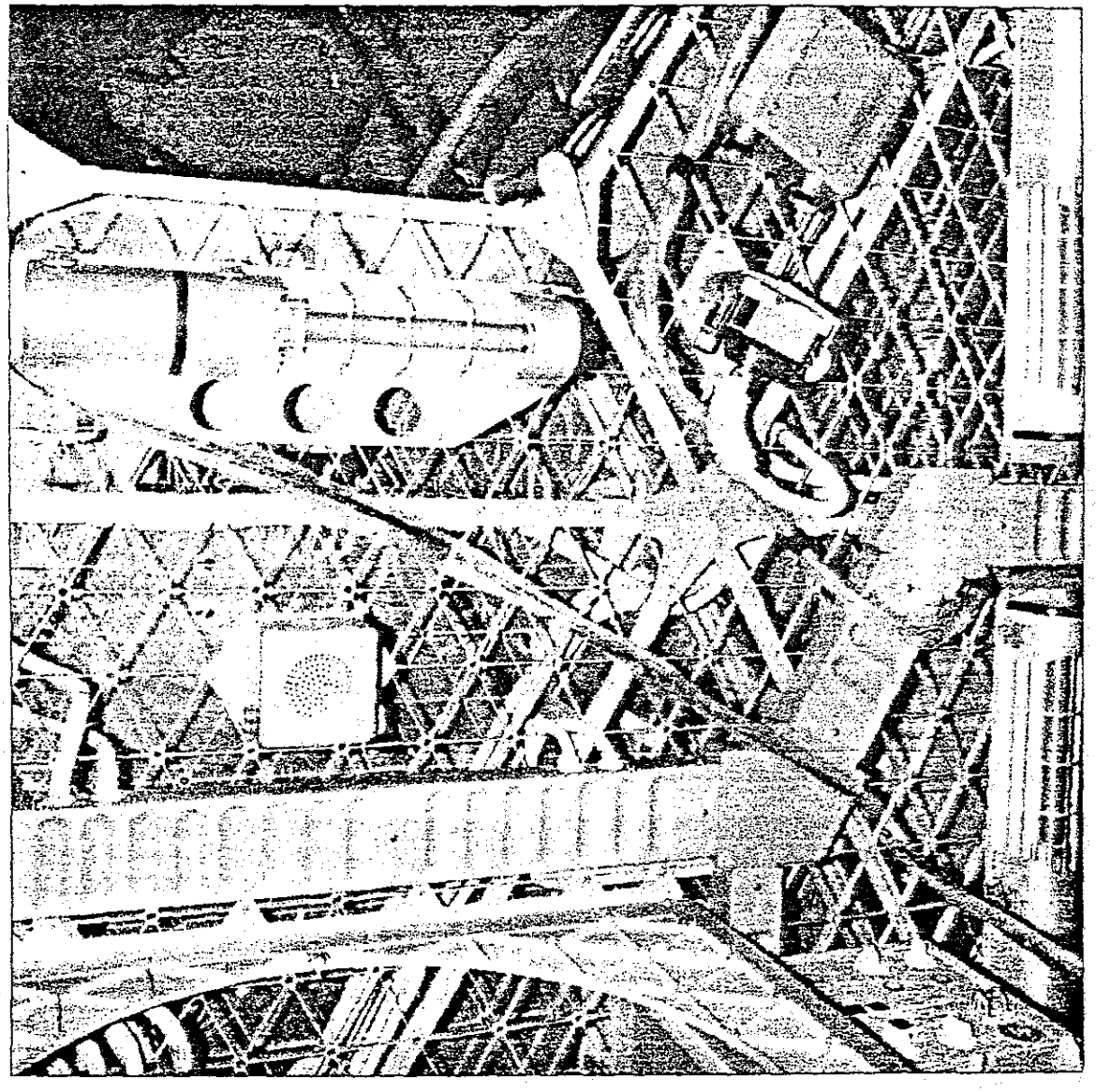


FIGURE II-9 - A Skylab Orbital Workshop interior view, showing how the nodal intersections of open isogrid panels were exploited to mount equipment components.

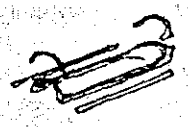
		
CAST FRAME		BUILT-UP
8390	MATERIAL $	1600
225	MAN-HOURS	900
99	PARTS	400
141	WEIGHT - LBS	167
10,865	TOTAL $	15,250
77	$/LB	91

FIGURE II-10 - A cost comparison between two designs of aircraft canopies, one containing 4 times as many parts as the other. This information came from a report of an Air Force sponsored symposium with the aircraft industry at Sagamore, New York, in 1972.

engineering official at the Douglas company - at the headquarters in Santa Monica. He claimed that the way to reduce cost was to hand a cost target to each designer when a design task was assigned and make him stick with it. Great idea, but who supplies the designer with the cost facts he must have to know where he stands? Further, who is going to furnish the enforcer of the edict with the facts he must know if costs are not within limits? How is this to be done? And who can do it? Curiously, cost analysis support, a routine practice at the El Segundo plant involved with Navy contracts, never did materialize at Santa Monica. There the Engineering Department, engaged in the design of commercial aircraft, was committing (maybe squandering?) the company's money.

The proof for any speculation about the effect of part count is obtained when a hardware program deliberately exploits the findings. This happened when a change in the Delta launch system required a new, full-diameter (8-foot) payload fairing. A typical sheet metal fairing for the Titan vehicle was at that time in production at the same facility. Its overall arrangement and a detail of a subsystem installation are shown in Figure II-12. As usual, even the simple installation in this

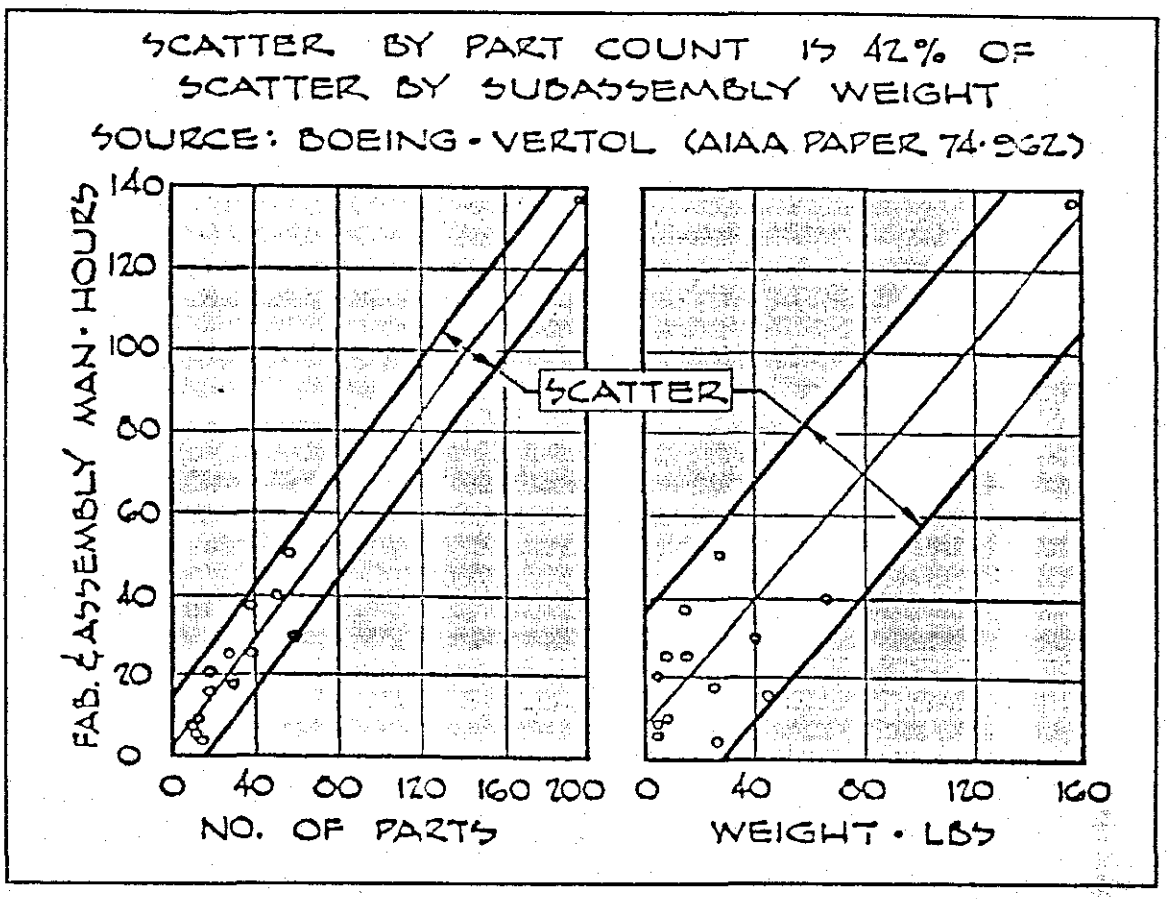


FIGURE II-11 - Another part count comparison by Boeing-Vertol, showing that a part count is more accurate than a weight estimate for the purpose of estimating cost. Of course, at the early stages of a design, a weight estimate is more readily available.

fairing required additional parts and reworking of the old ones to accommodate equipment. Figure II-13 shows the equivalent situation in the fully machined Delta fairing. Natural nodes at stiffener intersections provided more than enough handy fittings. Examination of the manufacturing hours per pound for these two major structural assemblies showed a ratio of 1 : 2.6, favoring the integrally stiffened machined design. This comparison was for the whole assembly, including similar sheet metal nose cones on both. Isolating and deleting the effect of that similarity to compare cylindrical areas only, revealed the more directly comparable ratio between built-up and integral structure to be 1 : 3.6. Substantial savings could then be expected if the half-cones were machined as proposed in Figure II-14. Of course, by the time this suggestion was offered, the damage had been done and the budget expended. Such a lapse should be carefully avoided once any commitment to integral construction is made. Go with it all the way.

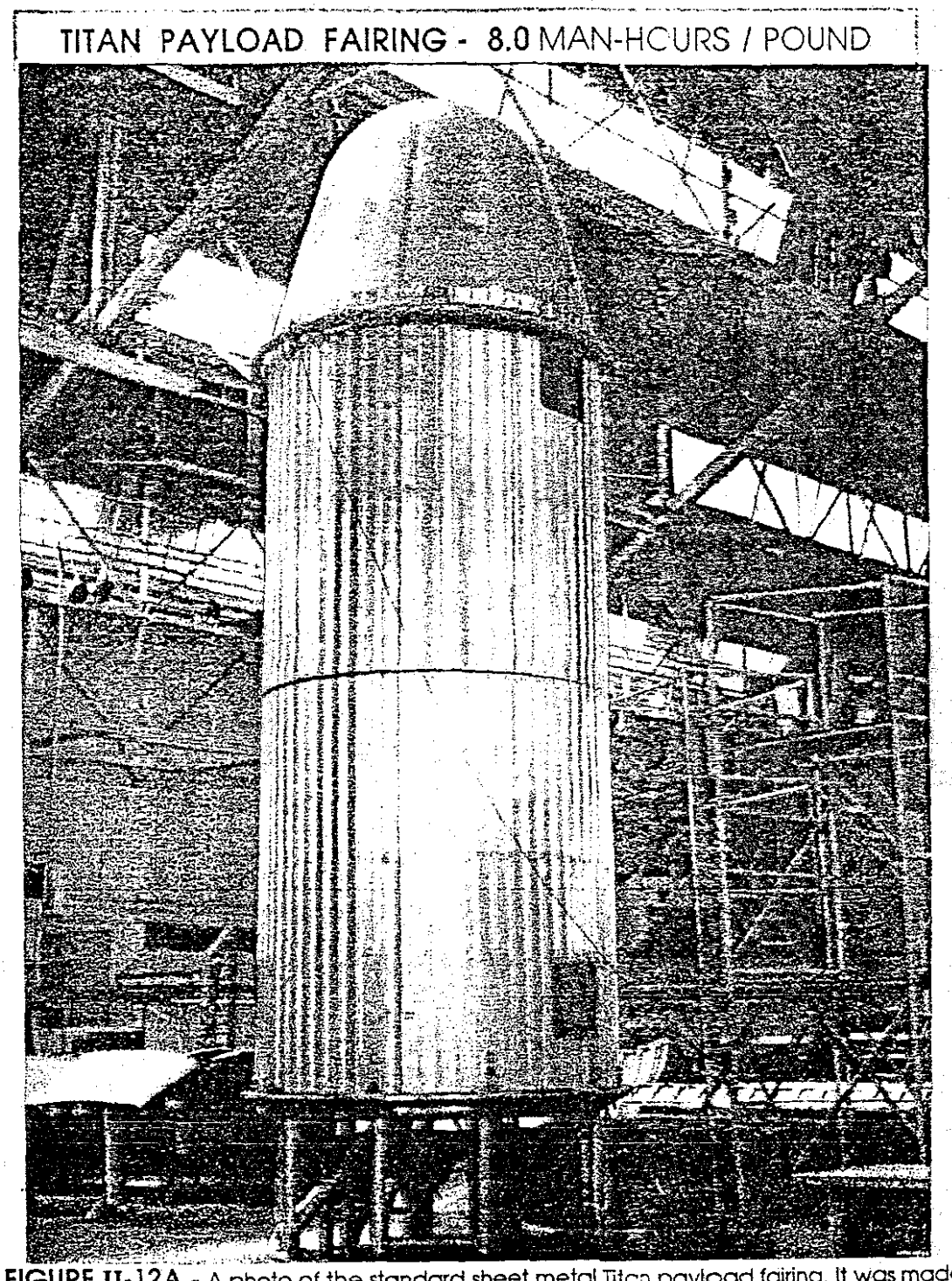


FIGURE II-12A - A photo of the standard sheet metal Titan payload fairing. It was made in the same skin-stringer-frame construction as the S-IVB aft skirt, with the stiffeners on the outside in the same manner.

Competitors seem not to have noticed that fully machined payload fairing designs consistently win production contracts. Any one should ask himself: If this method is "expensive", why would it be chosen for such an obviously expendable application? And why would it continue to win contracts?

As a further sequel to the same chain of events, the manufacturer of the Delta and Titan fairings responded to a military request for a new larger fairing for the Titan launch system. The chief competition came from an out-of-production unit which had been fully qualified and flown. The cost bid for a new integrally stiffened shroud (then undesigned and untested) was about 25 per cent lower and won the contract. When last heard from, this contract was on schedule and under-running its cost predictions.

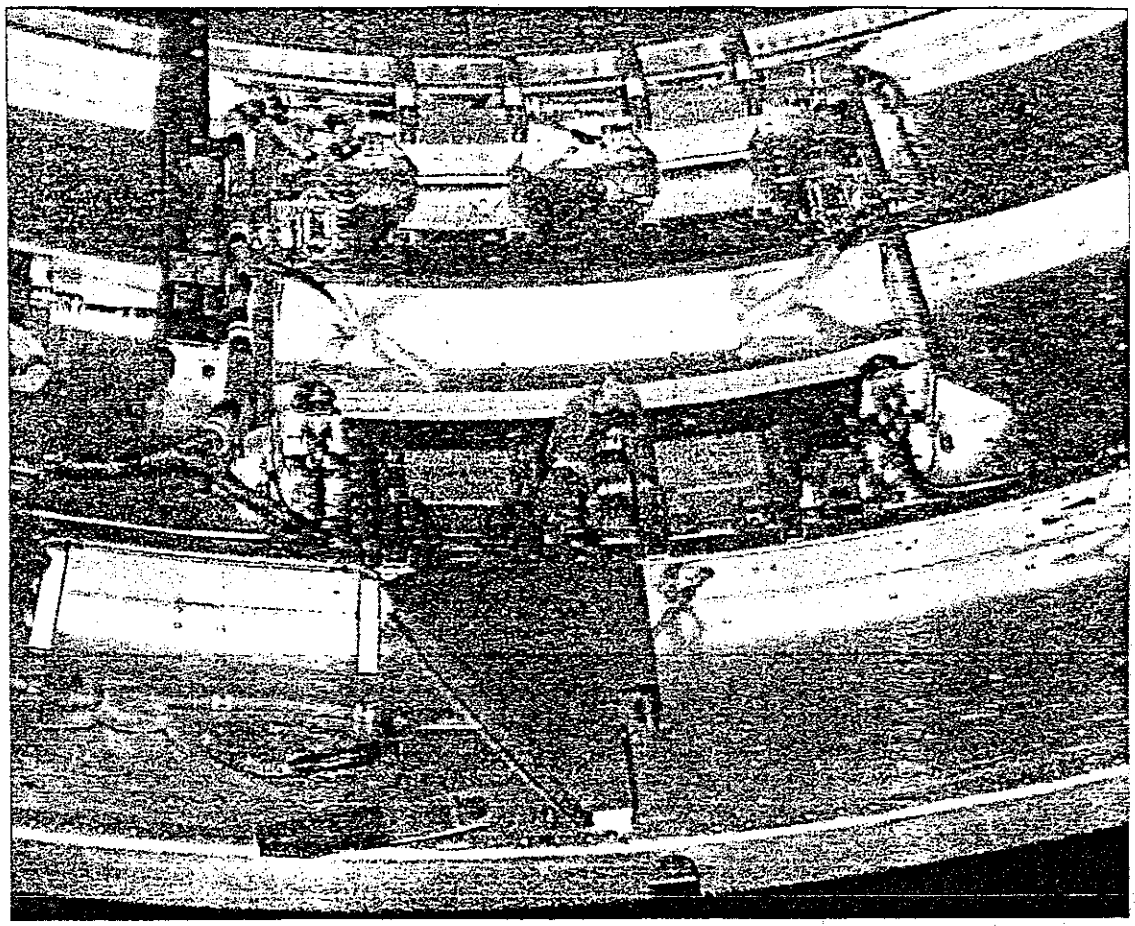


FIGURE II-12B – There are few installations like the one shown here in a shroud of this type but this detail demonstrates the reworks needed to accommodate equipment in a sheet metal design.

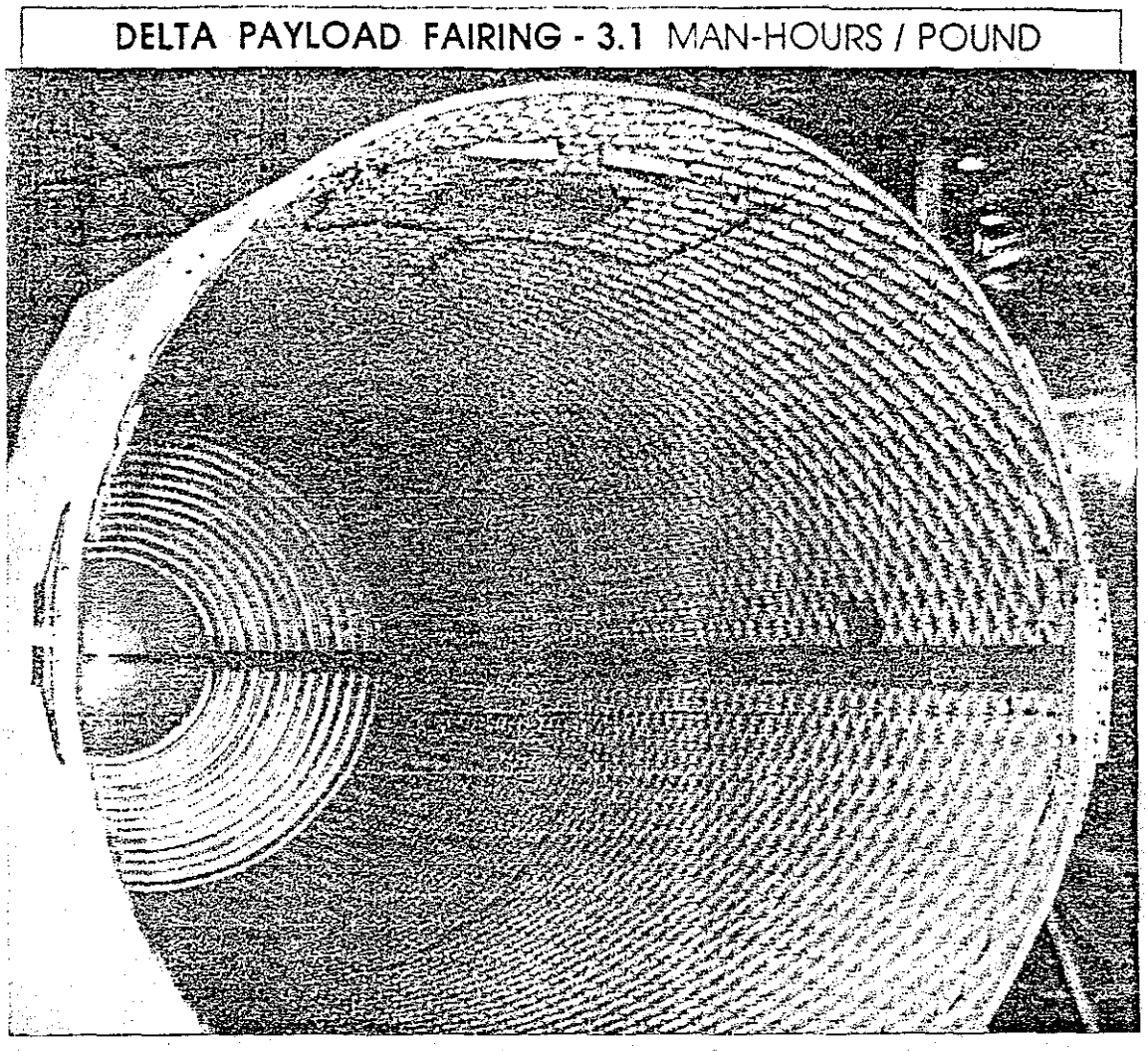


FIGURE II-13A - A photo of the integrally stiffened isogrid payload fairing for the Thor/Delta booster. As a direct result of the S-IVB findings, it was made this way to reduce expense and thus to assure a strong competitive position in the payload fairing business. The results exceeded expectations.

These examples of the effect of design on cost, while few, are about as many as are likely to show up in one place. Quite obviously, too little cost information is available to designers (or, for that matter, estimators), probably because the knowledge is collected and disseminated to satisfy auditors and to justify expense rather than to reduce it. It is hard to explain why designers haven't asked for such sorely needed feedback and guidance. Maybe it isn't sorely needed because there is no real economic competition in aerospace. The better liar wins.

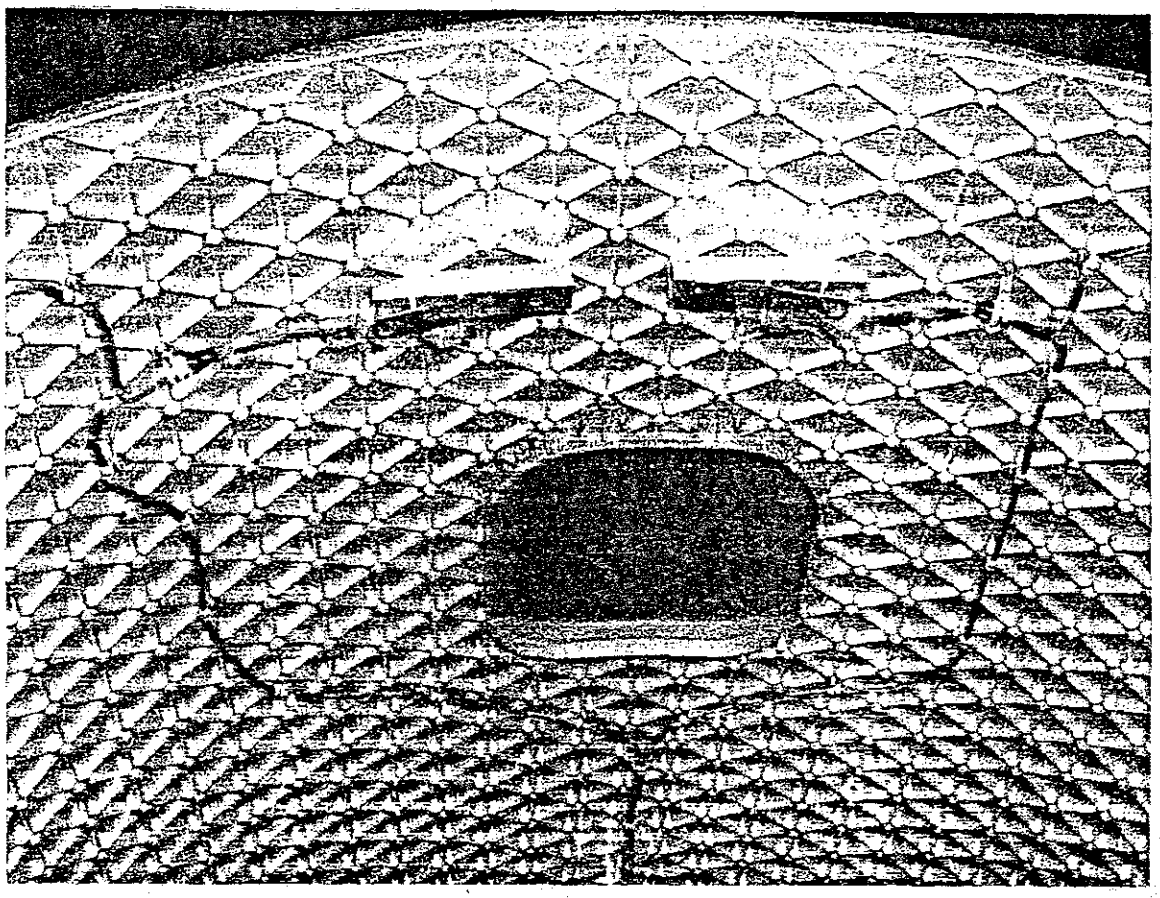


FIGURE II-13B - No rework of existing structure, except attachment at the stiffening nodes, is required to mount equipment, as shown in this detail from the Delta fairing.

One's "intuition" about low-production costs is not to be trusted. Nothing could be more misleading than the assumption that what an individual produces in a backyard or home "garage" project would be economical for aerospace. The missing ingredient is the cost of labor which the home builder donates to the project while he scrounges to minimize the cost of material. An aerospace company has the exact opposite point of view; labor must be paid for even if workers put in no more than their attendance, while material is relatively cheap. It is true that extravagance with material is more visible and likely to attract attention. However, labor costs more, is less easily tracked, and harder to use effectively at the start of the learning curve.

Just the same, there is a widespread "understanding" in the industry that sheet metal construction is economical and integral machined structure is so costly that it is only to be used when some structurally "important" function is accomplished. This is why airplane

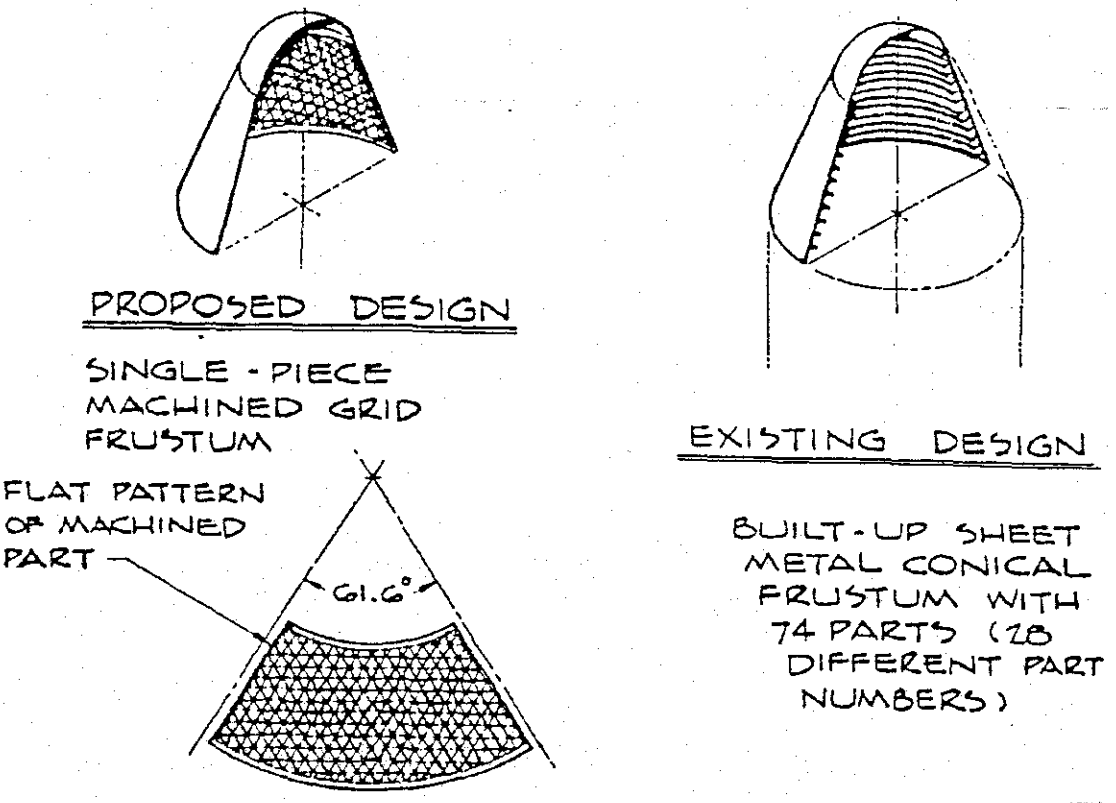


FIGURE II-14 - A sketch showing further simplification obtainable if the Delta payload fairing design philosophy had been extended to the nose cone.

wings are built with sculptured skins while fuselages are not. Since space booster propellant tanks correspond quite closely to airplane fuselages, there should be a distinct advantage to such construction in that application. A blending of the two different experiences should be in order but never seems to happen.

As it is, the bidder proposing a low cost system is on quite safe ground if he offers to do the job with riveted sheet metal. By proposing the "good old-fashioned" way, he will probably not have to prove anything. On the other hand, he who proposes to do it with integral construction, provably more economical, will nonetheless be regarded with suspicion and asked to furnish proof. In the early 1980's, a contractor who sought the "expertise" of the Battelle Institute on a study contract, showed their consulting expert photographs of the integral and built-up payload fairings described here earlier, asking her to guess which cost less. Without any hesitation, she selected the sheet metal design. As the actual facts show, she was in error by a factor of at least 3.

In any event, the practices which produce lower cost structure in the low production volume typical of aerospace, deliver an article which ***looks*** quite different than appliances and automobiles, objects usually associated with the idea of economy. The exposure to this knowledge leads to some simple and useful guidelines:

A. Keep the number of parts to a minimum. This means that structural elements must be made as large as possible, incorporating to the greatest extent possible, whatever fittings and local reinforcements are required. (Mechanism designs are often unable to profit from this practice because parts which must move with respect to each other cannot be combined, though simplification always helps.)

B. Anticipate potential change with standard features and patterns. For real structure (as opposed to "optimum") accommodating other subsystems must be considered and incorporated in the geometry of the stiffening arrangement - for example, the Skylab lattice or the grid stiffening in the S-IVB tank. Otherwise, these provisions will be added later, as they always are (and usually in an uneconomical non-standard fashion). The result is high cost, schedule overruns, or excessive weight - perhaps all three.

C. Minimize tooling cost with accurate, self-indexing parts. The machined pieces of the Skylab workshop floor fit together accurately and located the sheet metal beams between faces. In this case, the assembly had to be dismantled and inserted through a 40-inch diameter hatch to be re-assembled in the hydrogen tank. For low-quantity assemblies (like cradles in Shuttle) the principle also applies; built-up structures must be produced in assembly jigs of some kind and an assembly fixture can quite easily cost as much as one set (or, perhaps, two) of flight hardware built in it.

D. Anticipate access and intercommunication with ***open*** internal structure. This is a corollary to the need for attachment provisions. If the openings aren't there at first, eventually they will be. As unplanned afterthoughts, they destroy the efficiency assumed when study results prescribe an obstructive initial structural form without openings.

E. Avoid materials which cannot produce fittings. Integral construction can be described essentially as all fittings.

F. Modularize. This applies both to geometric patterns and modular

subassemblies. It follows from the implication that having fewer different kinds of parts is at least as significant a cost saver as simply using fewer parts. It also offers the opportunity to benefit from somewhat larger production quantities. That is, if an assembly is built from 12 identical subassemblies, there is, from the start, an edge in economy from the learning on 12 times as many units. Standardized design is not the same thing as using standard parts (like nuts and bolts), though there is some profit from that as well.

G Triangulate. Triangular arrays of bars can carry all types of loads without any skin and can stiffen skins to function efficiently. Such arrangements also possess torsional rigidity, acting like closed torque boxes to handle local eccentricities. They remain penetrable and less in danger of being modified. They also minimize the proliferation of extra parts by offering both support and access without modification. Three-bar (or six-bar) intersections are rarely, if ever, seen in sheet metal construction because they are hard to make and involve too many pieces. In integral structure they are simply co-planar remnants left in the plate after adjacent pockets or holes have been machined away.

Guideline "A" is the key. All the rest define actions which help to achieve part-count reduction. Conformance to these guidelines produces structure of different appearance than "conventional" construction although there is little departure from standard practice, and the effects are more than slightly beneficial. This was proven to work for the Delta booster and integrally stiffened payload fairings. In the case of Skylab, the benefits of standardization for adaptibility were noticed, but no cost saving was recorded. Oddly, although there is nothing proprietary about the idea, it has had little application elsewhere, and, for that matter, minimal exploitation where it started.

Cost Accounting in the Aerospace Industry

As already mentioned, the amount of cost information cited herein, skimpy as it may be, is still more than that generally available to designers of flight hardware. It is for this reason that designers are unlikely to act appropriately when cost reduction is mandated. Cost records are kept to justify existing costs and to establish approved charges for government contracts. They are meant to be seen by

auditors, not designers.

There seems to be an unwritten rule that the custodians of cost information in financial groups are to communicate as little as possible with engineers. For one thing, they fear that basic estimates, without the usual factoring to bring them into line with reality, are too low. If an engineer were to convey the information inadvertently to a customer representative, that person may conclude that his agency was robbed. This is the reason for the presentation of S-IVB costs as ratios, a perfectly satisfactory arrangement for the designer because that's all that really matters to him. He wants to know what practices produce the desired results, and how they compare with other alternatives. Furthermore, he needs to know how these comparisons changed by increasing production quantity?

When costs are estimated for proposals, the information comes from compiled ***averages*** of past performance. It is not habitual to look for the ***differences*** needed to predict the effect of a change from standard or accepted practice. This means that a designer who has actually designed appropriately for economy cannot expect acknowledgement for having done so. As the manager of parametric cost analysis at one company said when shown the material in this chapter, "This makes a lot of sense, but we don't have records that would give such information."

It is even worse than that. For instance, establishing so-called "representative" experience is always much easier when a large statistical sample is available. Unfortunately, these large statistical samples come from high volume industries - automotive and appliances, or the like - industries whose statistics do not pertain to low quantity production. For the aircraft industry, the last occasion offering similarly large statistical sampling was World War II, an event fading into distant history and based on outdated methods. But we did build over 100,000 airplanes in one year, a circumstance unlikely to be repeated in the foreseeable future. What all the statistics show is that machining is a relatively slow and costly production method which, in addition, wastes a lot of material if the starting blanks are not close to net size. It is always avoided, if possible, for mass production.

True as these indisputable facts may be, they really have nothing to do with the case. If one looks at just the first one hundred or fewer units of a large production run, it can be seen that all fabrication methods are expensive and that material cost is relatively small. The advantages of large volume don't show up until a breakeven point is passed - and that may happen only after tens or hundreds of thousands of parts have been produced. The economies are usually obtained by

quite large expenditures for mass production tooling - forgings and dies, automatic fabrication tools and assembly machinery, automatic conveyors and parts handlers, and production control by computerization. They are amortized as just a few cents per part when millions of parts are made. Low production quantities involve too few items to absorb the cost of such overhead. This, by the way, is why composite fabrication costs are unlikely to be reduced by more automation, as too often claimed.

More to the point, at low aerospace production levels, just the paper work to keep track of what's happening often costs more than actual fabrication. Add to this absorbing the cost of changes needed before the unit, whatever it is, can be considered operationally ready.

So it becomes necessary to make the most of small statistical samples and to interpret what they are trying to tell us. Interpretation of the S-IVB experience led to successful application of the lessons learned on the payload fairings made by the same company. The closest similar comparison between structural assemblies in the former case was that between the hydrogen tank and the interstage structure, the ratio being 1.0 : 1.4. Neither of these assemblies interfaced to any significant extent with installed equipment components. However, the ratio between costs of the Delta and Titan fairings was 1.0 : 2.6, probably more like 1.0 : 3.0 if the nose cones were left out. It means that the S-IVB findings were, if anything, understated, possibly because the cost analysts were unwilling to believe what they were discovering. Unfortunately, what it also means is that the knowledge has been applied to the kind of structure that matters the least. Much greater advantage should be gained by applying integral design where there is more involvement with equipment. This was thought to be the case in Skylab, but insufficient records were kept to prove it.

Misinformation seems always to be available. At the Douglas company, when the S-IVB investigation results were obtained, the information was circulated through the Structural/Mechanical design department, falling also into the hands of the Advanced Design people. At the time, they were working on the design of a nuclear powered upper stage. Its tank shell was intended to be made of honeycomb, it being assumed that sheet metal fabrication was more economical than machining. As one program manager put it, "We've been told that the S-IVB tanks cost two-and-a-half times as much as the skirts. Where did the information in this memo come from?"

It turned out that the source was the same System Cost Analysis group that issued the S-IVB assembly cost investigation results. When confronted with this conflict, the responsible analyst said, "That's what

we thought to be true ***before*** the S-IVB program started. Now that we have been able to review the record, we realize we were off by a factor of 10 ! What's more, it's plain that we should do this more often because this is the first time it has been done here. Before this, nobody asked."

It also means that, too often, the progress and improvement needed for competitive advantage (for instance, over foreign contenders like Japan or Germany) cannot be made because it cannot be identified. To consider an appropriate metaphor, a navigator cannot be expected to stay on his intended course if he cannot obtain the necessary information - the ***difference*** between his actual heading and where he is supposed to be going.

If we are to avoid bankrupting the national treasury, it becomes necessary for cost analysts to assist engineering by searching for cost ***differences*** between types of design, and for both to emphasize cost ***reduction*** rather than ***justification*** .

AEROSPACE EXTRAVAGANCE

Wernher von Braun, besides being noted as a genius for getting the job done, had a well deserved reputation for wit. This story is told about his encounter with a budget-conscious congressman who was visiting a launch site where the latest space miracle was being prepared for flight. It glistened with heat-emitting gold plate.

Horrified at such evidence of extravagance, the congressman exclaimed, " Mr. von Braun, is it really necessary to gold plate these things?"

" Oh, yes," von Braun replied, "absolutely! If we made them out of solid gold, they would never get off the pad."

III - "SIMPLICATING" TO ADD LIGHTNESS

This title has been stolen from a motto coined by Bill Stout, the chief engineer on the Ford Trimotor project. His original version was the admonition, "Simplicate and Add Lightness". The following examples suggest the way to proceed, while cutting expense at the same time.

The guidelines which produce economical structure are also weight reducing. This is primarily because, in typical sheet metal construction, wherever load intensity increases - around the edge of a penetration or where a concentrated load is applied - reinforcement must be added, often in the form of machined fittings and doubler sheets to spread the load. Where separate members cross there is an overlap, and where there is an overlap there is extra weight. This discourages the practice of providing intersections for equipment support. The resulting reworks add more weight. Combining parts, therefore, benefits lightness as well as economy.

The typical intricacy of structure beneath a sheet metal skin is dramatically illustrated in Figure III-1, a skeletal line drawing of an F-15 fighter. At hundreds of locations two members cross. Where this occurs, one of the parts gains higher priority; the other is cut, its load transferred across and around with shear clips, doublers, or tension fittings. The penalty for restoration of original strength is cost (more parts) and weight (repair splices and eccentric load paths). Restoration of original stiffness entails even greater penalties. Both the situation and its efficiency-robbing cure are inevitable, repeatedly, in built-up sheet metal construction.

Laid-up threads of linear, oriented graphite or other composite reinforcement exacerbate the problem even more, adding the complexities of interlaminar shear, pseudo-isotropic orientations, and part-to-part load transfer to an even greater extent. Part accounting complications are also raised to unprecedented levels of "sophistication", drowning development and production in paper work.

When one black graphite piece looks almost exactly like the next one in a layup except that the fiber direction is rotated 90 degrees and they must be properly oriented to work together, identification can be a problem. Printing a yellow number and a directional arrow on each piece would seem proper, except that the adhesive holding the laminations together may not stick very well at the marking. To solve this problem by

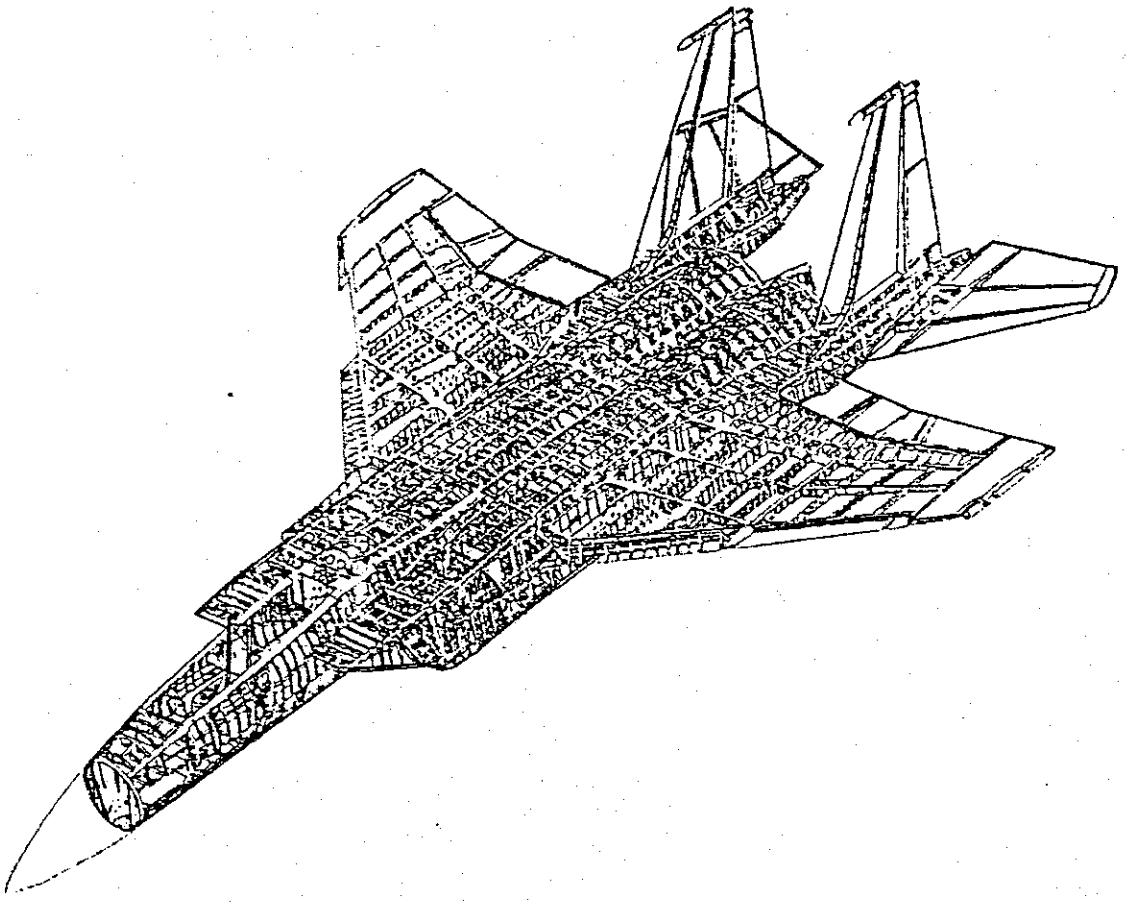


FIGURE III-1 - The intricacy of structure under the skin of the F-15 fighter is typical of sheet metal construction. Even though the wings are made from integrally stiffened plate, there are a lot of sheet metal shear webs, clips, and rib and spar cap material which are not incorporated into the outer shell.

temporarily attaching a removable adhesive label creates at least two new annoyances. The pressure-sensitive adhesive on the label can itself soil the bonding surface, or else the label can become detached before its time, confusing identification more than ever.

In integral construction with isotropic materials, such problems disappear. Co-planar stiffening elements are all part of the same piece, sharing the material at intersections. The size of the members and the thickness of the skin between them can also be tailored more precisely to changing local load intensity, something else which is not done easily in sheet metal or laminated composite construction and therefore

seldom attempted. For many of the same reasons, the efficient triangular stiffening system known as isogrid (because it is isotropic) is not found in sheet metal assemblies. A built-up intersection of three bars is a dauntingly difficult design and fabrication problem to encounter repeatedly - and hardly worthwhile with the splice penalties entailed. In integral construction, a node of this sort is simply the material remaining after adjacent pockets are milled out of a plate.

The Vickers "Wellington" bomber of World War II actually tried an open lattice construction of diagonal intersecting built-up curved sheet metal struts terminating at infrequently space longerons (or wing spars where it was applied to the construction of wings). This was the entire skinless structural frame, having been covered with a non-structural doped fabric fairing for drag reduction. Since the system was made from sheet metal with all the attendant splice difficulties, it was hard to build. To some extent this proved to be an advantage. Bits of it were contracted all over England in small shops, making it virtually impossible to put out of production by bombing. In addition, it could sustain drastic combat damage without coming apart. Because of its complexity, the construction was not adopted by any of the Vickers company's competitors and nobody seems to have noticed that the open frame arrangement was light, competitive with stressed skin construction in this respect.

One of the previously listed guidelines mentions that open internal structure anticipates access and intercommunication needs that must ultimately be satisfied. An example, showing how the practice can work to the advantage of the system, is the comparison of transport aircraft floor beams depicted in Figure III-2. The conventional design is a rectilinear arrangement featuring an obstructive shear web which has been penetrated for wires, control cables, and plumbing. It, of course, is the one in use. The open truss version can be machined from a single plate and offers so many natural opportunities for penetration that none need to be negotiatied or reinforced. For somewhat more than equivalent strength, the open design is about 13.5 per cent lighter, as demonstrated in this study. It is also stiffer, having no roundabout load paths like the reinforced edges of the oval cutouts. The shallow beams above and below them are not much help, either. It is clear that anyone wanting to route a wire harness or control cable should have little difficulty finding a hole when the the construction is about 90 per cent holes, 10 per cent or less, obstructions. Furthermore, the arrangement is torsionally stiff, resisting any tendency for a large span to roll under load. Less lateral midspan support is needed. Of course, the arrangement is also symmetrical in cross-section, having no off-center shear resistance to create the rolling problem in the first place.

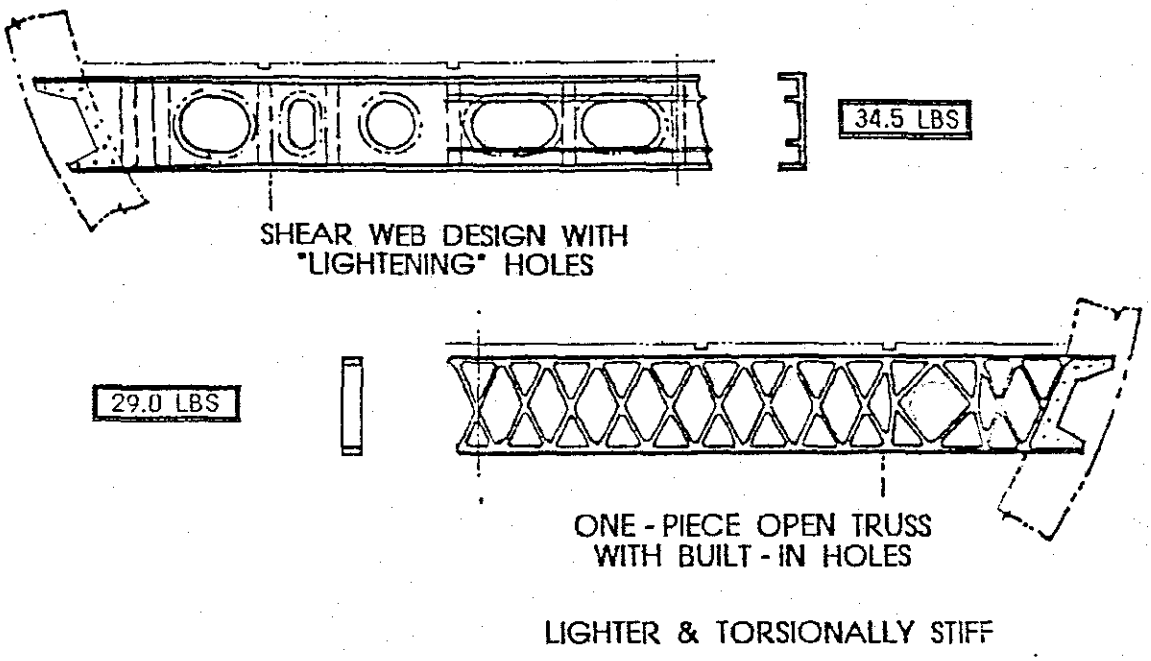


FIGURE III-2 - Comparison of a tension-field beam which has been chopped up to permit passage of sybsystem interconnections with an open truss construction inherently so full of holes that extra penetrations are not needed.

One of the more noticeable symptoms of "sheet-metal-itis" the built-up structure disease, is the habit of arranging structural elements in square patterns. It probably derives from the Cartesian coordinate system used to define points and shapes in space or describe vectors. Useful as this geometric system may be, it is still not necessary to locate structural elements where their positions are easily defined mathematically. They need to be located where they do the most good.

An example of the practice is a Shuttle-transported cradle for a classified military satellite (Figure III-3). The unclassified part is the cylindrical canister and a small boost stage at its open end. The satellite itself is inside the cylinder to protect its security - and inhibit its growth. The original canister design shown is conventional, ring frames and longerons. As sized for Shuttle launch loads. it weighs 3200 pounds. The inside diameter is 154 inches , the frame depth 10 inches.

Applying the integral construction philosophy to this problem by isotropically and integrally stiffening the shell and introducing loads into it tangentially, the result looks like the design in Figure III-4. The

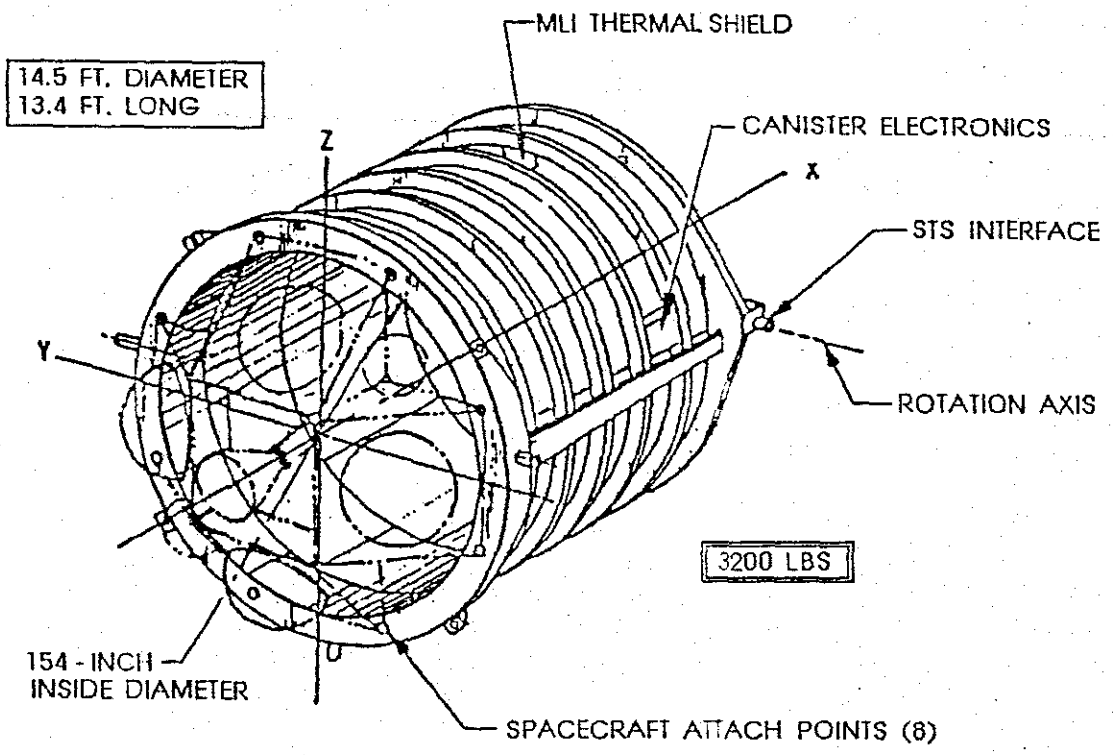


FIGURE III-3 - A satellite launch device in the form of a Shuttle-borne cradle. Typical ring-frame, longeron, and sheet metal skin design with elements arranged rectilinearly.

structural depth has shrunk from 10 inches to six-tenths of an inch, the frames having been eliminated entirely. The inside diameter has expanded to 160 inches, giving the satellite more rattle space. The weight has fallen to 1530 pounds while the stiffness has slightly ***increased*** (about 5 per cent).

There can be little doubt that part count is slashed in this design. Based on a derived estimate of unit cost equaling one-third (or less) of conventional practice, while weight is less than half, this version should cost about one-sixth as much. The "snowball" effect on production operations would also shrink its development and delivery schedule.

This canister design was created to convince a potential customer that the bidding contractor could indeed help him if he issued a contract for the cradle's development. However, it was never submitted for fear it might prove embarrassing. Presumably, the other design has since

been built.

Another phenomenon of sheet-metal design practice has been a constant effort to apply thinner and thinner material to save weight. Since the primary goal of structural design is to define stable shells which efficiently carry compressive load, this effort violates one of the paradoxical axioms of the art -- ***thin is heavy; thick is light.*** That is, a large cross-section or thick plate, by imparting column stability, allows compression structure to work at higher stress: when the material works at higher stress, less of it is needed. So it weighs less.

This kind of misdirection spurs the development of sandwich construction and honeycomb core. The honeycomb cells, by subdividing the sheet into very small patches, raise its compressive stability to the compressive yield stress of the material - unless it is de-bonded. The theory is fine but the construction has more than its share of difficulties: the hidden core-to-face bond is hard to inspect and unreachable for efficient repair when delaminated; the edge close-outs are relatively heavy. particularly around small openings; and concentrated loads exact heavy reinforcement penalties. Honeycomb

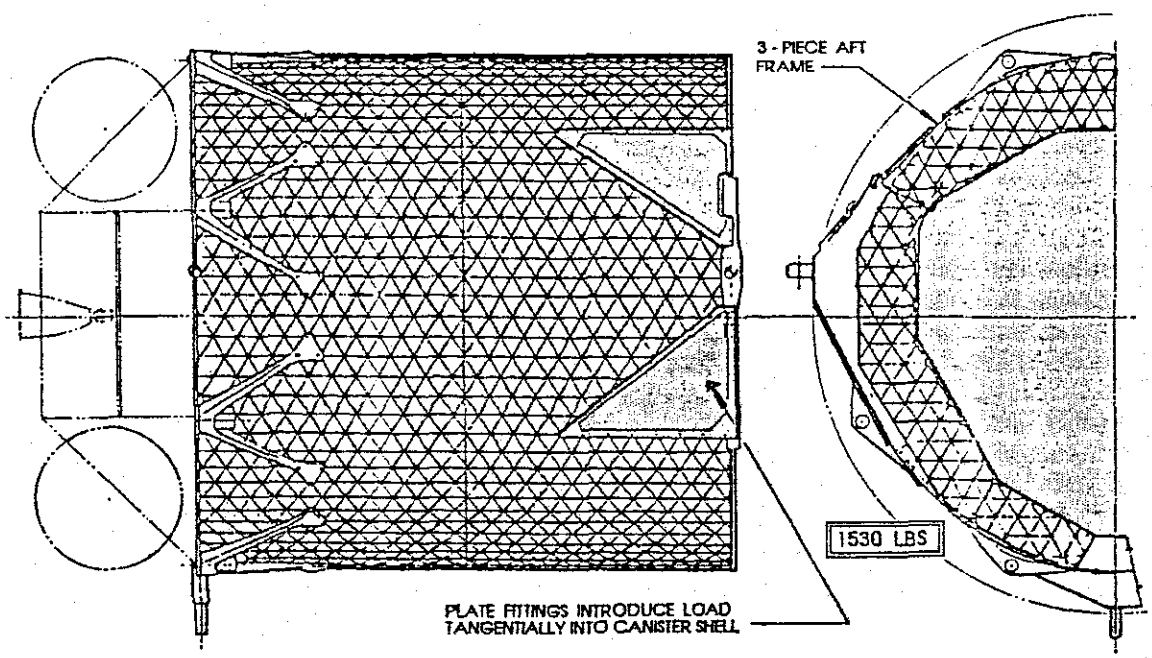


FIGURE III-4 - A proposed and analyzed alternative design with an integrally stiffened isogrid shell and tangential introduction of load. Weight is less than half as much while stiffness is about 5 per cent greater, demonstrating the value of efficient load paths.

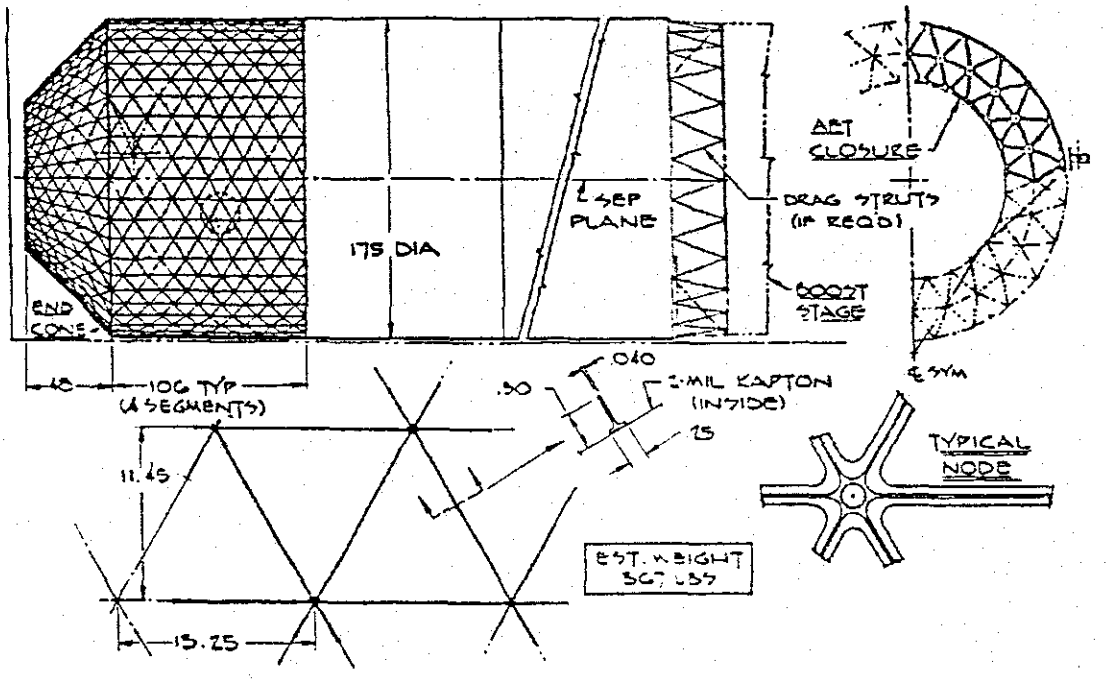


FIGURE III-5 - Integral open structure applied to a "minimum gage" problem, material gathered together into stable bars which frame weightless holes. This anti-contamination cover for a Shuttle payload, encasing the protected volume with a light kapton membrane, is light but surprisingly rugged. Only a small 3-foot by 4-foot sample was ever built.

sandwich is ideal structure when optimized for a completely uniform load over a large and perfectly constructed panel, a condition never known to occur on real vehicles. But it leads to convincing figures of merit and consequently inappropriate choices in "trade study" evaluations.

Particularly in the low-intensity "minimum gage" situations honeycomb is a poor choice. As the face sheets become thinner, the core cells must become smaller, the core denser. Two sheets are always required, doubling the irreducible minimum. Eventually, the parasitic weight of the core and adhesive exceeds that of the working faces.

In integral construction there is another approach to the "minimum gage" problem. This is to gather as much material as needed for the load into discrete intersecting bars, shaping the cross-section for column strength, and covering the large weightless holes between bars with a thin non-structural membrane. An example of this approach is shown in Figure III-5. This contamination cover for a Shuttle payload, 175 inches in diameter and 40 feet long, needs only to keep dust and dirt off a payload before launch and support nothing more than its own

weight. It is a half-inch deep sparse open isogrid frame with a bonded 2-mil Kapton film inner sheath. It is the ultimate producer of chips and drop-out slugs, retaining only 12 pounds of the 1000-pound blank required for each panel. While its complete weight is estimated at 367 pounds, the equivalent minimum gage graphite composite design has been estimated to weigh 825. It had previously been estimated that a shroud like this should weigh about 4000 pounds. No more than a small 3-foot by 4-foot sample of this structure was ever built, but the "feel" was quite convincing - in the absence of tests.

Figure III-6 illustrates another example of the advantage gained by efficient arrangement, irrespective of the material employed; that is, triangulating structure rather than arranging it in conventional squares and rectangles. Shown are two arrangements for speed brakes, aerodynamic speed control devices for combat airplanes. Typically, the

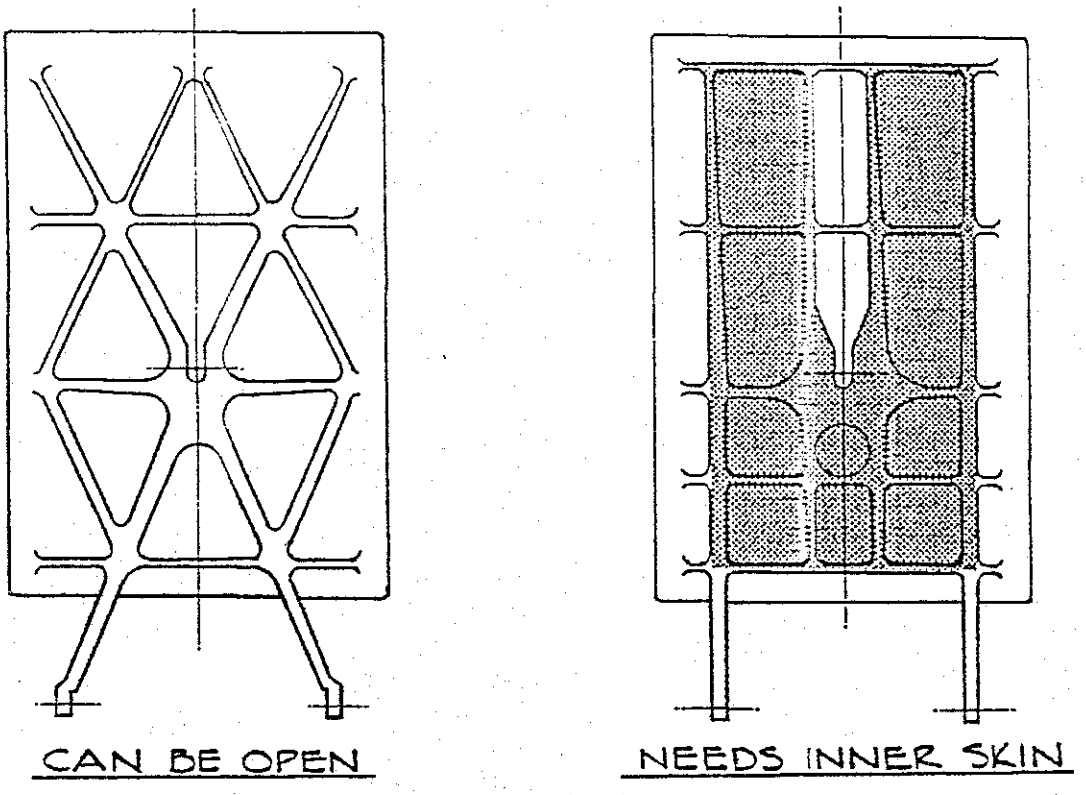


FIGURE III-6 - A comparison of rectilinear and triangulatec designs for a simplified aircraft speed brcke. Test comparison was made with small balsa wood and paper models.

layout for current aircraft, probably without exception, is that on the right, rectangular with an inner skin closing the torque box. Torsional stiffness is a necessary attribute of these structures since torsional flutter induced by buffeting flow can destroy them. Paper and balsa wood models were made of the two designs, both of the same dimensions, including depth. The closed box rectangular design weighed 6 grams, the other one, without an inner skin, 5.5. Twisting loads were applied to each at one edge, the same distance away from the clamped strut ends, as shown in Figure III-7. Deflection measurements showed that the triangular arrangement of arms and beams, while slightly lighter (5.5 grams versus 6.0 grams), was twice as stiff.

It is difficult to confirm the correctness of a "trade study" decision because the only study candidate eventually built is the "winner". The discriminators are numbers, not actual hardware. Consequently, there is little evidence around to prove it when a wrong choice has been

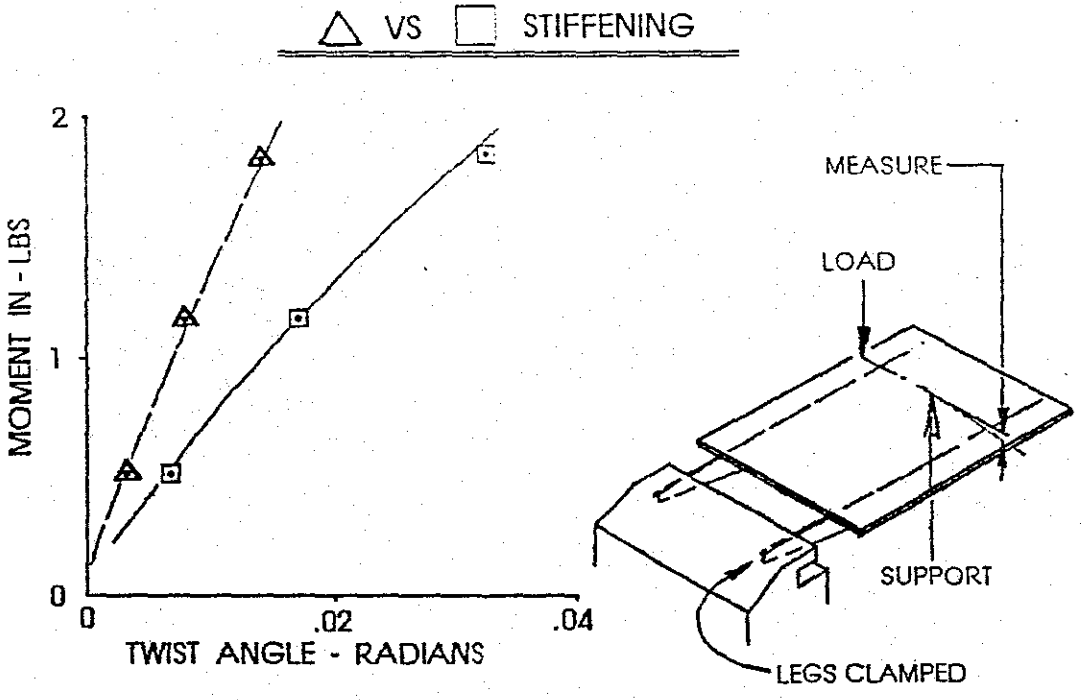


FIGURE III-7 - Results of the miniature model torsion test of competing speed brake designs. The triangular arrangement with no inner skin deflected half as much under the same load, yet was about 8 per cent lighter.

made. If nothing else, time should by now have proven that engineers, accustomed to justifiying foregone conclusions with plausible but fictitious numbers, have too often demonstrated an inability to make sound choices from the paper evidence. This is why an example like that shown in Figure III-8 is so valuable.

Pictured are three alternate designs of a bypass duct for a military jet engine. The first design (on top) is the standard chem-milled titanium unit with ten years of experience behind it. The second (middle) assembly is a graphite/polyimide composite design intended to save weight and moderately successful in doing so. The third specimen is the response of the production subcontractor to the experimental test article. It is essentially identical to the first design except that the material has been more efficiently arranged, allowing the same chem-milling process to remove another ten pounds of titanium. With this small a difference, the first and third units can be expected to cost about the same (200 hours worth at the 250th unit, according to the maker, Chemtronics, Inc.).

At the same production quantity, the estimated cost for the composite design is 550 hours, to give it the benefit of the doubt. The doubt, in this case, arises because the ***first*** composite production unit had yet to be built a year and a half after the test article. Considering the negative benefit to be gained, it hardly seems worth pursuing.

With its length of peripheral bolting flanges and the large number of support fittings and penetration reinforcements, complete with splice penalties, this duct design must be considered a poor application for laid-up graphite construction. It shares this distinction with too many other laid-up composite structures. The unidirectional nature of graphite tows and tapes and the consequently awkward load redistribution around interruptions largely accounts for the failure of composite structures to capitalize on the really remarkable properties of graphite - low density being the most significant. Too much emphasis is placed on the direction of strength, too little on the disadvantage of a transverse direction of weakness. In fact, a direction of strength ***implies*** a direction of weakness. Thus, the pseudo-isotropic layups realize about 30 per cent of theoretical capability. Worst of all, the oriented fibers are not suitable for making fittings, the most significant item incorporated into integral structures.

Designers of the Learfan turboprop business airplane, an all-composite design venture, reported that the commitment was worth it for the wing but that the fuselage showed no gain in comparison with more conventional aluminum designs. Much the same thing was reported about the Beech Starship, except in a more indirect way. It

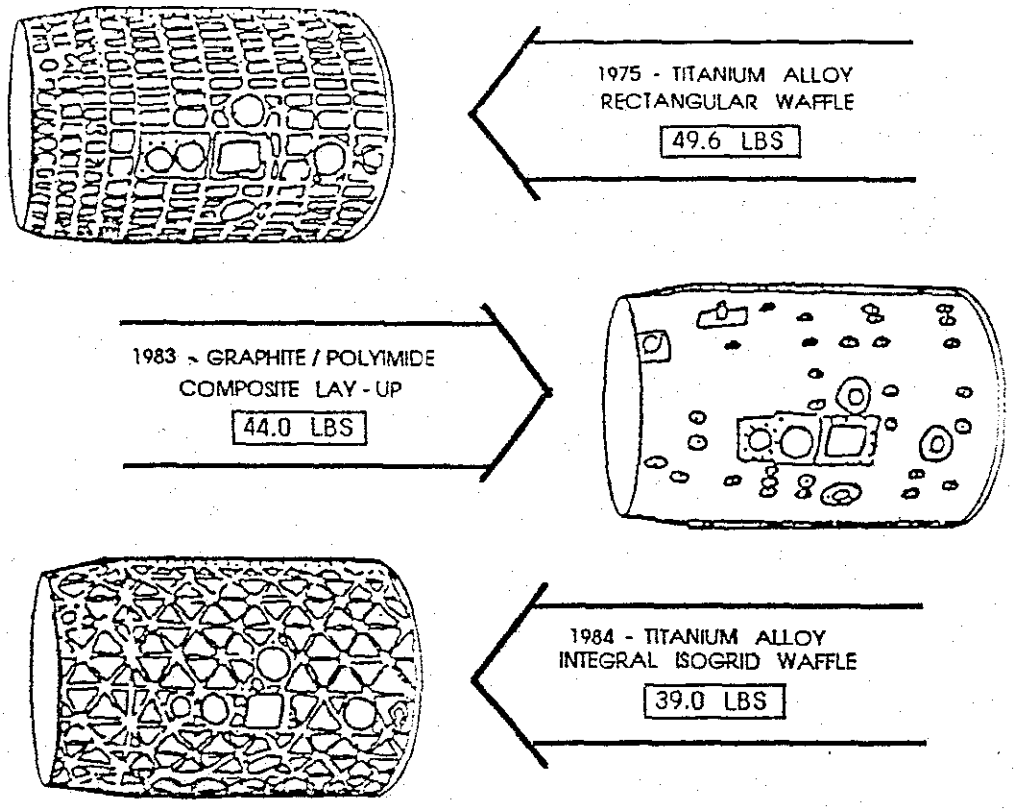


FIGURE III-8 - A comparison of jet engine bypass duct designs with titanium and graphite/polyimide composite materials, showing the advantage of properly arranged integral construction even when material properties, particularly density, are not favorable. Two units were actually built and tested - the third was extrapolated from an almost identical design built for a competing engine builder.

seems to have a useful load about 500 pounds less than that of the more conventional Piaggio Avanti, a similarly unconventional overall configuration. The information is sketchy, but it can be surmised that laid-up composite construction suffers unusually heavy penalties for the installation of equipment. If it can't efficiently accommodate this primary function, it should not be considered an appropriate construction choice.

As indicated earlier, the metallic structure which costs least and weighs least is that made of the fewest parts, and one which inherently contains provisions for support of and access to other subsystems. This

means that integrally stiffened structure made from machined panels is essentially ***all*** fittings. The drawback, then, of composite structure consisting of woven or glued unidirectional strands is that the raw product itself makes the attainment of integral design impossible. Such designs contain all the adverse qualities of sheet metal construction to an even greater degree, since the minimum equivalent of a single metal sheet is a multi-layer pseudo-isotropic layup of at least 3 plies - in most cases, 5.

To reiterate, the main contributor to low cost in structure, ***low part count***, is also effective for reducing structural weight. Economical structure can be light at the same time, but careful attention must be given to its arrangement. In addition, the role of structure as a physical integrator of all the other subsystems must never be forgotten because any estimate which overlooks this consideration is fictitious.

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PROPER IDENTIFICATION

One day, during World War II, a young lady riveter who worked for the Douglas Company was stopped by the security guard at the gate as she tried to enter. "Where's your badge?" he asked.

So she showed him. It was pinned to the back of her not-so- slack slacks.

"That's not where it belongs," he said. "You know the company rule: Badge is to be worn on outer garment in plain sight."

"Sure, I know," she replied, "and that should be in plain enough sight. It's where you always look!"

IV - MODULARITY FOR SPACE TRANSPORTATION SYSTEMS

The word "module" conveys the impression of organization. Its derivative, "modularity", is a fashionable cliche' which has even been misidentified as a technology. Actually, as a philosophy of design, it can be applied to any system at any level of technology if the application is recognized or requested. Effective standardization of modules reduces uneconomical proliferation of parts.

What modular standardization does is break a system down into separate removable and interchangeable elements or assemblies which can be individually sized or modified to permit revision, repair, replacement, technological updating, or substitution to enhance system growth. Sensibly designed, it can also allow shrinkage - growth in reverse. Its success demands careful definition of interfaces, thought out with enough foresight to assure continued usefulness. Since fit and structural continuity are implicit in any such arrangement, ***the philosophy might as well start with the structural design.*** Failure to do so can be expected to entail weight penalties which discourage the practice.

If a cost-effective and competitive modular system can be developed, it should provide at least the following results:

- A general system which can be tailored to specific missions
- A system which can grow - and shrink (growth in both directions)
- Incremental and economical introduction of new technology
- Shortened turnaround time with parallel processing
- Simplification and organization of spares provisioning
- Incremental, economical procurement.

In the ***System Engineering Management Guide***, a text used in the Defense Systems Management College at Fort Belvoir, Virginia, a management philosophy of Pre-Planned Product Improvement (P^3I) is mentioned as a goal of future defense systems acquisition. It is suggested that modular design may offer a way to achieve its objectives of system cost reduction, risk avoidance, delay of obsolescence, high life cycle performance, and operational readiness.

Since no other alternative was mentioned, this must be considered an endorsement of the modular philosophy. However, it was also mentioned that it ***must be a part of the acquisition strategy*** ; if the proposal request doesn't ask for it, bidders, adhering to the rule of strict responsiveness, will not be likely to offer it. In any case, they don't very often seem to think of it.

An unspecific collection of platitudes might describe modularity in a general sense without conveying much meaning. Specific examples are much better and are cited here to define the practice. In any case, for most aerospace operational hardware ***it needs to start with the structure,*** as will be demonstrated.

Common Modular Systems

One of the commonest examples of modularity in commercial products is the 35 mm camera. Starting with the film cartridge itself, the entire photo industry accepts standard dimensions and operational interfaces. After that, each manufacturer's standards, especially the mounts for interchangeable lenses, are consistent only with its own product line. Still, the makers of accessories have managed to standardize the accessory bracket on top of the camera and the tripod socket. Large, expandable systems, built around camera bodies of varying sophistication, involve lenses, bellows, extension tubes, filters, copy stands, motor drives, and flash equipment.

Personal computers, similarly based on central processors, offer many options in displays, keyboards, disks and disk drives, printers, and other peripherals, including networking links. The connections between units are more electrical than physical, though the peripheral ports themselves must conform geometrically. The lack of physical linkage, in fact, has created a market in computer furniture to organize the sprawl.

Audio and video equipment is in many cases similarly modular, offering expandable systems of tuners, amplifiers, tape decks, monitors, speakers, recorders and record players, and so on.

In the transportation field, the most outstanding example is provided by the continent-spanning rail system, where cars of varying size and function as well as the engines that haul them all fit a standard spacing between the rails they run on. They also feature interchangeable couplings which make mechanical and electrical connections simultaneously. A more recent extension of the system

involves standard shipping containers for which provisions are made on trucks and sea-going vessels as well. The pre-packaged load moves from truck to train to ship, allowing the transportation methods to continue operating without standing idle while individual items are unpacked and re-packed.

The popularity and effectiveness of these systems mainly derives from their ***adaptability to the dissimilar demands of their users.*** The same can be expected to apply in aerospace - if it is ever tried.

A Modular Booster for Minimum Development Cost

This description illustrates a modular approach to the design of a low cost expendable launch system. Capable of placing into low earth orbit a payload weighing as much as 200,000 pounds and as large as 50 feet in diameter in its maximum configuration (Figure IV-1), this system is built around a single standard module 200 inches in diameter (Figure IV-2).

The maximum 7-module cluster, 6 around a single-unit core, sidesteps an uncomfortable situation: a heavy-lift vehicle with no way to shrink. A conventional system of such dimensions and weight would be oversized for most applications and very uneconomical to develop for limited use. The Saturn boost system found very little application after Apollo.

The standard module for this variable system would be a very useful first stage for a low-end launcher designed to orbit payloads with masses up to around 30,000 pounds and dimensions consistent with the Space Shuttle payload bay. In this minimum application, the 100-foot high assembly would be stacked below a second stage something like that shown in Figure IV-3. In a pinch, all other Shuttle space being booked, a system at the low end of the launch spectrum like this should suffice. For a non-return mission, it might be preferred because it should cost less.

Other cluster arrangements could be assembled to handle a range of lift capabilities between the limits described. They would call for new second stage designs in most cases. Shortened basic modules with smaller engines might also work, retaining standard features to a greater extent.

The selected basic module diameter of 200 inches is related both to the maximum payload diameter mentioned and the size of

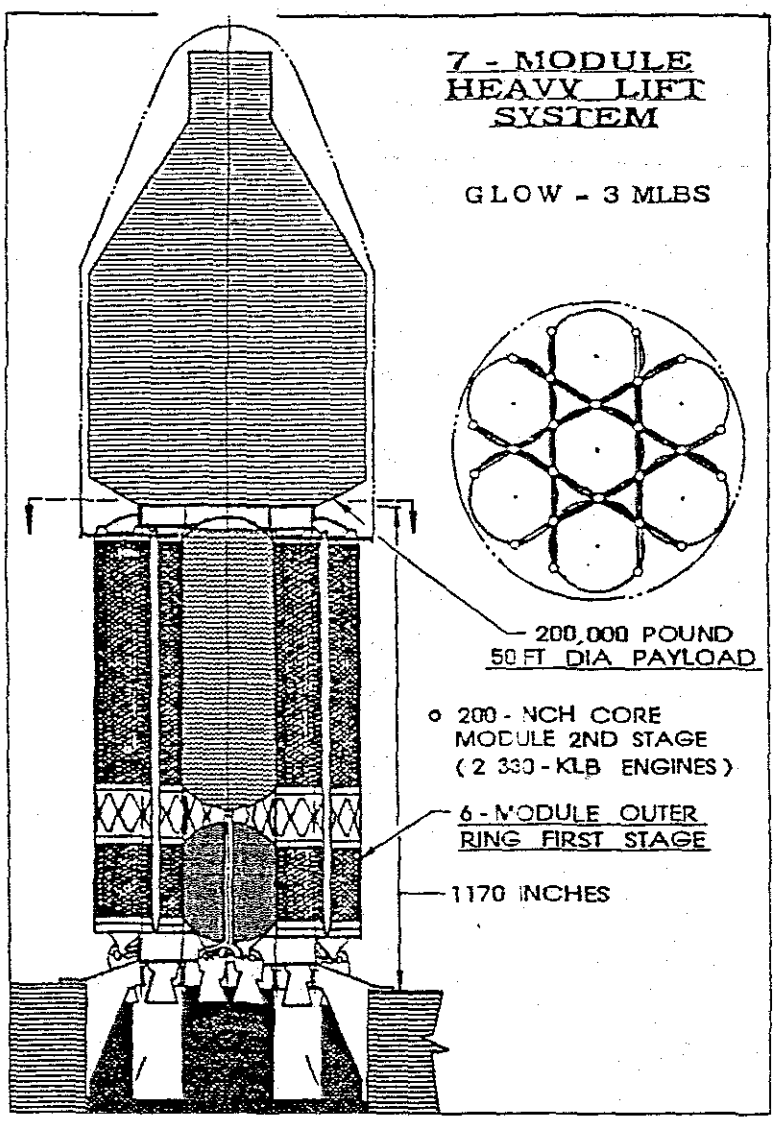


FIGURE IV-1 - A seven-module expendable booster for putting 200,000 pounds of payload into low earth orbit. The six elements in the outer ring form the first stage. After they are ejected, the identical center module becomes the second stage.

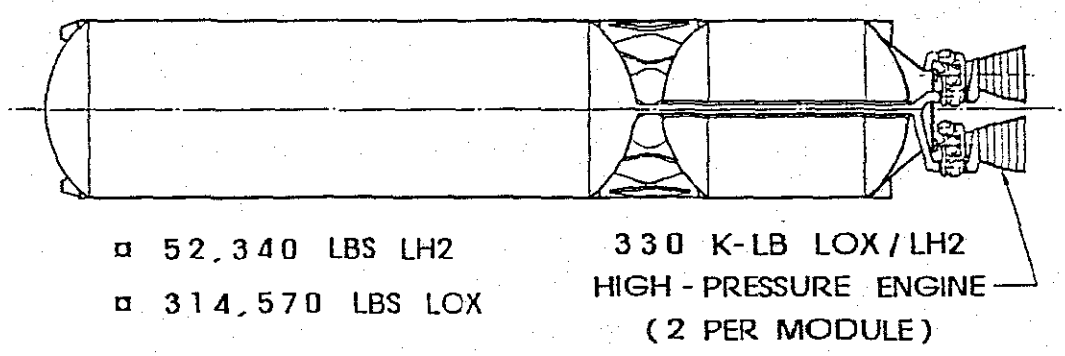


FIGURE IV-2 - The basic launch module, 200 inches in diameter to accommodate payloads intended for Shuttle. It, with a smaller upper stage, can become a launch system for delivery of 30,000 pounds into low earth orbit.

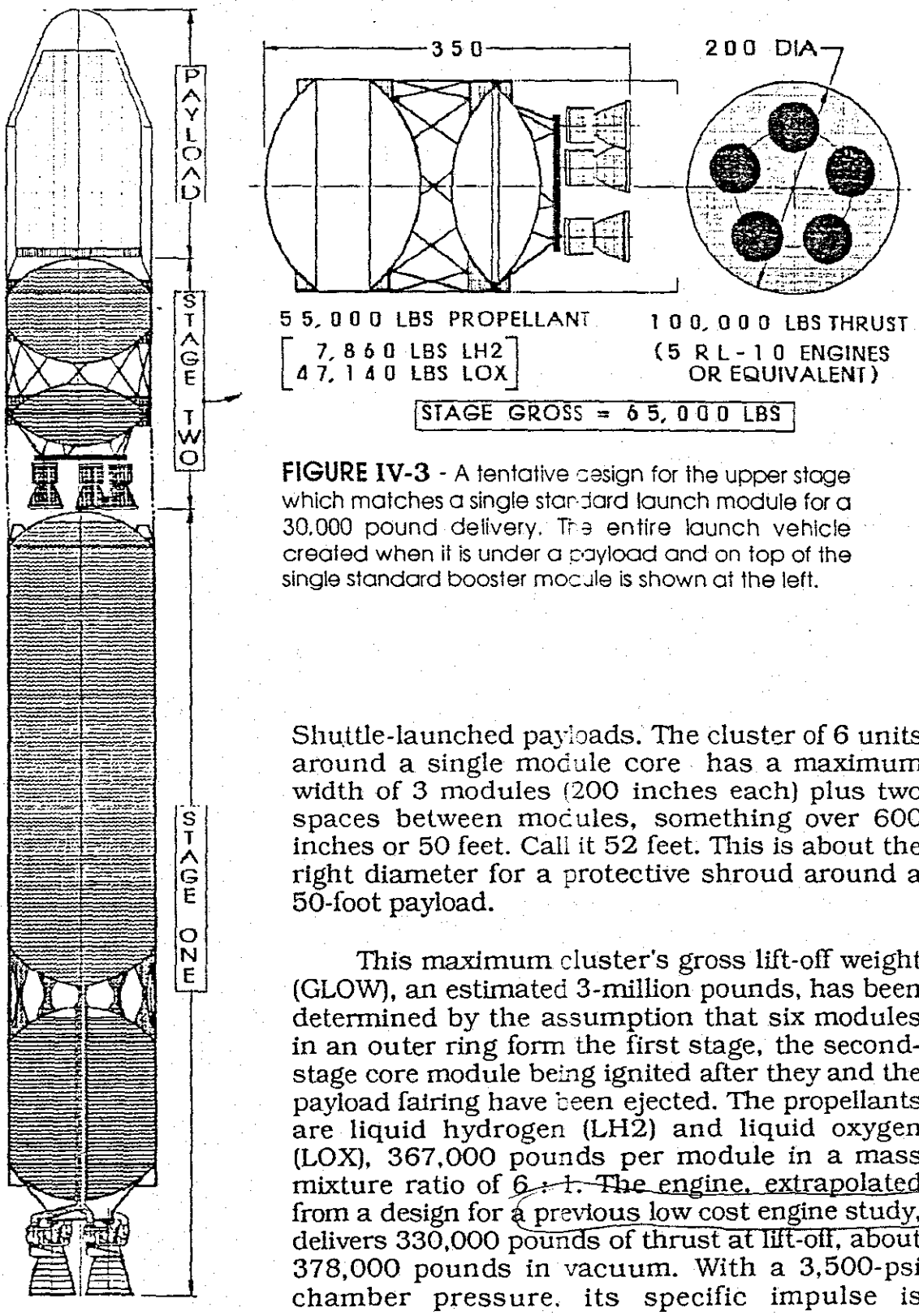


FIGURE IV-3 - A tentative design for the upper stage which matches a single standard launch module for a 30,000 pound delivery. The entire launch vehicle created when it is under a payload and on top of the single standard booster module is shown at the left.

Shuttle-launched payloads. The cluster of 6 units around a single module core has a maximum width of 3 modules (200 inches each) plus two spaces between modules, something over 600 inches or 50 feet. Call it 52 feet. This is about the right diameter for a protective shroud around a 50-foot payload.

This maximum cluster's gross lift-off weight (GLOW), an estimated 3-million pounds, has been determined by the assumption that six modules in an outer ring form the first stage, the second-stage core module being ignited after they and the payload fairing have been ejected. The propellants are liquid hydrogen (LH2) and liquid oxygen (LOX), 367,000 pounds per module in a mass mixture ratio of 6 : 1. The engine, extrapolated from a design for a previous low cost engine study, delivers 330,000 pounds of thrust at lift-off, about 378,000 pounds in vacuum. With a 3,500-psi chamber pressure, its specific impulse is

estimated at 460 sec in vacuum. Two per module provide needed redundancy.

To minimize development cost, all the modules in a cluster have been considered basically identical - the same propellants for first and second stages, the same propellant capacity in each module, and the same engine in all cases. The interconnecting structure for different module arrangements, meeting different energy and lifting capacity requirements, will necessarily be different and will affect a module's skirt structures.

The 7-module maximum configuration is the basis for preliminary sizing of the system, but by no means the only possible combination. Single modules or other arrangements of 2,3, or up to 5 units, some with undefined second stages, are also possibilities. Adjustments in propellant capacity to go with such combinations can be achieved with off-loading or changes in tank volume from insertion or extraction of plugs in the cylindrical sections of the tanks. Since this latter tactic changes the height of the stack, it should be applied with caution. Its effect on the ground launch facilities suggests that they should also be designed with built-in stretch or shrinkage, or at least movable work platforms. Different engines, designed to fit a standard mounting geometry, may also be considered, though the changes in this case are not as simple or economical as those involving the structural system. They are, however, logical growth steps for extending the viable technological life of the system. Eventual development of a recoverable engine pod should also be considered - or even total recovery of the entire booster.

While the proposed system is intended to handle a large range of anticipated future space transportation needs, it is not seen as a resurrection of the "big dumb booster" idea so popular about ten years ago. It needs to be a "big smart booster" to attain some of the economic advantages of efficiency. The propulsion system design, in particular, must therefore consider such refinements as throttling and restart.

The system's unmodulated acceleration at first stage burnout is close to 8 g's, probably an unacceptable condition for upper stages and payloads, which suggests that some degree of throttling, modulated or in steps, is desirable even at the risk of increased engine development cost. Shutting two engine pairs off and restarting them after the other first stage engines have burned out may be a lower cost alternative, though it entails the risk of restart failure, and also means providing restart capability, perhaps not initially

available in a low-budget program. Discarding modules in balanced pairs on ascent is a tactic which should also be considered as a means of increasing payload.

Ideally, all 14 engines, including the pair in the second stage, should be running and quickly checked out before the system leaves the launch pad. This adds further complications, like deep throttling of the core engines soon after lift-off. On the other hand, these engines would normally start up after first stage ejection in the usual and accepted multi-stage tandem configuration, so waiting to start up after staging would not be a departure from established practice.

It is also possible to consider a cross-feed operational mode which, emptying three tanks by burning and cross-feeding their contents, allows them to be ejected early. This would make the cluster a 3-stage system. The resulting performance gain should allow some reduction in total system size. This more complex mode of operation could, in fact, be an eventual up-grade modification to improve performance as the system matures.

If each module contained a single engine, the consequence of an engine failure would be loss of the mission if the fuel in that module's tanks cannot be cross-fed to units still functioning. Cross-feed also permits all the engines to be ignited at lift-off, trading the risk of complications in valve and interconnecting components for the security of assured ignition before the start of a launch. However, for operational simplicity, a dual-engine propulsion system in each module is recommended for a starting arrangement. This launch system, like all modular systems, does not have to start out equipped with all the "bells and whistles". They can wait.

Since cost feedback has shown the least costly parts of structure to be those which are integrally machined from large pieces and that the effect of subsystem installations has been to increase cost by forcing changes, the construction philosophy in this design is to make every subassembly of the largest possible parts with built-in initiation of component mounting provisions, the latter to accommodate unforeseen installations by anticipation.

Starting with the propellant tanks, the cylindrical portions are integrally stiffened isogrid with no frames. If they are to be insulated with spray-on foam like the Shuttle external tank, the stiffening can be on the outside. All attachments to this shell, inside or outside, must be made at nodal intersections of the stiffening pattern since so many opportunities have been provided and shouldn't be wasted. Each cylinder end joins to a single-piece (if possible) "Y" ring with

flanges for welding to the end domes and mechanically attaching to skirts and intertank panels. They would be made from the largest obtainable rolled aluminum alloy ring blanks. A 200-inch size is stretching available capacity a bit but well worth the cost of development. At both ends, these "Y" rings extend away from the main tank structure to include enough skirt for reinforcement at the inter-module cluster beam structure.

The end domes are spherical segments rather than the usually seen ellipsoidal shape. This serves to open up the angle at the dome-to-skirt intersection and stiffen this area enough to eliminate frames. The spherical shape, with its uniform curvature all over, allows all penetrations to be circular and of identical form, whether centered or not. While this arrangement is likely to show a theoretical weight penalty as a pressure vessel, the elimination of frames and other simplifications are expected to save weight as well as cost. The geometry, if not the type of construction, has a precedent; it is the same as that of the widely used Delta booster.

The intertank structure, incorporating 12 built-in access openings, is made of 12 identical panels, the filled X-shaped structures between the holes. They are intended to be single-piece members sculptured from blanks 110 inches long, 54 inches wide, and 6 inches deep, weighing about 3600 pounds at the start but ending with a part weighing less than 200 pounds. If demand later increases production quantity enough, the starting blank can become a very large press forging to minimize machining time and reduce the chip disposal problem. To the maximum extent possible, the subsystem components in each module will be installed on the inside of panels covering the rhombic access holes, forming easily accessible, removable, and replaceable module-doors.

Components directly related to engine functions are expected to be mounted on the conical thrust structure which is an open isogrid lattice (no skin) made of no more than two or three parts.

The basic construction material for all of the elements is expected to be aluminum alloy, weldable where the tanks are involved (2219, probably), but whatever alloy offers the best efficiency at lowest cost elsewhere.

A modular cluster launcher spectrum of this kind should be interesting enough to pursue in greater depth. It is in some ways not unlike the eight-tank cluster in the Saturn I, except that, in that case, the individual tanks were not separable, along with the engines they fed, for rearrangement in other combinations. It is doubtful that weight was saved or cost reduced by doing it that way, but quite obviously nobody considered a variable system at the time. At any rate, if the idea of modularity and the adaptability that goes with it are to be preserved, a firm hand must guide such a project to make sure that the options remain open - and the sub-elements readily separable.

A Shuttle-optimized Upper Stage System

This system has been devised to explore the possibility that Shuttle-launched missions conducted beyond the Space Shuttle's parking orbit (that is, just about all of them) might be better served by a single adaptable and variable system of modules than by a set of single-purpose, unadaptable and very expensive procurements - like IUS, Centaur, OMV, and projected high energy OTV's. The one invariable quantity in the problem is the Space Shuttle Orbiter and its payload bay, for which the physical measurements and environmental parameters have been quite completely defined. This system, shown in one of its upper range forms in Figure IV-4, starts with a flat-faced payload-supporting and equipment-carrying platform. Its aft face supports a ring of three pairs of cylindrical tanks of variable length whose aft ends are additionally supported during launch by a tilt-up cradle, withdrawing from this support at separation. The gap, of variable length like the tanks, is bridged with a core structure, also of consistently variable length but with standard interfaces at both ends. A standard main engine interface at the separation plane is designed to accommodate engine packages variably tailored to system size - up to a maximum diameter of about 60 inches and extending to, or slightly beyond, the aft face of the cradle structure.

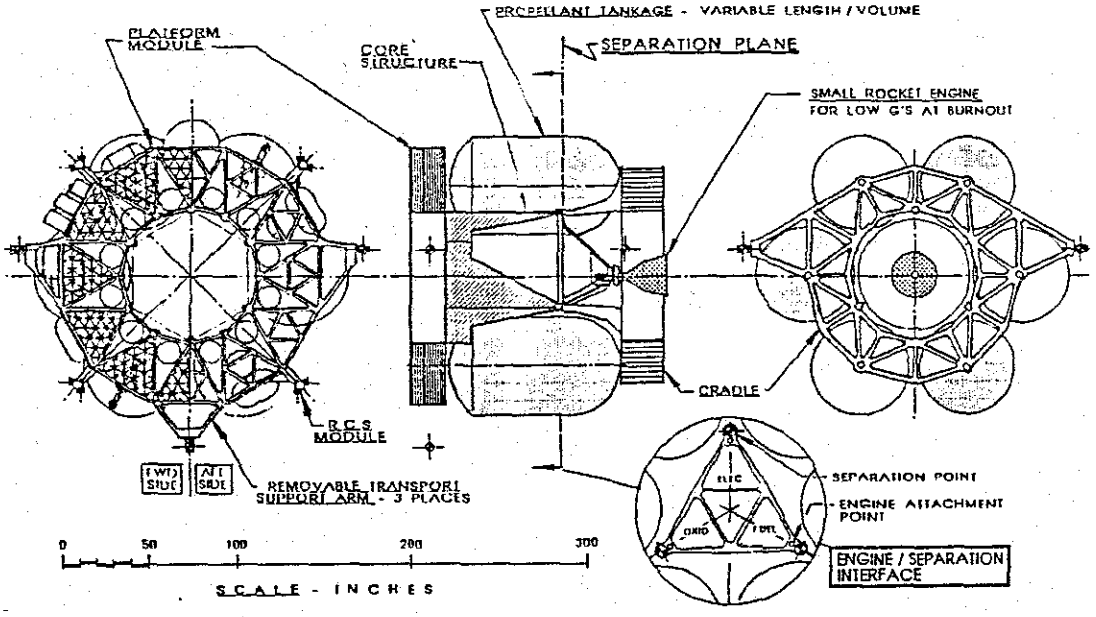


FIGURE IV-4 - A standardized upper stage design for the Space Shuttle, variable in mass and length to accommodate a range of payloads - from about 2500 pounds to 12,000 pounds raised to geosynchronous equatorial orbit (GEO).

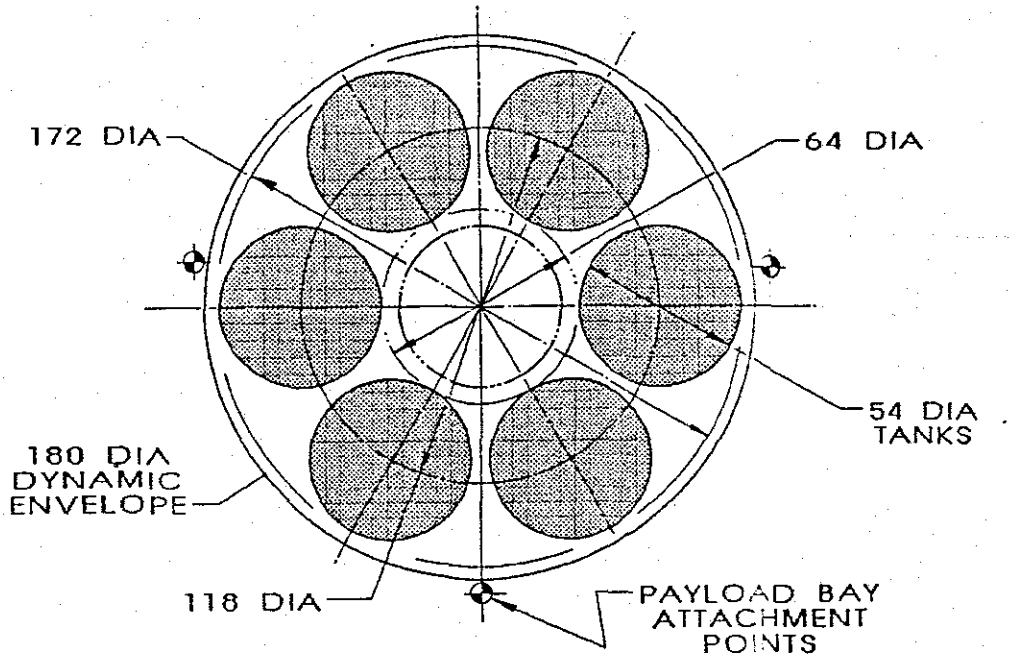


FIGURE IV-5 - Cross-section of the tanks for the standardized stage, showing how six, with room for a center core of the same size, fit comfortably within the Shuttle's 180-inch payload dynamic envelope.

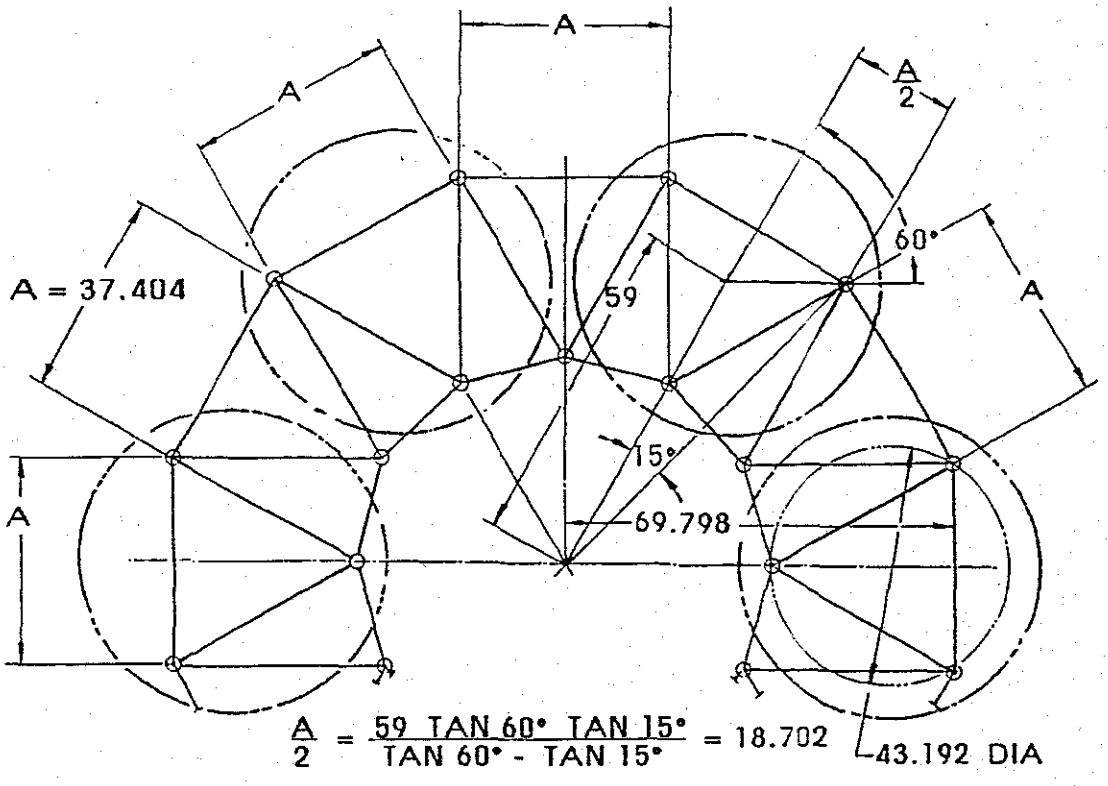


FIGURE IV-6 - The basic geometry of platform beams for the stage structural platform. Three intersections are centered over each of the six tanks.

The tank cluster is sized, as shown in Figure IV-5, to fit comfortably within the payload bay dynamic envelope 180 inches in diameter. The tank diameter consistent with this arrangement is 54 inches. Figure IV-6 shows a platform beam arrangement which offers 3 points of support at beam intersections for each of the 6 tanks. The polygonal edges between tanks, along with identical ones in line with the tanks, form a regular dodecagon, thus providing identical geometry for equipment modules in the accessibly open platform perimeter (Figure IV-7). Figure IV-8 illustrates a module fitted to this geometry, in this case a reaction control system (RCS) module. It is an element which is typical for any upper stage or satellite, and can be standardized to cover the entire range of stage sizes possible with this modular system. Size of thrusters and tankage volume can be tailored for specific applications. That is, different RCS modules, all fitting the same installation envelope, can be substituted for each other as required for specific missions.

Vehicles which can be made from this system are of varying mass and total impulse, structural adaptation being accomplished by making all the elements of standardized geometry but of different weight. That is, the elements, machined from aluminum alloy plate, are sized to the loads

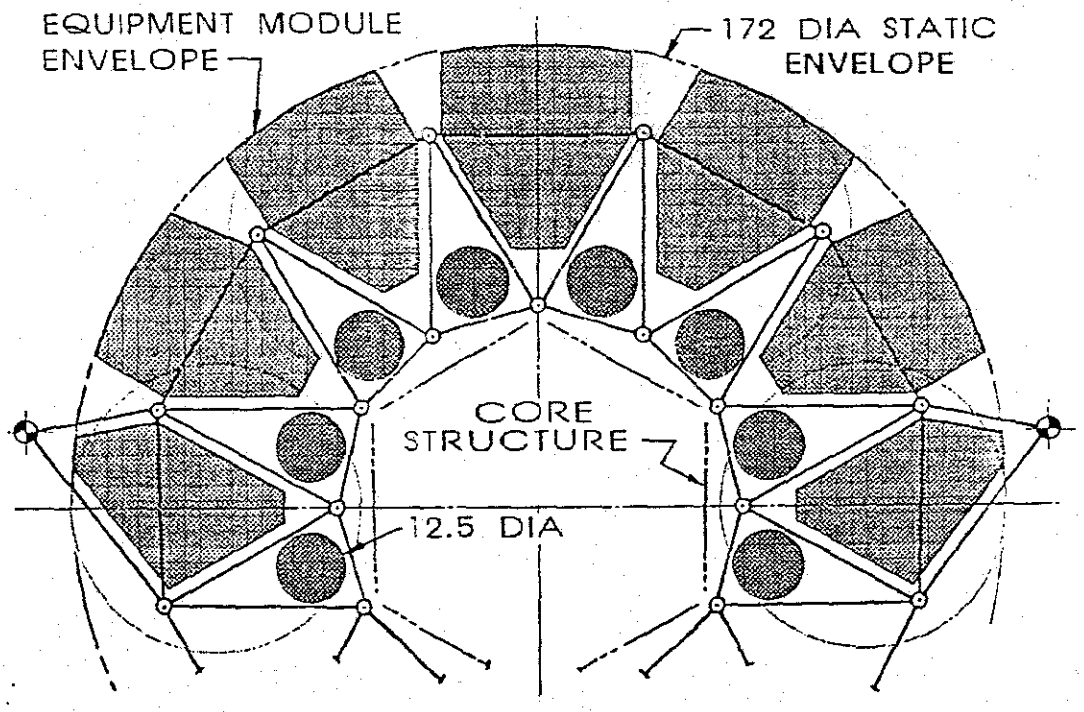


FIGURE IV-7 - Subsystem accommodations between the faces of the stage platform. Plug-in units can be inserted from the outside because none of the cells is closed. The small wedges are open from front to back.

by differences in the amount of metal removed. The attach points and intersections are all in the same locations but the bars between vary in cross-section (though always the same depth, being made from constant thickness plates). The range of vehicles made possible by this variable arrangement and selection of modules is considerable:

- Storable bi-propellant OTV's (Orbital Transfer Vehicles) of a range of sizes
- OMV (Orbital Maneuvering Vehicle, an intended separate, individual procurement but cancelled before it flew)
- Standard satellites with integral propulsion
- Modular tanker resupply system (variable size)
- Space-based cryo OTV (with space assembled aerobrake)

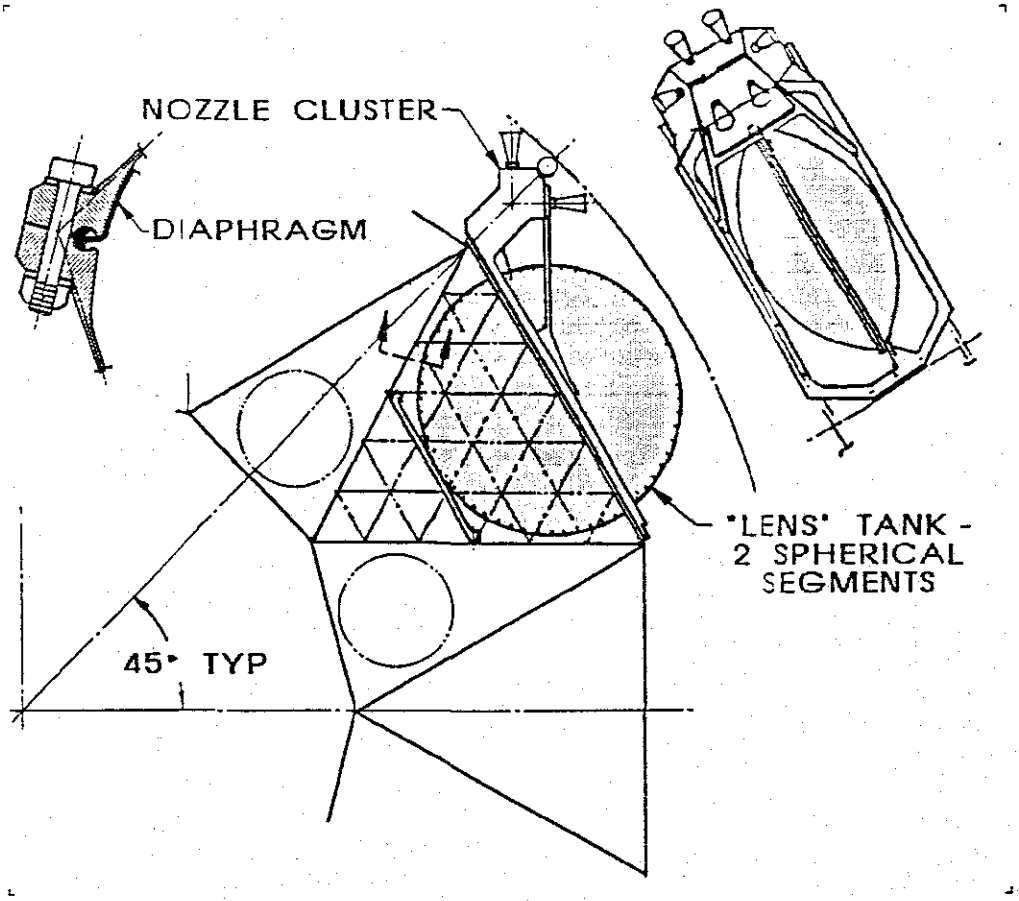


FIGURE IV-8 - An example of a plug-in module, a reaction control unit consisting of nozzles and a supply tank. Typically, four such modules would be supplied for a specific configuration.

- Space assembled OTV (too big for one Shuttle load)

Figure IV-9 compares an arbitrarily sized group of three standard upper stages, each containing 1.5 times as much propellant as the smaller one preceding it, starting with 20,000 pounds capacity of MMH (mono-methyl hydrazine) and NTO (nitrogen tetroxide) in the equal-volume mixture ratio of 1 to 1.64. The overall length of each, expressed as a percentage of the Orbiter payload bay length, is that percentage which corresponds to the overall weight percentage of Orbiter advertized lift capacity (65,000 pounds). The remaining volume available for payload in all cases can be filled with equipment at a density of about 1.5 pounds per cubic foot - in some cases, slightly less.

Table IV-1 is a compilation of the capabilities of the three configurations for payloads delivered to GEO (geosynchronous equatorial orbit). The differences shown depend on whether the propellant tanks are staged (ejected when their contents are depleted, as is possible with this design), integrated with the mission-peculiar equipment on the forward face to make a satellite with integral propulsion, or simply used as an expendable boost upper stage without integration or staging. "Discretionary" payload, in this context, means mission-peculiar equipment mounted on the forward face and separable from it as is typical for most satellites today. This indicates clearly the considerable benefit to be derived from simple expedients like tank staging and satellite integration with the propulsive unit's frame.

The crude and somewhat fanciful sketch in Figure IV-10 conveys some hint of the possible kinds of vehicle that can be produced by blending mission-peculiar equipment with the upper stage to make an integrated satellite. As depicted, the fragile appendages are deployed ***before*** departure from the Orbiter to make sure that everything is working. This kind of operation dictates a ***low thrust*** engine.

If, with considerable modification, the aft tank cluster can be converted to carry liquid oxygen while an appropriately large liquid hydrogen tank is added up forward, the cryogenic OTV shown in Figure IV-11 results. This change, major in scope, but retaining the basic platform geometry, permits expansion into a whole new series of very high energy upper stages without major redesign of the structural system or starting all over in the usual fashion. Aerobrakes (not shown) would be space-assembled accessories. The oxygen tanks are still removable, ejectable if necessary, and replaceable with new ones as long as the interface works properly.

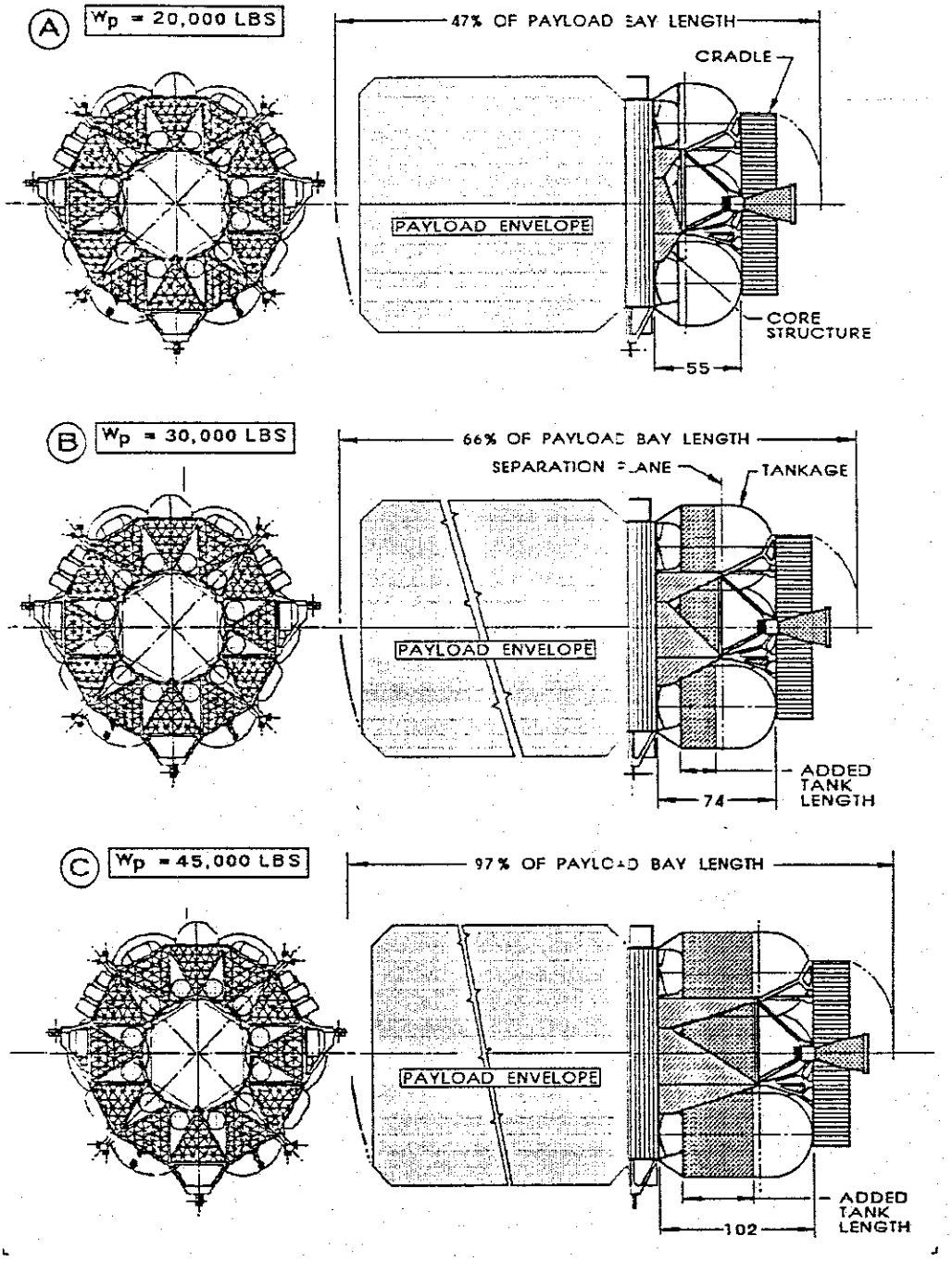


FIGURE IV-9 - An arbitrary set of three standardizec stages built around the same theme, ranging in propellant capacity from 20,000 pounds to 45,000 pounds. Each unit is 1.5 times as large as the one preceding it.

Table IV - 1
Delivery System Payload Growth

	A	B	C
Propellant Mass - lbs	20,000	30,000	45,000
Payloads - lbs			
Unstaged Discretionary	2,900	5,300	8,800
Unstaged Effective	4,300	6,900	10,600
Staged Discretionary	3,700	6,400	10,300
Staged Effective	5,100	8,000	12,100
Payload Improvement - lbs (%)			
From Staging (of tanks)	800 (28)	1,100 (21)	1,500 (17)
From Integr w/Satellite	1,400 (48)	1,600 (30)	1,800 (20)
Gross Weights - lbs			
Unstaged	29,500	41,600	61,500
Staged (larger payload)	30,300	42,700	63,300

Assumptions:

ΔV to GEO = 14,300 feet/sec
Specific Impulse (Isp) = 320 lbf-sec/lbm
Orbiter Payload Capacity = 65,000 lbs

Heading in the other direction, stripping the system down to the

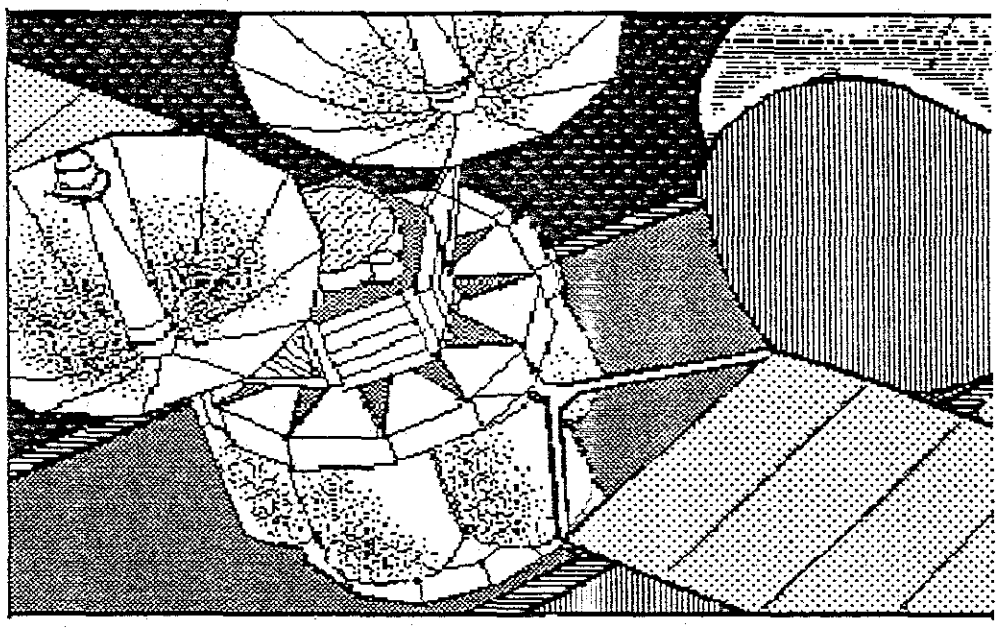


FIGURE IV-10 - A sketch of a hypothetical satellite built on the standard platform, its appendages extended before departure from the Space Shuttle. Low thrust in the stage engine is required for this type of operation.

equipment module with modified, flattened tanks on its rear face, the OMV (Orbital Maneuvering Vehicle, also known previously as Teleoperator Maneuvering System, TMS, or Teleoperator Retrieval System, TRS) shown in Figure IV-12 can be made. Since there is no longer any cradle to support the aft end, the single trunnion fittings previously carrying support loads at the payload bay side longerons have been replaced with double ones. With a bit of foresight, this kind of modification can be accommodated.

Finally, the system can be converted to a resupply tanker as shown in Figure IV-13. The resemblance to the standard upper stage in Figure IV-4 is not coincidental. After all, a tanker is simply an upper stage without an engine, if it's part of the same overall system. The tanks are the same and, by being interchangeable and removable, they offer another way to resupply - other than by pumping from one tank to another. A propellant module like that shown in Figure IV-14 allows both propellants and pressurants to be exchanged at the same time. It's like replaceable propane cartridges found in stoves, heaters, and similar camping equipment.

The system described was designed to serve the general upper stage

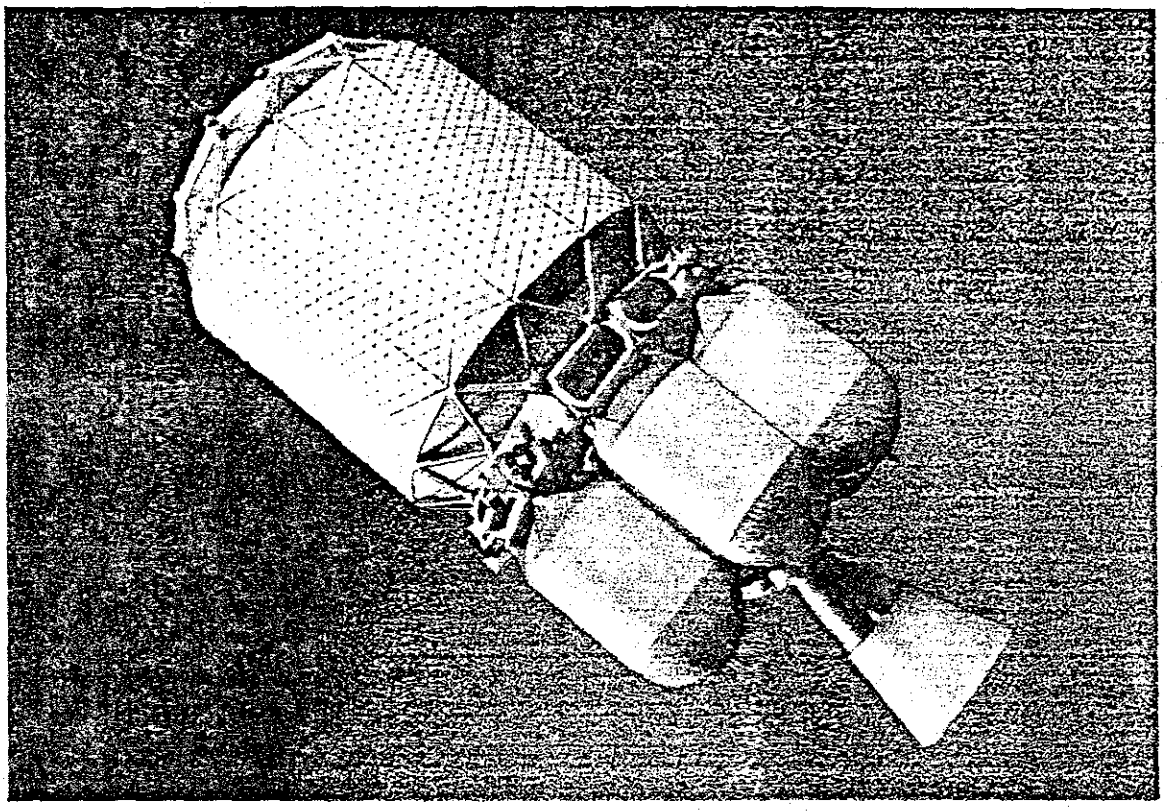


FIGURE IV-11 - Another possible variation on the theme, converting the aft tanks for liquid oxygen and adding a large liquid hydrogen tank. This offers a whole new series of space-based high energy stages.

functions of the Space Shuttle for which it has been sized. The funding which could have procured it has already been squandered on single procurements like IUS (Inertial Upper Stage, formerly known more appropriately as the Interim Upper Stage), PAM (Payload Assist Module, more suitable for the Delta launch system than Shuttle), and Centaur (since mercifully cancelled) which share no common elements.

These were to have been followed by an OMV with minimal expansion capability and no interchangeability with any other Shuttle upper stages. Since the cancellation of this program, there is still an opportunity to start the development of this type of modular upper stage if the procurement is ever resurrected. As matters stand, however, there is little chance that the potential savings can ever be realized for an existing transportation system. However, the idea should still have plenty of mileage in it long after the current crop of vehicles (and, with any luck, the haphazard procurement policies which spawned them), is gone.

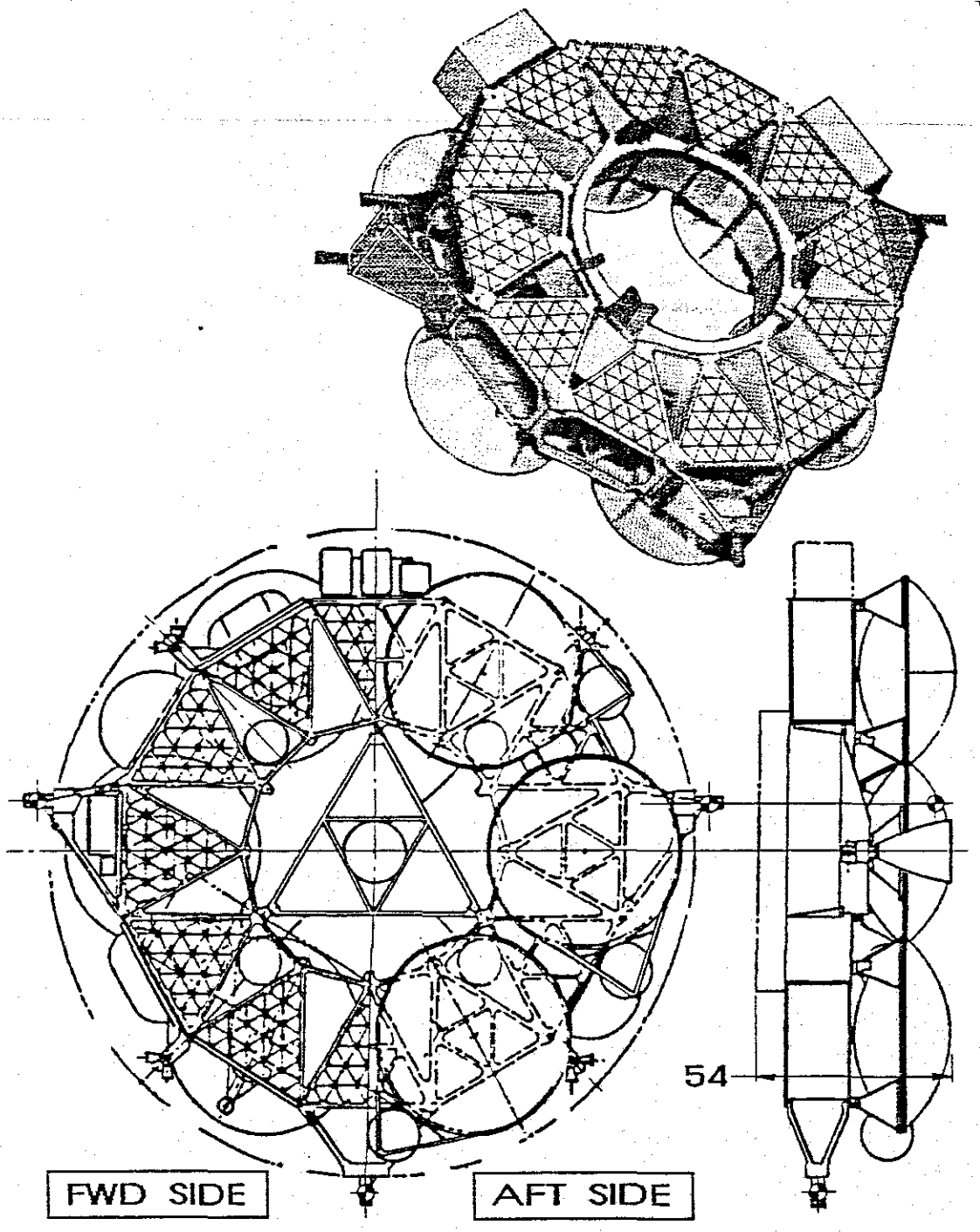


FIGURE IV-12 - A minimal short range upper stage, a part of the standard series which does the same things as the current OMV, a typical single-purpose procurement.

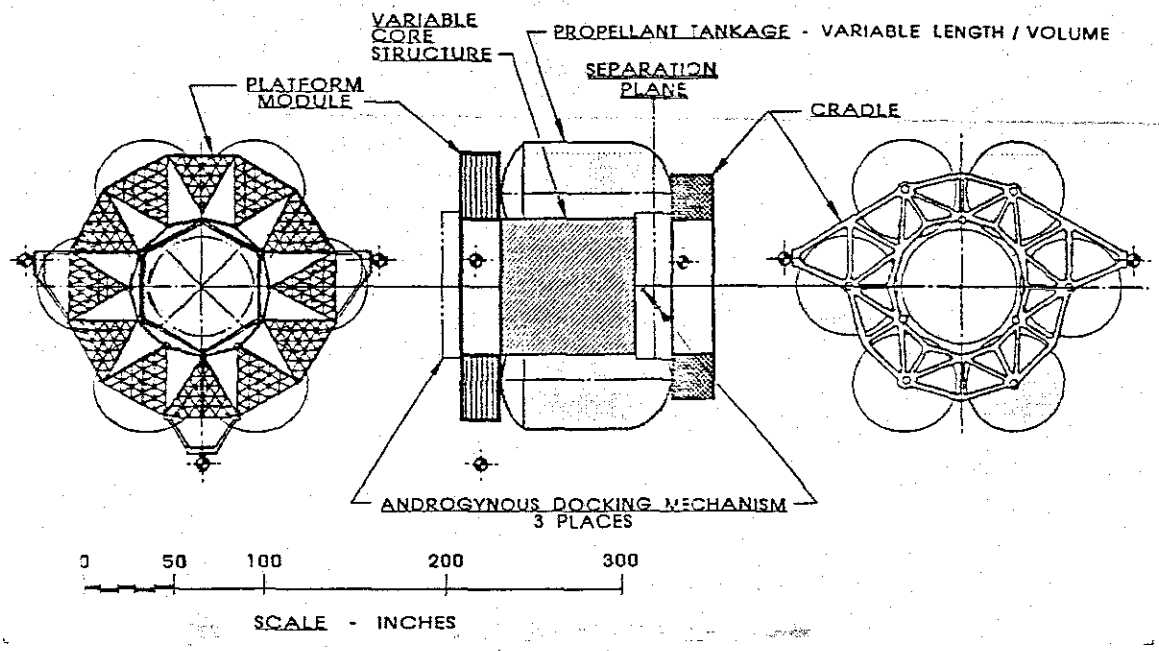


FIGURE IV-13 - A standardized resupply tanker variation on the basic series, allowing propellant resupply by pumping or by exchange of tanks. The tanker is just an upper stage without an engine.

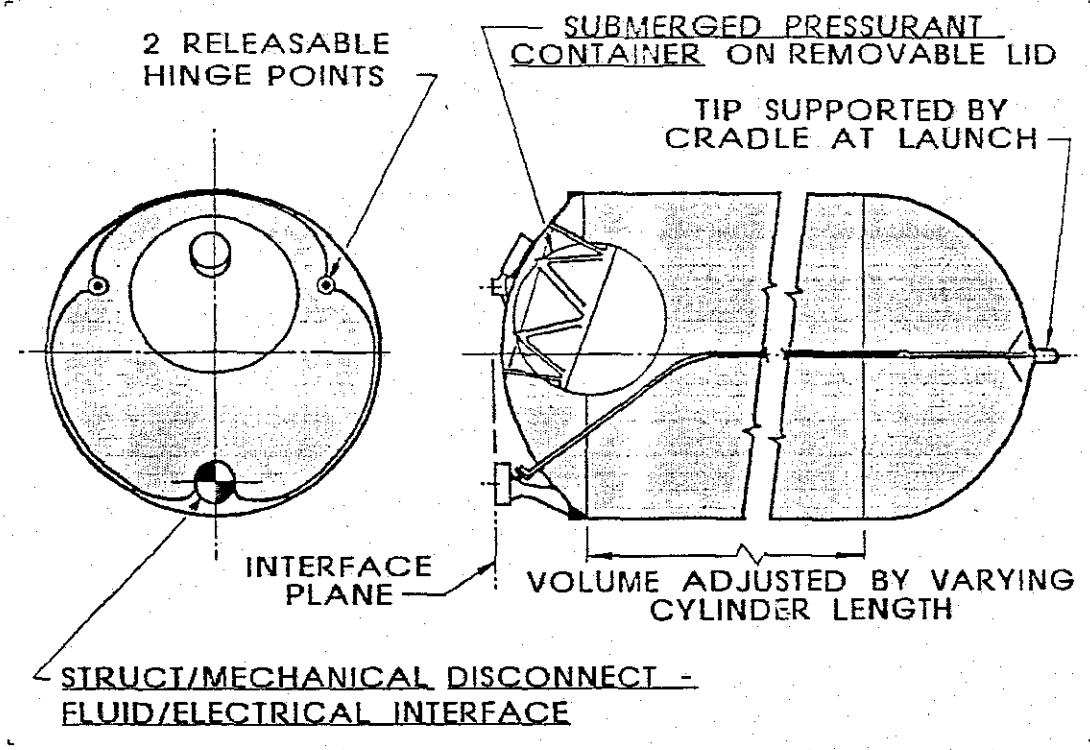


FIGURE IV-14 - The kind of module, containing both propellants and pressurants, which could be exchanged for resupply. Its size is variable.

A General Modular Space Platform Construction System

The construction system here described, a space station variation of the modular approach, follows a design logic based on the following premises:

- The carrier is Space Shuttle and its payload bay
- The initial configuration will need alteration and growth
- Re-shaping dictates endlessly repeating cell groups
- All lattice bars are the same length
- Structural efficiency requires a triangular/tetrahedral form
- Pressurized modules are bars interchangeable with struts
- Closed form indicates a need for a lateral berthing approach
- Adaptability means no adapters, loose parts
- Modularity starts with the structure

A committee of installers won't get there (which is why NASA's "official" Space Station design is a very bad economic bargain).

The construction system derived from these considerations consists of elements 55 feet long. None of the pieces is this long, but the nodal center-to-center lattice element made from any allowable combination is always this length. A tetrahedral lattice geometry can, if time and budget allow, grow to fill the entire known universe. It is the kind of lattice which can be visualized as the interconnection of the centers of congruent spheres in close hexagonal packing. The space between these intersection points is always equal to one sphere diameter.

In normal circumstances the form of the construction will be confined to fill only that part of universal space which is of immediate interest, but it can do so in almost any conceivable shape and can be changed from one shape to another as dictated by hindsight. The cost of development should be reasonable with only seven basic units. All peripheral accessories, such as power modules, experiments, manipulators, work stations and logistic storage modules, are accommodated (always at pressurized nodes) by the same docking/berthing interface which connects pressurized modules and receives visiting spacecraft and supply vehicles.

The geometric key to the system is the form of the hub at bar

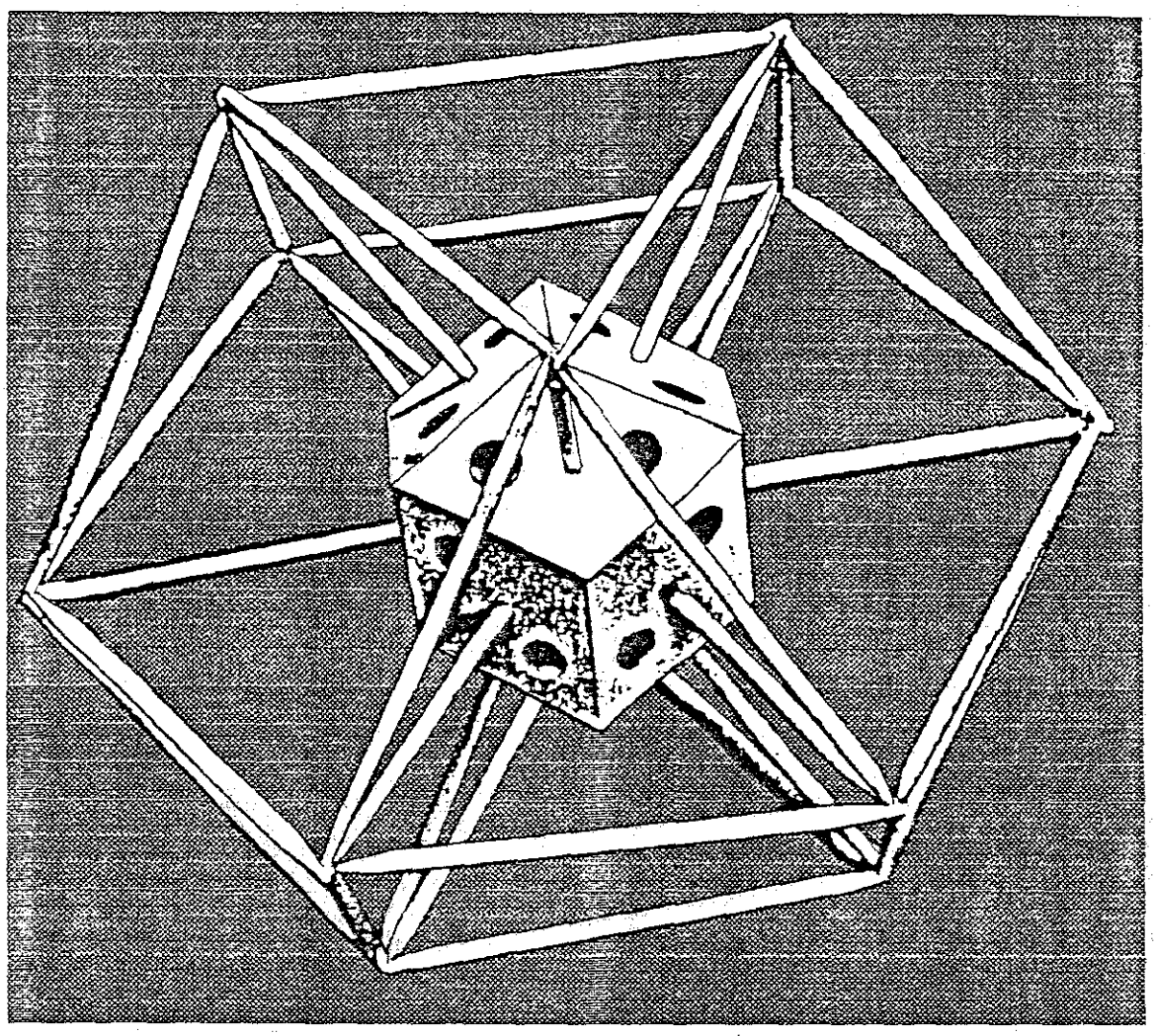


FIGURE IV-15 - A rhombic dodecahedron, the polyhedron which presents a face to each incoming bar, at a node of a tetrahedral lattice.

intersections. The bars run in the same directions as the 6 edges of a tetrahedron so that a fully occupied hub has one incoming and one outgoing bar for each direction - 12 in all. The polyhedron whose faces are perpendicular to the intersecting bars is the rhombic dodecahedron illustrated in Figure IV-15. A spherical node subdivided by the projection of this polyhedron's edges is shown in Figure IV-16. It is made from 12 identical subunits as shown, each fitted with the standard docking interface. This connection which also serves as an airlock port, a berthing joint, and a passageway after assembly, is shown in Figure IV-17.

Habitable modules are integrally stiffened cylindrical shells with conical ends as shown in Figure IV-18. They also feature the nodal ball's

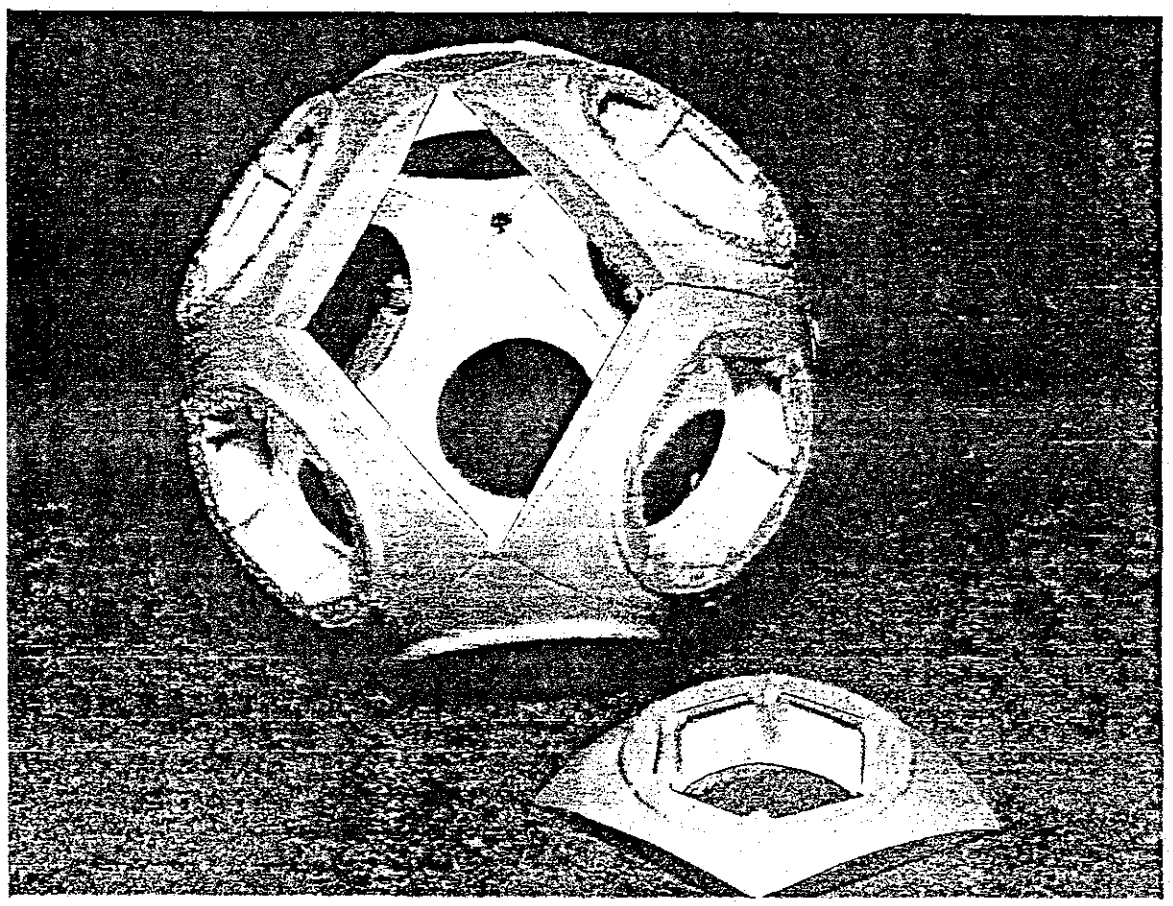


FIGURE IV-16 - A pressurized nodal sphere, its surface divided by the projection of rhombic dodecahedron edges from its center. Each unit incorporates identical mechanical, electrical, and access provisions for a standard interface.

androgynous interface on each end. Their construction is intended to incorporate attachment opportunities at each intersection of the stiffening ribs, as shown in Figure IV-19. Reworking structure to provide attachment as an afterthought can be difficult and is bound to produce clouds of unwanted chips and debris. With such a standard stiffening pattern details like windows can be added quite late in the production sequence (before the unit has left the ground) as shown in Figure IV-20. A window can be both light and safe if its viewing area is divided into openings between stiffeners, not cutting any of them. The window itself, on the inside, cushioned in an edge sealing retainer and supported at every stiffener node, would be a single pane.

Typically, a minimum habitable module would be furnished with standard "housekeeping" equipment at its conical ends. as indicated in Figure IV-21. A single end-to-end interconnection tunnel would

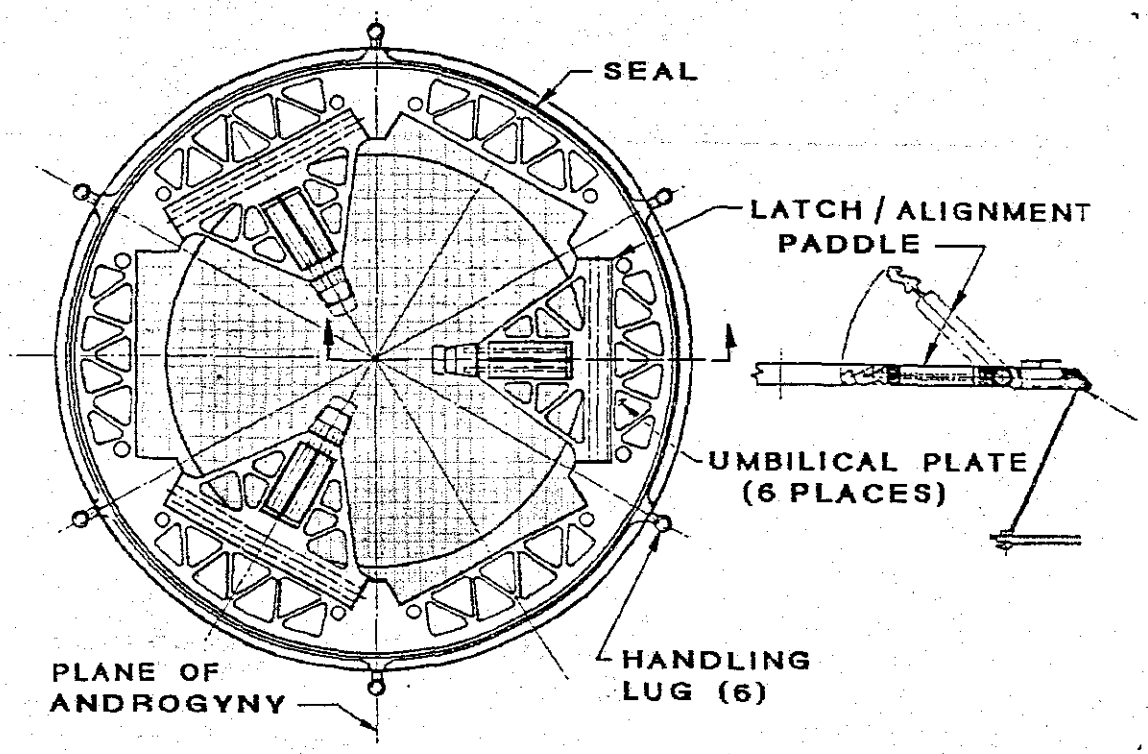


FIGURE IV-17 - A closer look at the details of an androgynous docking interface, 12 of which are provided at each pressurized node.

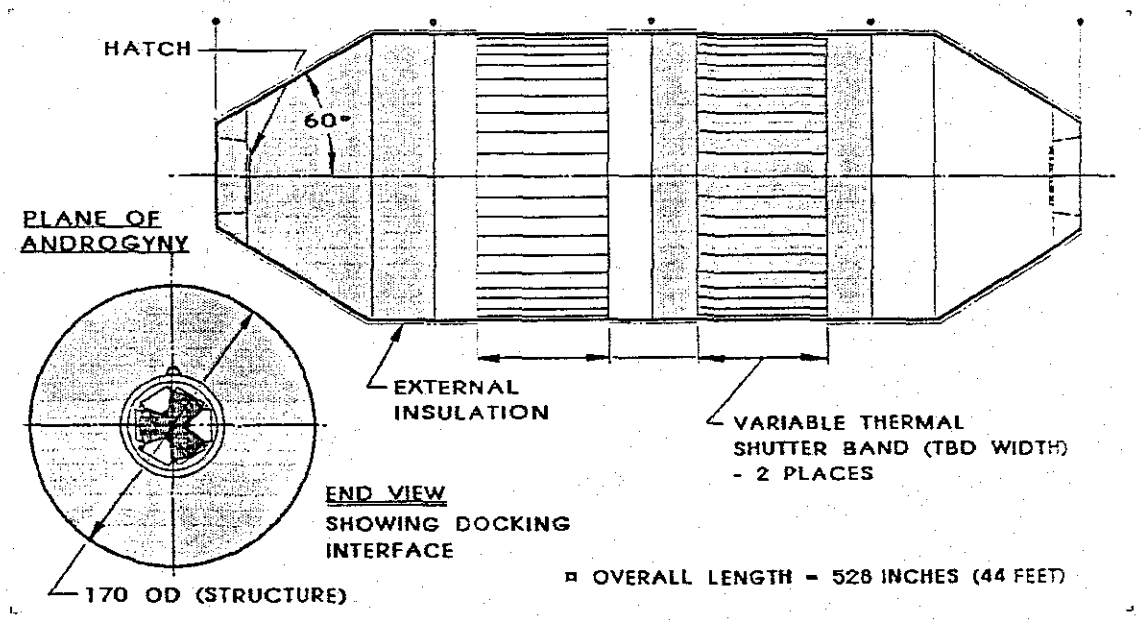


FIGURE IV-18 - A standard pressurized habitable module which fits between pressurized nodes, each end featuring the same standard androgynous interface found in 12 places

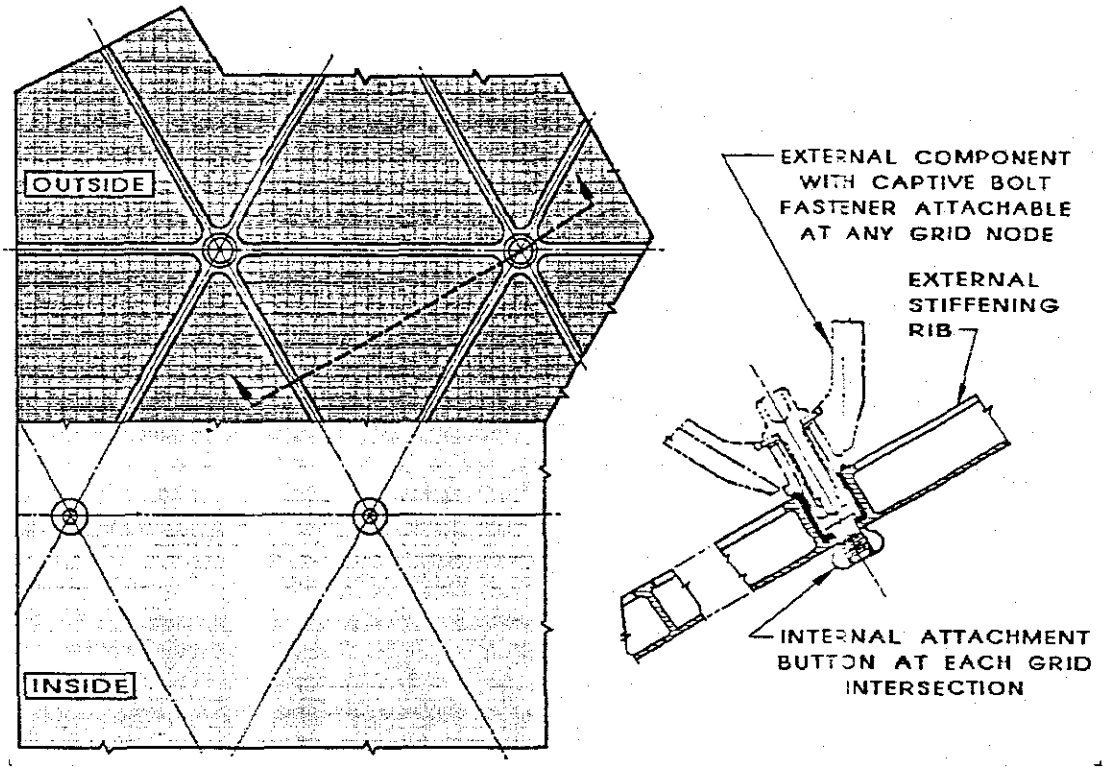


FIGURE IV-19 - The external stiffening ribs of the habitable module shell contain standard attachments at each nodal intersection, with a corresponding set of attachments on the inboard smooth side.

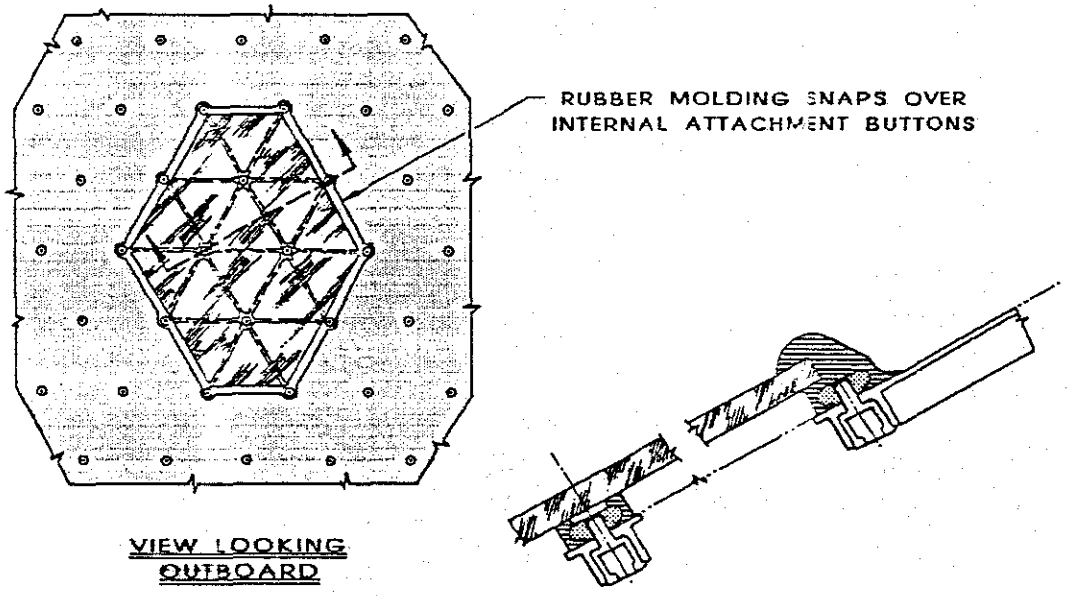


FIGURE IV-20 - A standard, integral shell like that described, offers limitless opportunities for window installations like that shown. The skin is cut between stiffeners, not through them, for a mullioned window effect

span the gap between and would contain power outlets, ventilation ports, and lighting. The cylindrical constant cross-section volume would be reserved for the variable equipment required for special functions such as command center, sleeping spaces, ward room, laboratory, repair workshop, recreational space, and hygienic facilities.

A hypothetical two-dimensional assembly of the 7 basic construction elements is shown in Figure IV-22. The elements are also identified as:

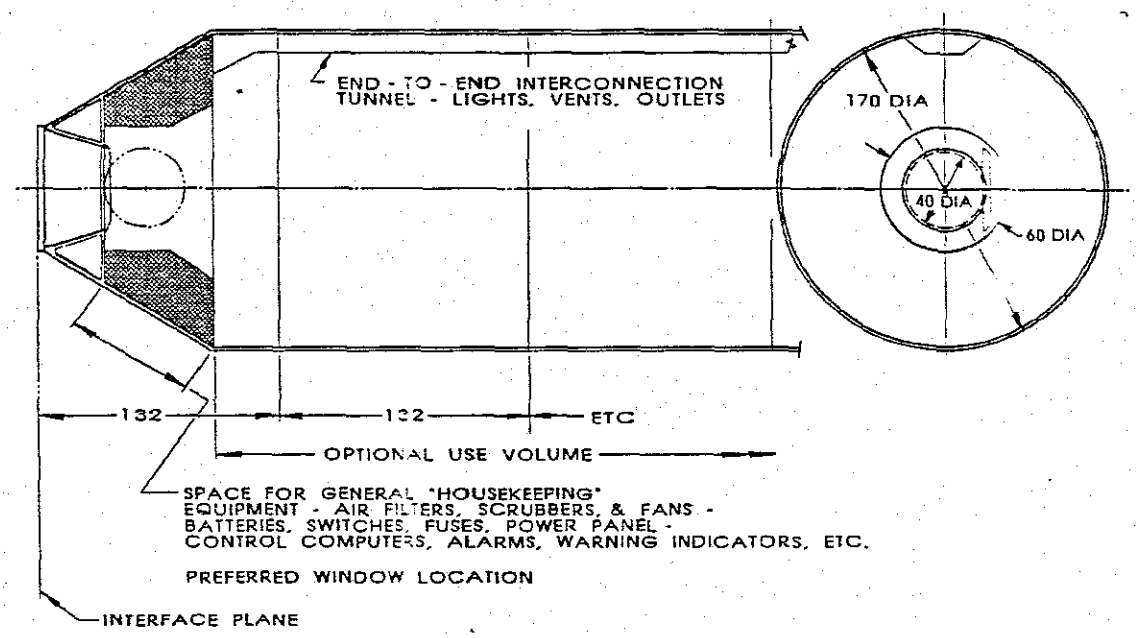


FIGURE IV-21 - A minimal standard pressuized module would contain basic "housekeeping" equipment in the conical ends, leaving the constant cylindrical section for variable equipment suitable to any specific application - control center, laboratory, ward room, etc.

(1) 12-port spherical nodal ball

(2) Cylindrical portion of the habitable module

(3) Habitable module end cone with standard interface

(4) Tapered half-strut which nests for transportation

(5) Tripod which serves as a short half-strut

(6) 12-stub strut-connecting "hedgehog" nodal fitting

(7) Tunnel interconnecting separated pressurized elements

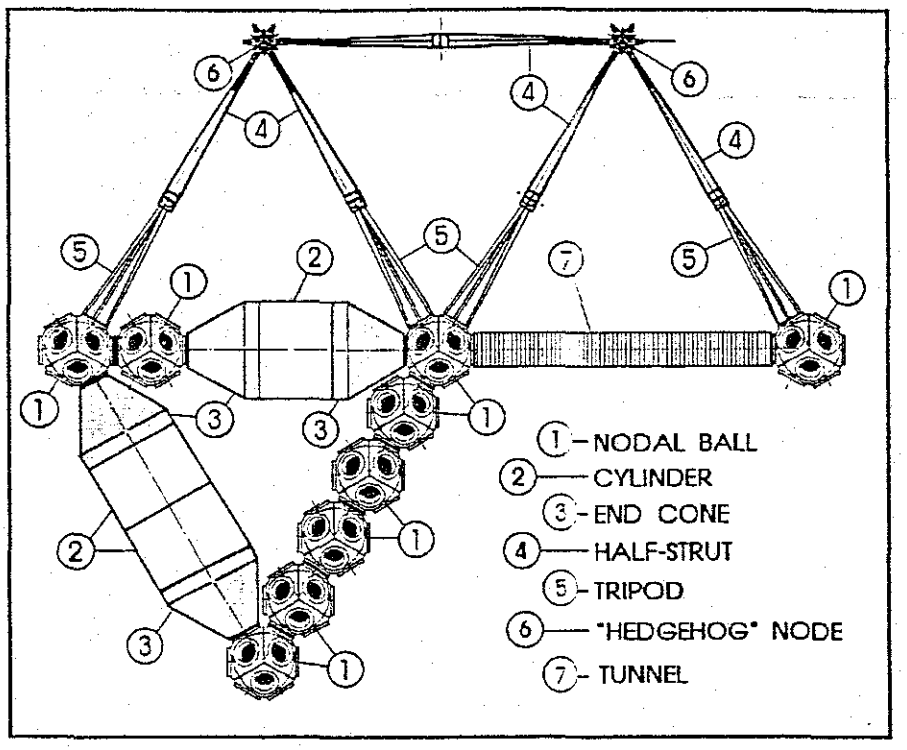


FIGURE IV-22 - The seven basic modular elements in a planar array to show where each unit is applicable.

The strut androgynous end fitting which also appears at each "hedgehog" stub is shown in Figure IV-23. It is shown as a connector for the electrical power bus which is automatically extended as the structure grows, and is switched off when the mechanical connection is dismantled. This function can be performed (and is more likely to be) by the tunnel which has at its ends the larger interface common to balls and habitable modules. However, it may do no harm to have some subsystem integration in both elements. Figure IV-24 shows the "hedgehog" whose nodal geometry, like that of the nodal ball, is based on the rhombic dodecahedron. Groups of these fittings can be assembled to each other to make a tetrahedral lattice frame that can provide a structural bridge for their transport to orbit. (Figure IV-25) The picture merely hints at this assembly. More work is required to define it and the peripheral fittings which pick up the Shuttle's attachment provisions.

Appropriate application of the system is defined in the following guidelines:

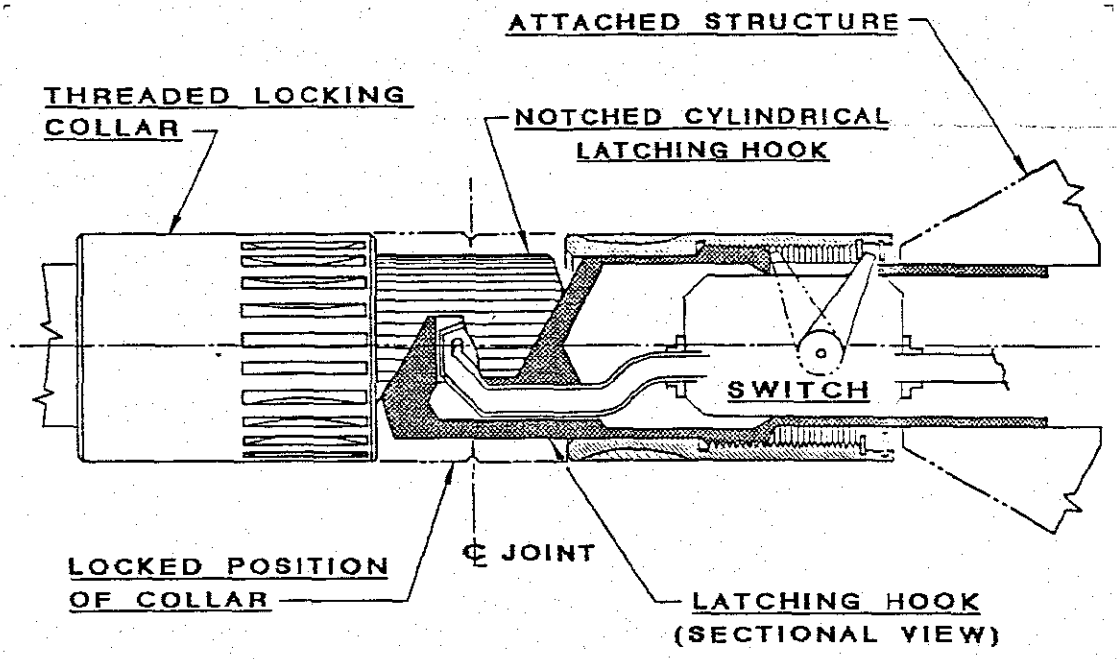


FIGURE IV-23 - An adrogynous connector for struts in the unpressurized portions of a platform assembly.

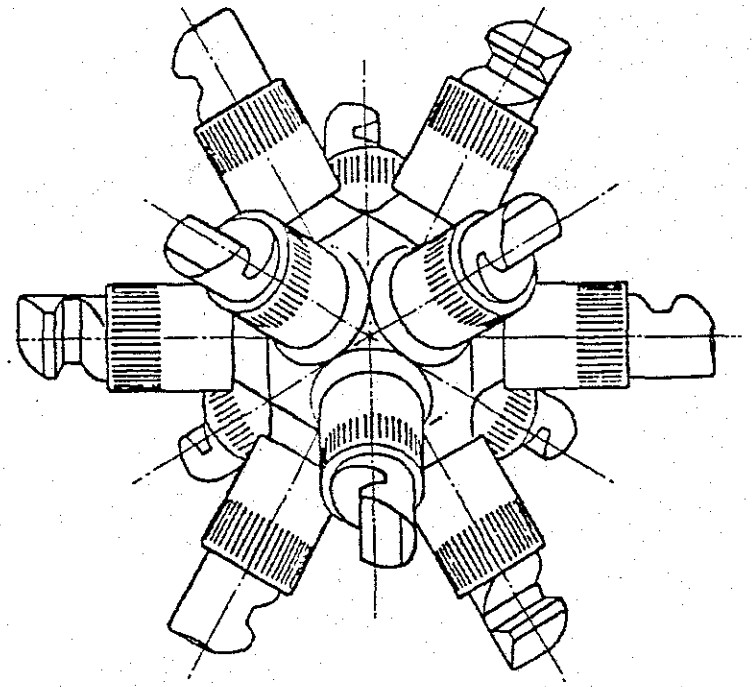


FIGURE IV-24 - The "hedgehog" cluster fitting at each unpressurized node corresponds to the nodal ball at pressurized intersections. The geometric basis is the same rhombic dodecahedron.

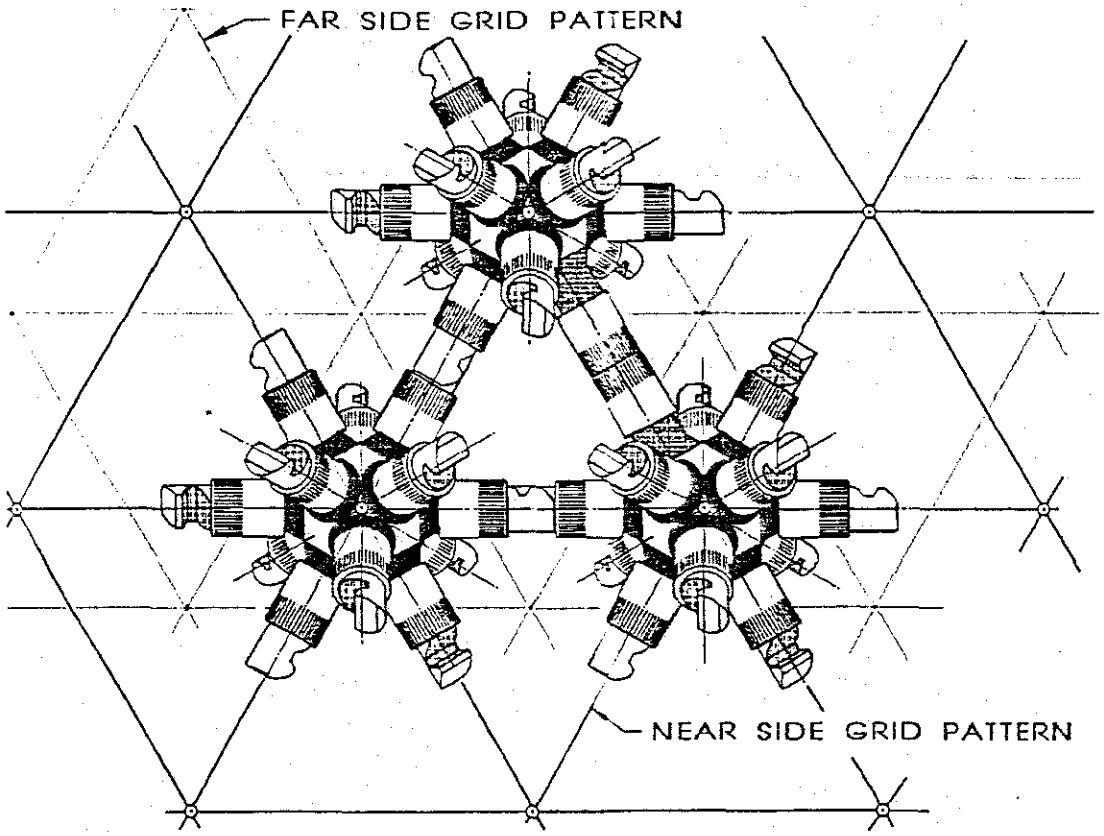


FIGURE IV-25 - Assembled "hedgehog" fittings can form a space truss to bridge the Shuttle payload bay, providing their own cradle for transportation to orbit.

- The nodal port interface is androgynous and common to module ends, upper boost stages, resupply systems, satellites, power-collection assemblies, and experiments.
- All open frame constructions attach to pressurized modules by way of tripod struts attached at nodal ball ports.These ports thereby remain accessible for EVA.
- All nodes (balls and hedgehogs) are identically oriented.
- All accessories - power modules, battery packs, fluid tanks and clusters, experiments, etc. - are attached at nodal ball ports.
- External accessories which seal at the nodal interface are accessible from the inside of a nodal ball. No EVA to reach them.
- All "hangar" spaces are formed by fabric "walls" (or the equivalent) stretched between bars inherent in the construction.

- All docked spacecraft (OMV, OTV, etc.) are separably attached at ports in the nodal balls.

- Spacecraft in hangar spaces may be tethered to strong points on the nodal balls between the ports.

Modular Growth with a Growing Module

Assemblies of modular elements can themselves become modules, suggesting a method of planning the growth of a large space base. That is, it eventually becomes large after having started out as the minimal habitable cluster of 3 pressurized cylinders shown in Figure IV- 26. Since one orbiter load consists of a habitable cylinder and a nodal ball, this group can be carried in 3 trips, after a power module like that shown in Figure IV-27 first becomes operational.

The complete 4-launch configuration is shown as a perspective sketch in Figure IV-28. It is roughly comparable to the Skylab mission, an ambitious enough starting point for the eventual establishment of a space station or operational center. Of course, it is also possible to start out with

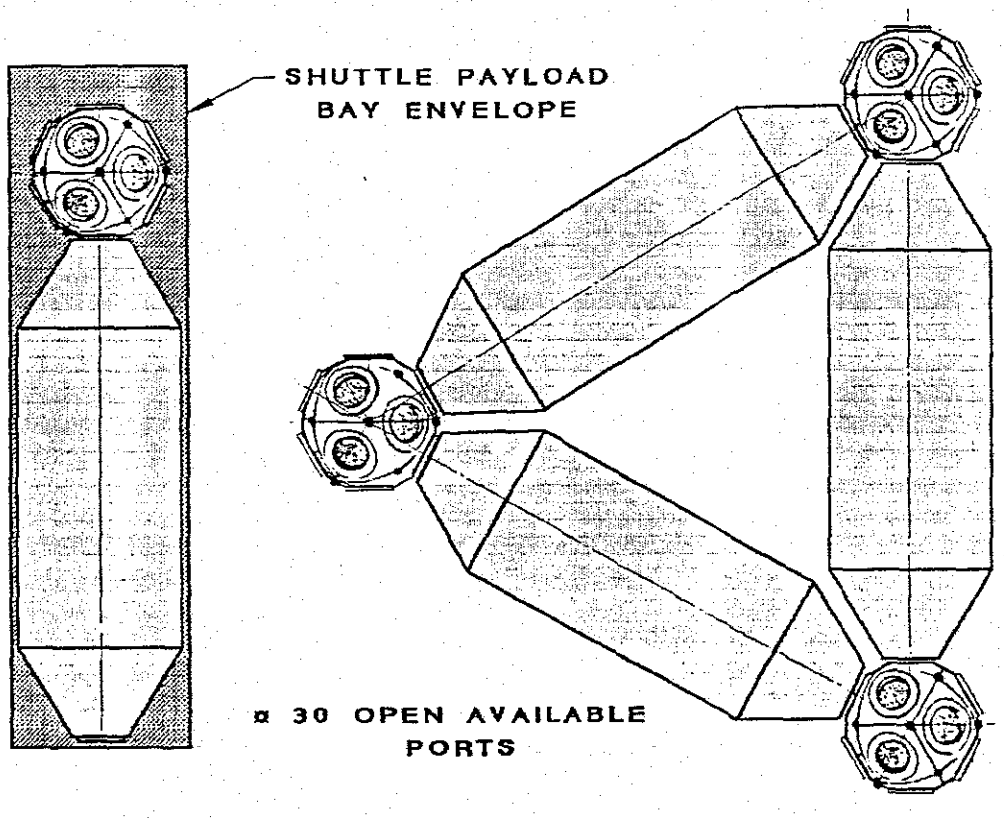


FIGURE IV-26 - A minimal 3-module habitable assembly which can be taken to orbit in 3 Space Shuttle trips - one node and one module per trip

station or operational center. Of course, it is also possible to start out with a single pressurized module, probably unmanned, attached to the same power module. Two launches will do it. As shown in the next illustration, Figure IV-29, the triangular group can be slightly enlarged to a tetrahedral shape by adding struts. A merger of 4 such units (adding 3 more) creates a 2nd-order tetrahedron as depicted in Figure IV-30. Figure IV-31 shows how the replication of larger and larger tetrahedrons makes the elements for further growth to bigger ones. In other words, the module for this system is in every case a tetrahedron, larger at each progression. By the time the assembly becomes a 4-th order tetrahedron, it contains 96 bars, interchangeably struts and "hedehogs" or habitable modules, spherical nodes and tunnels. In the center is a multi-purpose octahedral volume of 627,000 cubic feet. Eventually, (but not finally) a next replication step produces a large 8th-order tetrahedral space base with a 5 million cubic foot center space and a half mile of useful edge length (Figure IV-32). Continuation of the process can lead to a space city. With special planning, identical units can be assembled into a space base for familiarization and training before being broken off for some such space exploration as a trip to Mars or a return to the moon.

On the other hand, the size of each individual cluster can remain small as many of them are grouped loosely in a co-orbiting formation of cooperating units. The appropriate choice can be made after accumulating some first-hand experience while the option to go either way remains open.

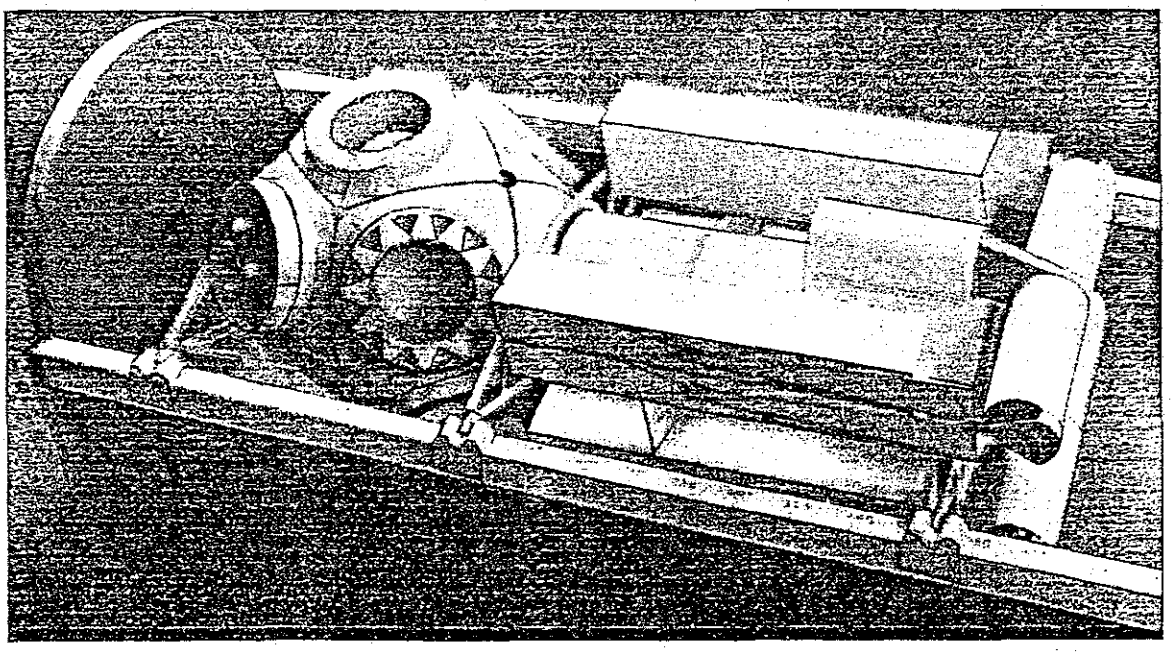


FIGURE IV-27 - An energy module with folded solar arrays can be built on a nodal ball as shown. Two can fit into the Shuttle payload bay. One may be sufficient for starting operations.

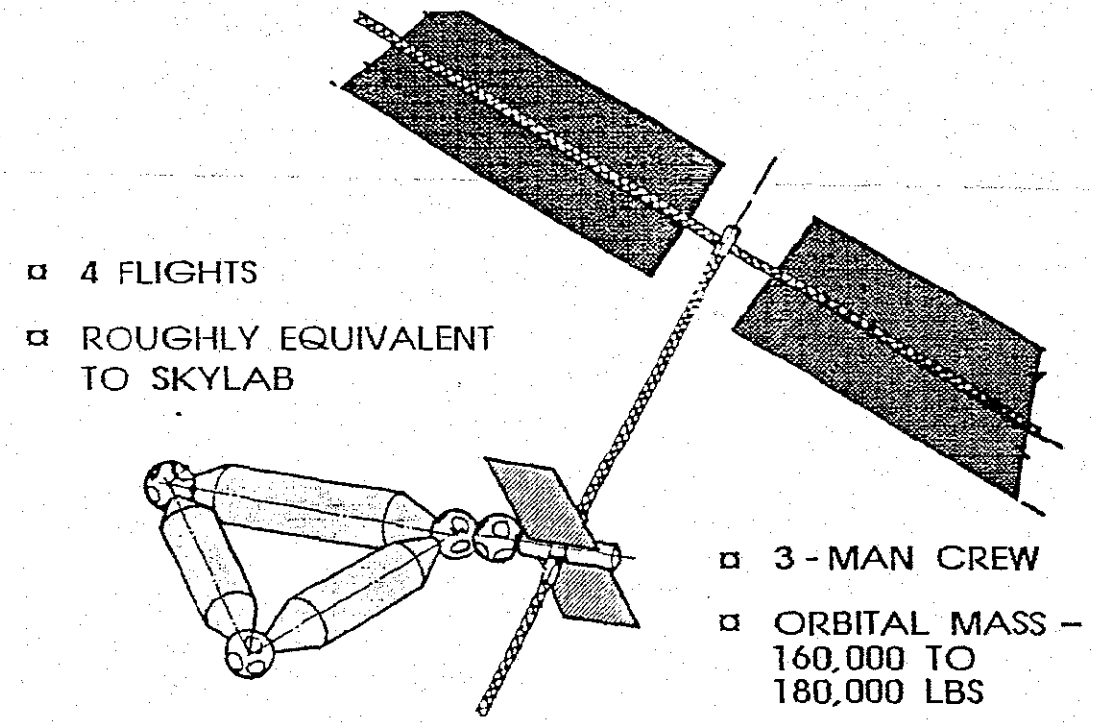


FIGURE IV-28 - A suggested starting space station configuration with about the same internal volume and weight as Skylab.

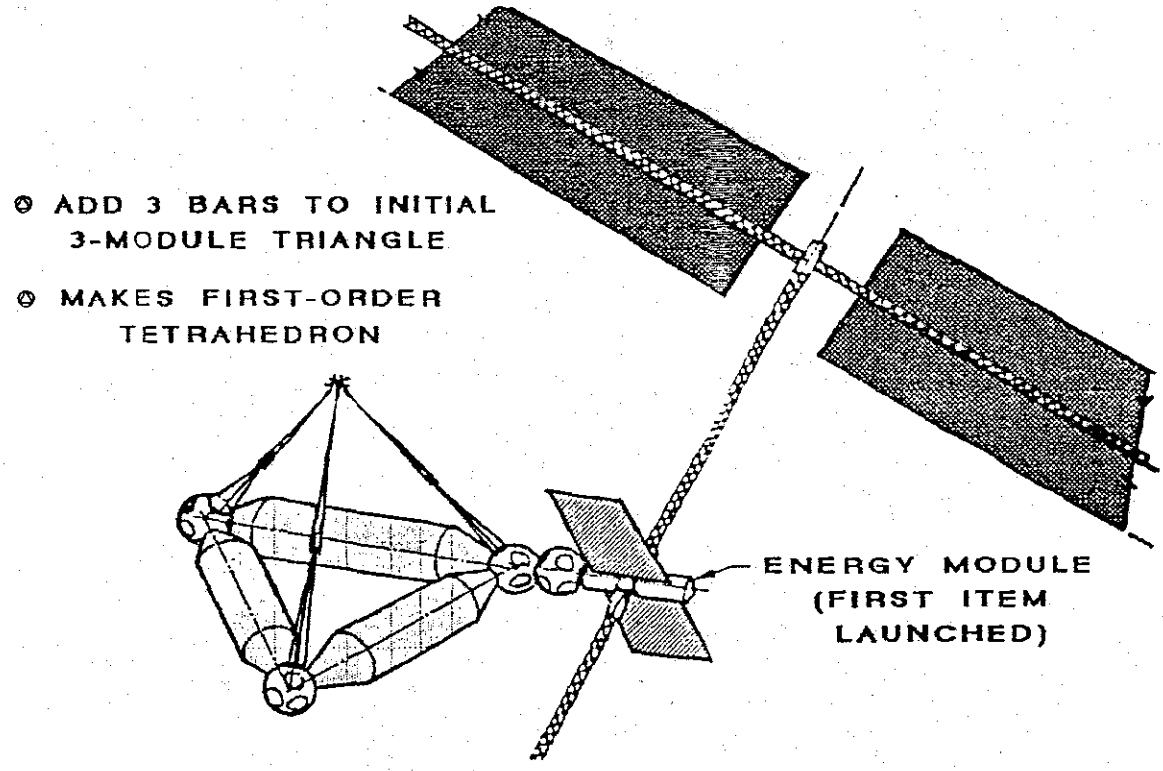


FIGURE IV-29 - Addition of three struts to the starting triangle makes the configuration tetrahedral.

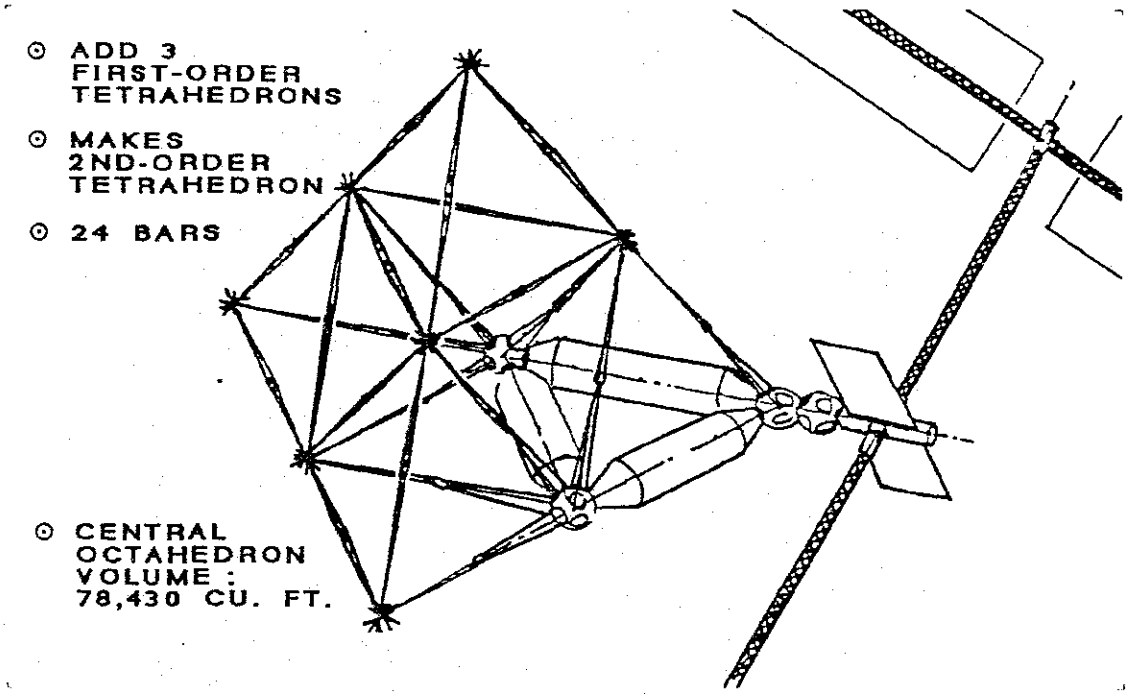


FIGURE IV-30 - Combining three more first order tetrahedrons with the first one, produces a second order tetrahedron. Any of the bars can be pressurized or unpressurized units.

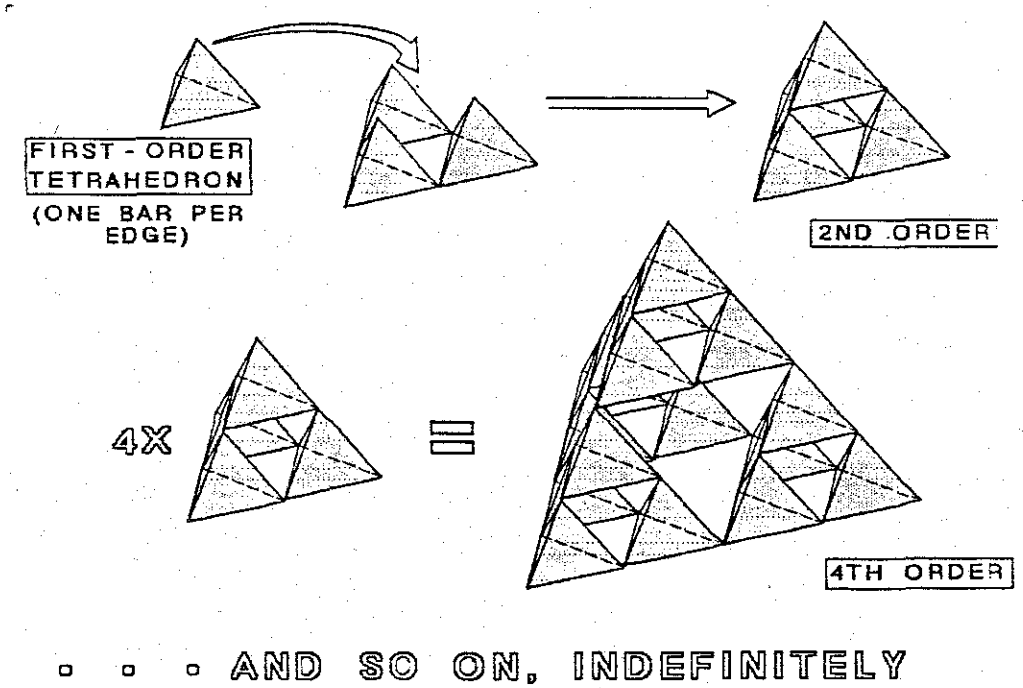


FIGURE IV-31 - Tetrahedral growth involves combining continually larger tetrahedral elements - the same shape in all cases. The process is essentially endless.

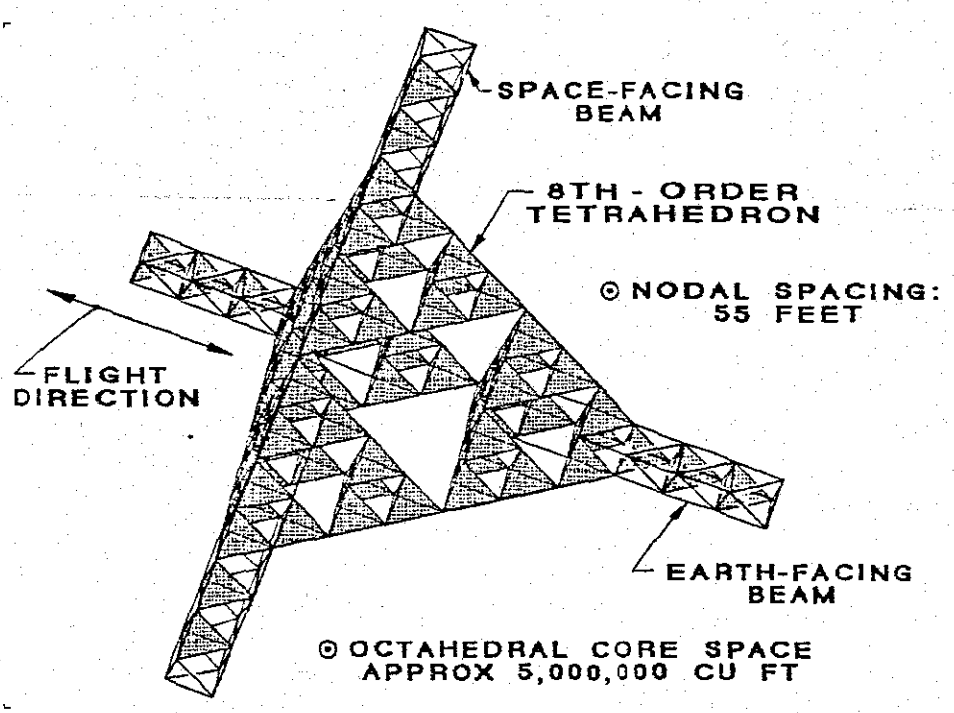


FIGURE IV-32 - If four fourth order tetrahedrons are combined as shown, a space village or town could be the result, a system well on its way to becoming a space city. But that is far in the future.

Payload Bay and Subsystem Modules for a Reusable Launch Vehicle

Space Shuttle payloads, as removable and launchable packages, can be described as modules, but the payload bay itself is not. Therefore, each flight manifest must be integrated and installed after the previous load is removed following a flight. This kind of serial operation places limits on the possible turnaround time reduction for a reusable delivery system, as it once did in the unloading of ships, trucks, and railway cars. These forms of surface transportation have simplified their problem by containerizing cargo and freeing the delivery vehicles for continuous service. The containers in this case are interchangeable and transferrable between the three modes of conveyance, but they are quite heavy. A full-bay STS container would be like a payload bay within a payload bay, a structural duplication which would severely limit space payload delivery weight.

The suggested alternative, shown in Figure IV-33, is a cargo bay door functioning as a payload carrier. Such a door would also be a carrier platform which occupies none of the valuable payload volume. That means that already-designed payloads would not have to be changed too drastically to work with it. A cargo could then be assembled and checked out while the reusable launch system is in orbit on a mission. After its return, the doors would be exchanged. If other operations are speeded up to reduce the rest of the turnaround time, more doors can be built and processed in parallel, keeping these time-consuming activities from

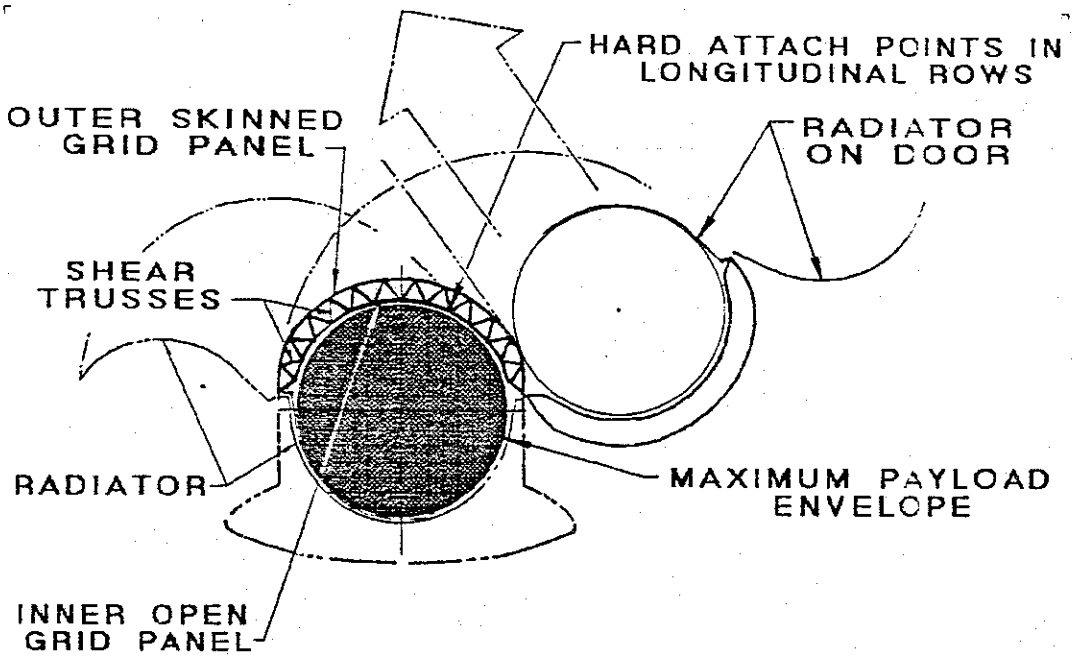


FIGURE IV-33 - If a strengthened payload door becomes a payload carrier, the next payload manifest can be installed on another door while the Shuttle is on a mission. On its return, the new installation can be substituted for the old, with considerable reduction in

constraining the schedule.

How some of these other ground operations can be shortened is suggested in the rearrangement of mid-body structure shown in Figure IV-34 . Here the payload bay liner has become the load path between longerons and keel, leaving the outer surface removable for access. The resulting panels, as indicated in Figure IV-35, can become support structures for equipment installations, being thereby transformed into modules which can be replaced, updated, or removed for more convenient servicing away from the vehicle which carries them. When they swing out, they also leave space for access to other equipment which could otherwise not be reached. Denser packaging in this manner can permit more efficient use of available space, or reduction in vehicle cross-section.

Equipment in the center body section can thus be reached even when the payload bay is full. A large part of the present access problem comes from the need to remove components and break into systems to get at the components having difficulties. There are also delays caused by having to hold up work while thermal protection tiles are replaced. If panels can be removed and serviced, the TPS refurbishment task can also be accomplished away from the launch vehicle and the launch pad, a pre-

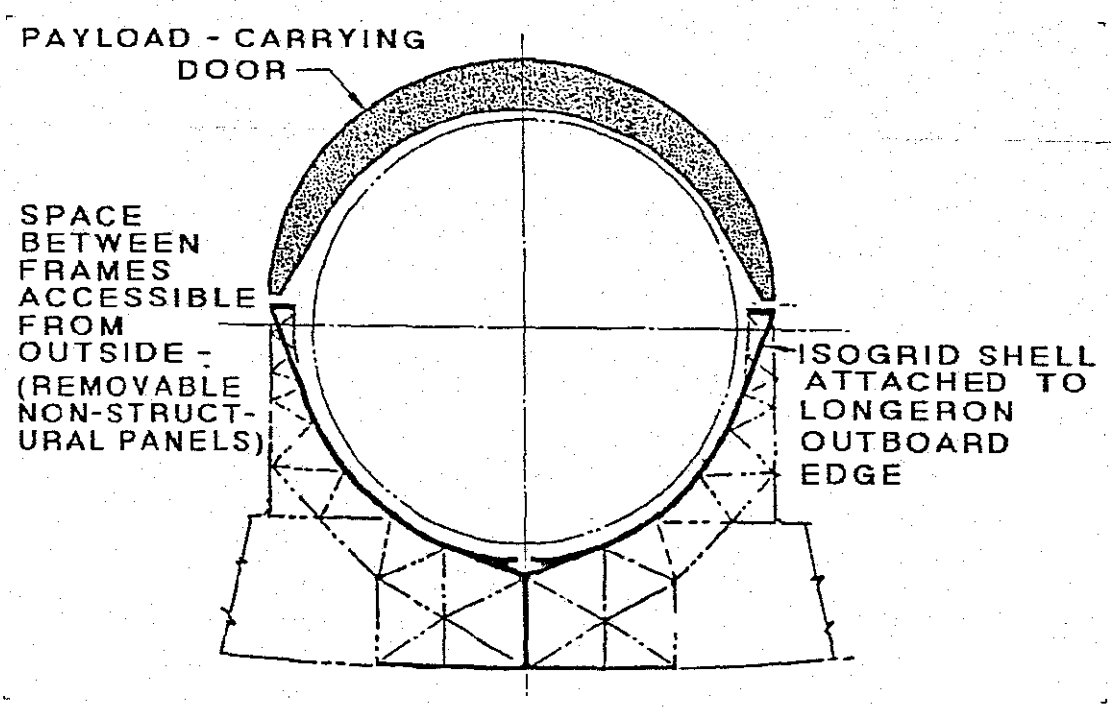


FIGURE IV-34 - The fuselage cross-section for a payload-carrying door scheme includes an "inside-out" structure with the outer surface openable for access.

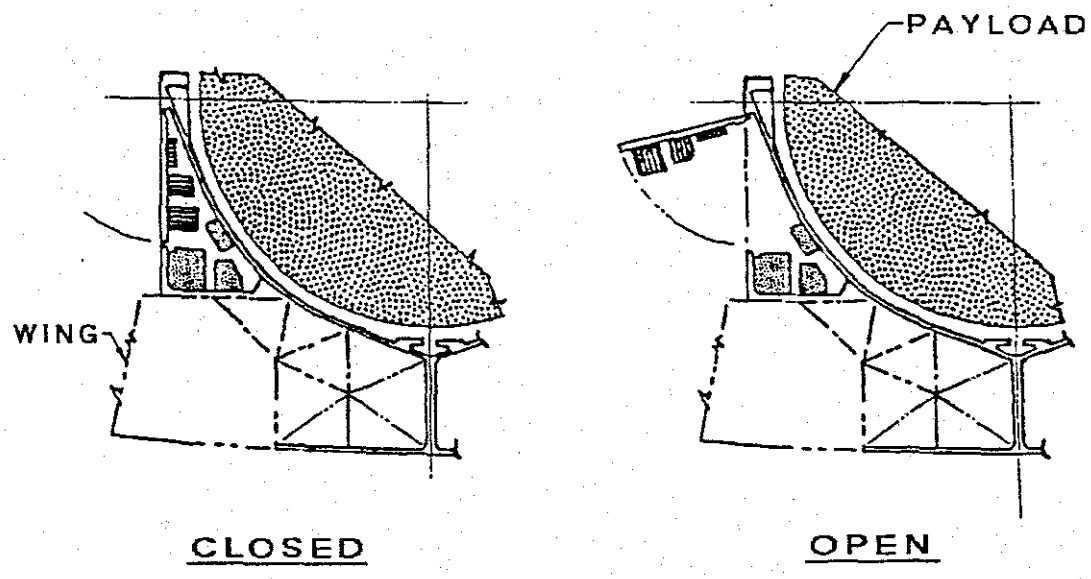


FIGURE IV-35 - If equipment is mounted on an external access door as shown, the door and its equipment become a replaceable module. Because the equiment swings away, making equipment behind it also accessible, packing density can be increased.

assembled panel replacing a damaged one.

A Modular Element for a Variable Component

Carrying the modular theme into a more detailed application, a customized pressure vessel - a container for high-pressure helium, for example - can be made in a variety of shapes and capacities by developing the sphere-torus segment shown in Figure IV-36. Six of them make the 6-lobed sphere-torus shown. Each segment is defined as a wedge bounded by two planes passing through spherical centers and the center axis of the assembly; that is, all the seams are radial equatorial cuts through the centers of the spherical lobes. Assembly welds are located in these planes.

The advantage of this kind of pressure vessel is that it can be made in a variety of shapes and capacities, as will be shown, and yet its weight per unit of volume is as low as that of a sphere, generally conceded to be the lightest form of pressure vessel. One advantage it has over a sphere is the

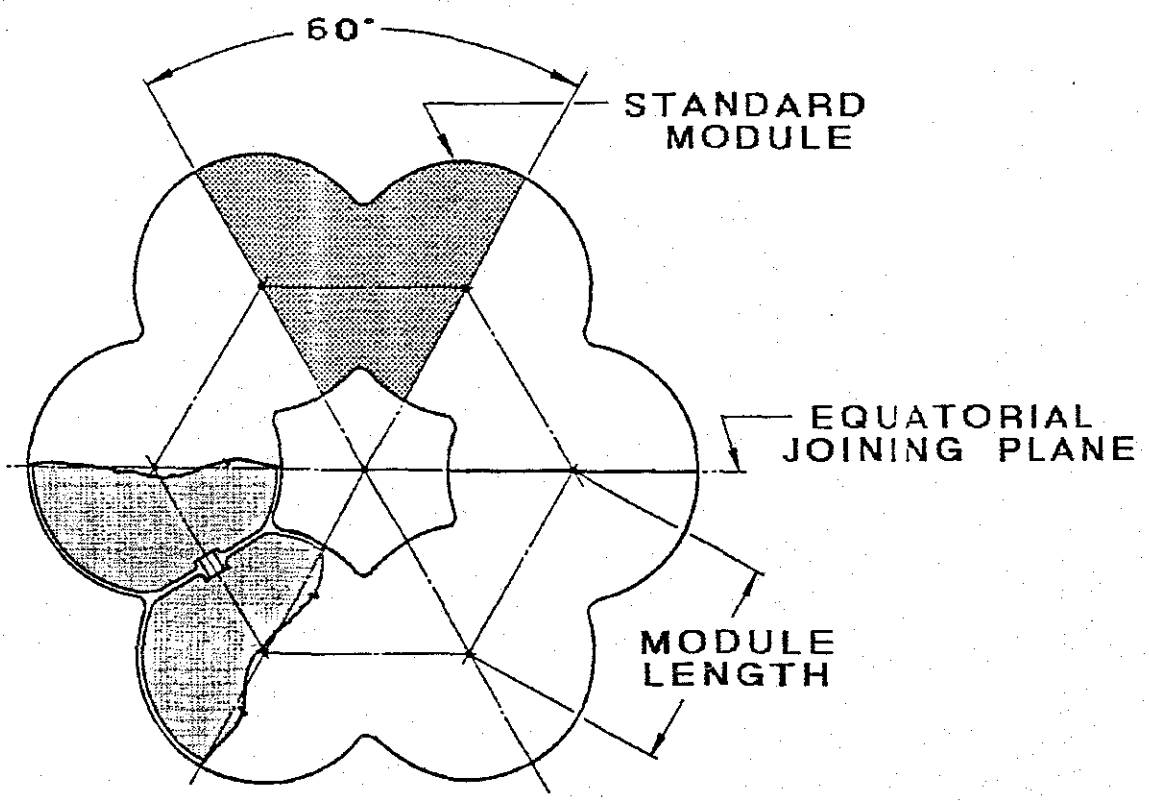


FIGURE IV-36 - A standard pressure vessel module is formed from two merged hemispheres with a membrane at the intersection. Six make a sphere-torus ring.

presence of convenient "handles", the grooves at the intersection of spherical external surfaces and an internal diaphragm. The support of spheres can sometimes be quite unhandy; the grooves are less "slippery."

Figure IV-37 suggests a manufacturing sequence since there is no prior experience to draw upon. Initiating the fabrication of this article (or perhaps a series of different basic sizes) is likely to entail considerable investment, an expense not likely to be tolerated for any single procurement and therefore a good candidate for general research and development.

A six-lobe torus being an unlikely design choice, other shapes must be made from this module, one of which, an eight-lobed torus, shown in Figure IV-38. It is made from the same module, adjacent units being rotated through the same angle in opposite directions to change the assembly's curvature while remaining in the same plane. An eight-lobed torus is no more appropriate for most applications than a six-lobed one, but the illustration demonstrates how the assembly curvature can be changed by rotating identical elements.

Continued rotation can produce any desired curvature to suit available space - which may be one of the awkward annular spaces between a

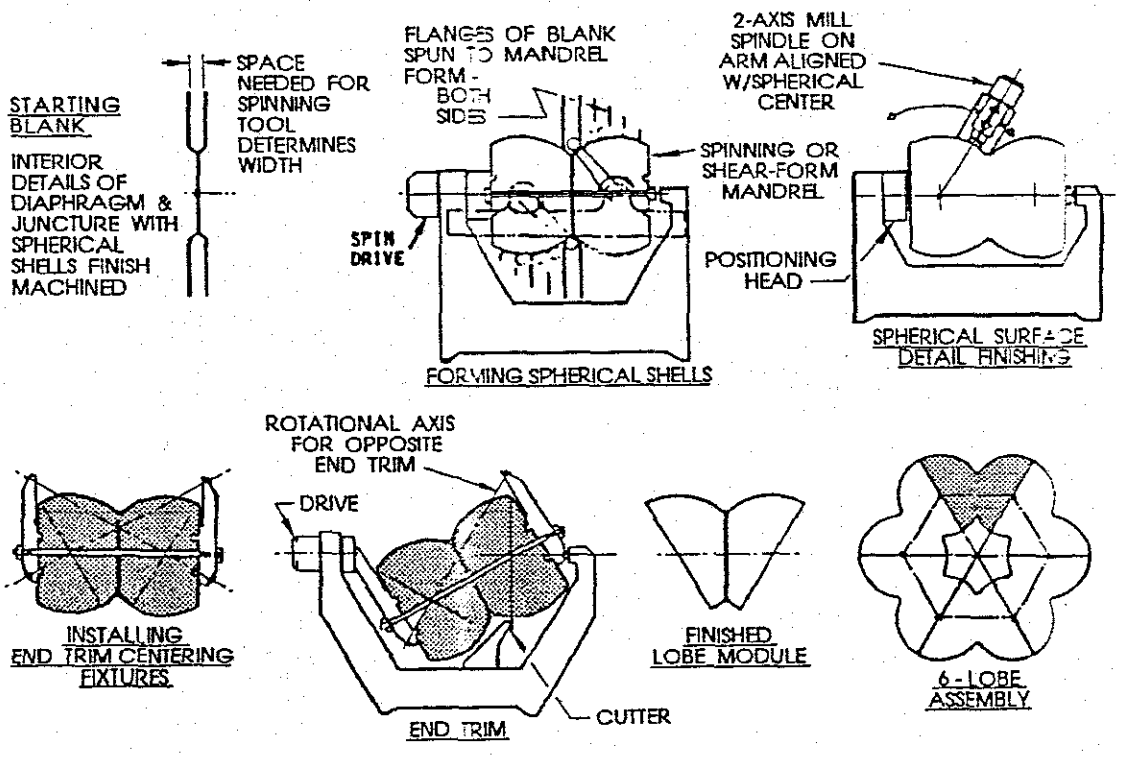


FIGURE IV-37 - A suggested fabrication sequence for a standard sphere-torus element.

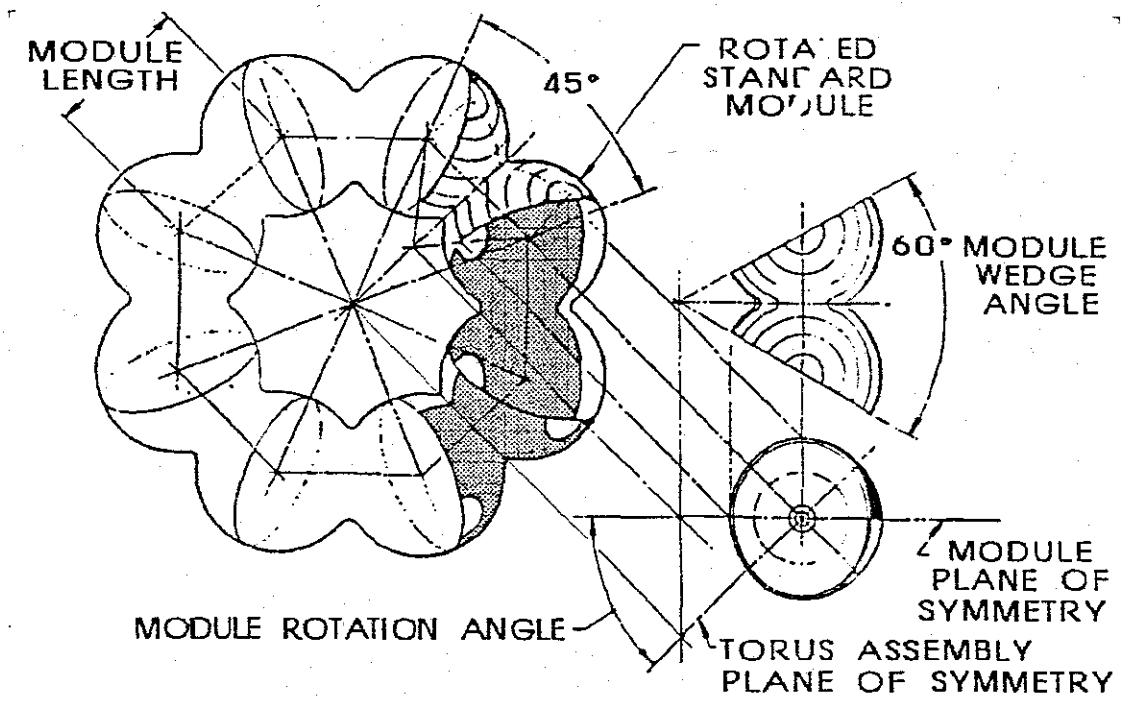
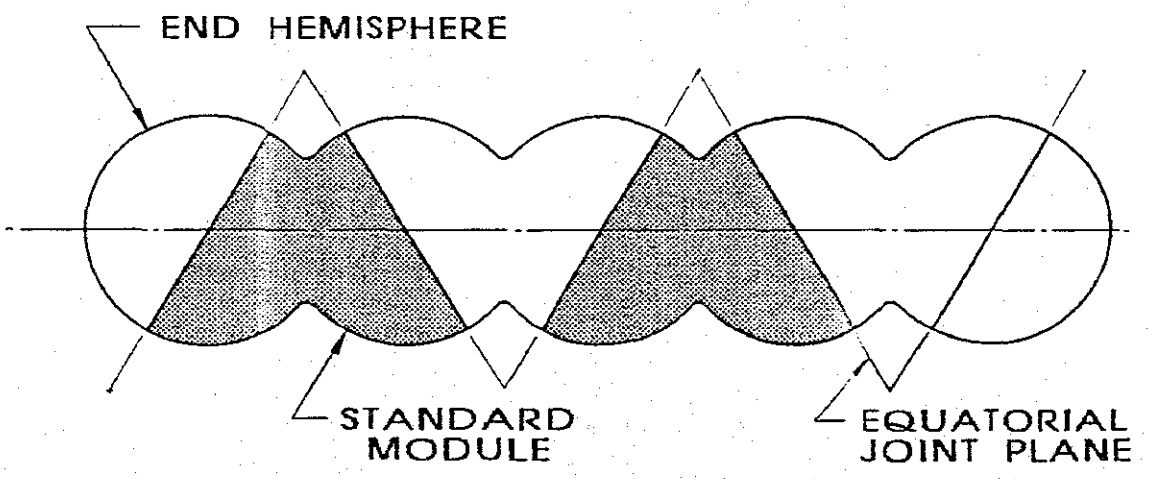


FIGURE IV-38 - By equal and alternate opposite rotation of adjacent elements, an eight-lobe spherical torus can be made from the same pieces that built one with six lobes.



◎ NARROW END OF WEDGE MODULE ADJOINS WIDE ENDS ON BOTH SIDES

FIGURE IV-39 - Eventually, when adjacent elements are rotated 90 degrees from their original positions, a straight lobed pressure vessel is produced.

propellant tank end dome and a skirt. Ultimately, 90 degrees of opposite rotation in two adjacent modules lines up the narrow end of one wedge with the wide end of the next, making the radius of curvature infinite and the pressure vessel straight, as shown in Figure IV-39. The ends are closed by appropriately co-developed hemispherical caps.

Availability of a unit (or a series) like this may avert some of the damage to designs which is inflicted when an inappropriate container is specified because it is "off-the-shelf" - or nearly so. Examples of this kind of misapplication are abundant enough to warrant consideration of more standardized ways of doing business.

Conclusion

As demonstrated by the previous examples, there are a number of ways to apply the principle of modularity, each case arising mainly from approaching the problem with growth and re-configurability in mind. It is also useful to remember, as stated in the ***System Engineering Management Guide*** previously cited, that modularity should be a normal acquisition request. What is more, it should be accorded appropriate consideration when gratuitously offered in a proposal, even when nobody asks for it.

There is little reason to expect any cost or weight penalties if it is effectively applied. On the contrary, it should help to identify those cases where a single procurement can serve a spectrum of functions as effectively as multiple ones, as in the case of upper stages, satellites, and resupply vehicles. It should also assist in the standardization of interfaces, particularly docking devices, as will be required for all of these vehicles, space stations, and launch systems.

THE SELF-FULFILLING RUMOR

The old Santa Monica plant, for many years the headquarters of the Douglas Aircraft Company, was a rabbit warren of old hangars and shops connected to each other by overlapping roofs. Its centerpiece was the B-19 hangar, jutting above everything else like a camel hump. In it, on a level above the assembly floor, was a wide wooden-floored mezzanine. For about 15 feet back from the railing, the floor was empty and open to all the noise of the rivet guns. A glass-paneled wall at this point closed off a work area where a tool design group was housed.

This group was busy, crowded, and expanding with the work load, a circumstance which gave birth to a rumor. Some of the designers in about the middle of the hierarchical pecking order started it, claiming that there was a plan afoot to move all the junior designers out onto the open mezzanine to relieve the congestion. The story persisted for some time with no action at all, finally convincing the troops most likely to be affected that it was groundless, after all.

At about this time the word finally got to the boss working in his cubbyhole at the back of the space. Looking up and noticing that the members of his crew were almost stepping on each other, he exclaimed, " By George, it ***is*** pretty crowded out there. That sounds like a great idea!" And so the move was made.

The moral to the story seems to be: ***If you can't get anyone's attention in a sluggish organization, start a rumor!***

V. FLIGHTWEIGHT MATERIALS AND THEIR FABRICATION

Except in the case of tension cables or pressure vessels the major problem in structural design is the efficient arrangement of material for compressive stability. Also, to repeat a previously stated paradox: ***thin is heavy; thick is light.*** This is because a thicker plate or deeper section is more efficient as a compressively loaded column. Other properties being equal, a low density material can be thicker for the same weight and, therefore more stable over a larger span. Stiffening can be sparser and lighter. That is why the property of low density is the most desirable characteristic for flightweight hardware.

For a panel to resist buckling, whether from shear or compression or a combination of the two, it must satisfy this mathematical expression:

$N_{cr} = KEt^3/b^2$, where:

N_{cr} = critical load intensity in lb/inch

K = buckling coefficient dependent on type of loading, panel aspect ratio and shape, and boundary conditions such as edge restraint

E = material elastic modulus

t = material thickness, inversely proportional to density

b = panel width

Since the important characteristic of buckling resistance is most influenced by material thickness, low density in the material, by allowing greater thickness, permits the unsupported panel to be larger, the stiffening lighter, and the construction simpler. What all this means is that weight saving does not require exceptional combinations of material properties like those suggested by the unidirectional strength of graphite; just low density, combined with effective arrangement, will do. For example, magnesium alloy, with strength and stiffness about 65 per cent that of aluminum, and a density lower by about the same amount, can, with proper exploitation of the density characteristic, be made into a lighter structural shell (by about 5 to 10 per cent). A side advantage, especially when load intensities are low, is that the larger cross-sections of lighter material are less weight sensitive to dimensional tolerances.

A near term gain can be expected from lithium-aluminum alloys

currently being developed. They offer small but realistic improvements in both stiffness and density. Even more important is the expectation that, since they are usable with common practice, the prospect of obtaining material in the large sizes needed for real economy is good.

The fact that oriented fibers of graphite or Kevlar have been badly utilized does not mean that they are useless. There are sensible applications, to some extent going unnoticed in the prevailing emphasis on theoretical "trade study" numbers without proper consideration for the system integrating role of the structural frame. For example, Kevlar has been made into very strong, flexible, and non-conducting cables and ropes. They have been successfully used as guy cables for transmission towers. Being non-conductive, they eliminate the need for porcelain insulators (one of the targets of vandals and unsuccessful hunters). They are also lighter and more flexible than traditional steel wire strands.

The under-tread reinforcement for radial tires is often aramid fiber, the generic term for Kevlar. The quantity used for this purpose far outstrips its use in the aerospace industry besides being a more appropriate application. One must constantly remember that aerospace production is low, offering little inducement to a material developer except through heavy government subsidy - and government subsidies are extended to those who follow the "party line" - that is, the interests favored by a government laboratory, for whatever reason.

There is another worthwhile application for strong, unidirectional filaments. They are valuable as an overwrap for pressure vessels, not so much because they save weight, but because they enhance safety. Ever since combat aircraft flew high enough to benefit from stored breathing oxygen, the storage bottles have been tightly wrapped with wire, the purpose being to contain the lethal shrapnel when they are hit. This converts a destructive explosion into a rapid but safe blowdown. High pressure helium containers on vehicles carried in the Shuttle payload bay should be good candidates for similar treatment. So should pressurized storage tanks menaced by meteoroid damage from long term exposure in space - those on long range exploration vehicles or at a space depot.

If someone could produce a homogeneous, isotropic composite material with strength and stiffness no greater than aluminum but with the density of magnesium, real (as opposed to illusory) structural weight savings are achievable in general purpose structure with integral fabrication. Direct substitution for aluminum alloy without dimensional changes would yield a 35 per cent saving. Redesigning to make the best use of material properties should bring weight reductions in ***well designed*** (that is, well arranged) structure of about 40 per cent. Too often, of late, miracle materials have been called upon to rescue

inefficiently arranged structures or applied where their properties are offset by excessively large splice penalties. It is also common practice to claim composite superiority by comparison with badly designed sheet metal alternatives.

As luck would have it, some molded chopped fiber composite work has been done, but on such an unnoticeable scale as to have little effect on the usual way of doing business. Evidently, it has been intended that this method be applied only to fittings in conjunction with laid-up sheets. Since integral construction, recognizing that structure is mostly fittings, eliminates sheet material altogether in metals, the same can and should be done with composites for cost as well as weight reduction. This consideration introduces a need for ***massive scale-up*** of random fiber stock size from little 1- by 4- by 6-inch fittings and test specimens to ***plates*** 4 to 8 feet wide (or even wider) and as long as machine beds will accept. Before that, methods which produce consistent homogeneity and material properties must be developed.

The chopped fiber strips comprising the material in the molded part shown with its tooling in Figure V-1 are 1-inch "broom straws" made from carefully oriented unidirectional "prepreg" tape. The 1-inch tape lengths are crumbled into pieces about a sixteenth of an inch wide.

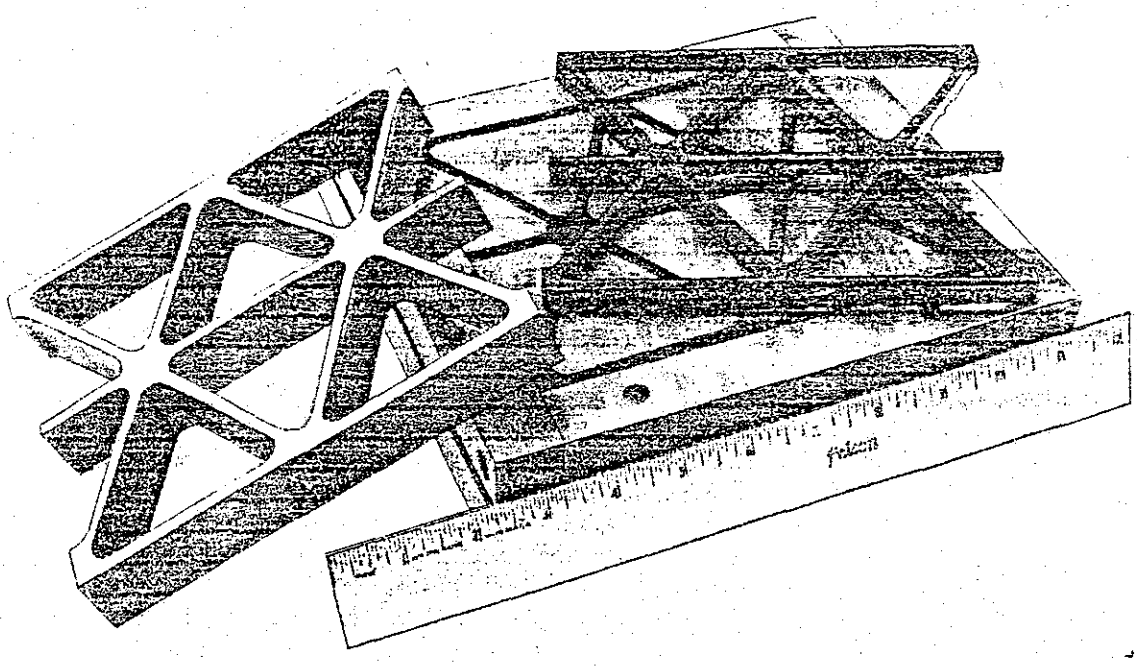


FIGURE V-1 - A small chopped-fiber section of isogrid mace from 1-inch pieces of crumbled pre-impregnated tape. It is shown with the tools which made it.

Cured in a mold under heat (700 degrees F for polyimide, 350 for epoxy) and pressure (1000 to 2000 psi), the resin coated on the strips flows to fill voids and solidifies to produce a shaped part. Possessing nearly isotropic properties, this part has a surface much like the "flakeboard" occasionally available at lumber yards. It is not very homogeneous, a fact which may create problems if it is subsequently machined. Also, its integrity in the short transverse "grain direction" (the direction of molding cavity closure) may be less than desired. However, it is certainly a step in the right direction - a very short step, entitled to a lot of magnification.

Reinforcement fibers in a matrix pick up load from adjacent fibers by shear forces transmitted through the matrix and transferred to the fiber by surface adhesion. The maximum load a fiber can carry is determined by its cross-sectional area and tensile (or compressive) strength. Assuming that one-third of a fiber gathers load, the next third carries it, and the final third sheds it to the matrix, the relationships shown in Figure V-2 apply. Therefore, if the fiber and matrix properties are approximately as shown, a fiber's length must be at least 150 times its diameter to function effectively as structural reinforcement. Proportions on this order have been shown experimentally to be about right for practical structure. The chopped fiber "broom straws", about a sixteenth of an inch wide and 5 mils thick, consist of several "tows", perhaps thousands of fine filaments. It has been established that they are more effective at the one-inch length than when shortened to a half-inch. Greater length may be even better, but also more likely to be forced into preferential orientation by the shape of the mold, not always advantageous.

True random homogeneity calls for much shorter fibers and economy requires a raw material which has not had so much time and effort already lavished on it. As it happens, individual graphite fibers before being spun into tows have an average diameter of about .0004 inch. To satisfy the requirement of L/D equal to 150, they only need to be about .060 inch long. Let them be in the range of .060 to .100. Since coating such fine fibers with 'B stage" resin is out of the question, suppose that the resin is thinned and absorbed by a fine compressed dry fiber felt to produce the ultimate volumetric proportions of 60 per cent fiber, 40 per cent resin.

The resulting mixture when compressed and heated to exclude all voids should yield a fine-grained homogeneous block with the desired weight saving properties previously mentioned and suitable for making a test specimen.

The ultimate goal of molded composite R&D should be scale-up to

elements as large as can be made in aluminum. Sooner or later, someone will suggest molding a large grid panel close to "net dimensions." There is always someone who worries unnecessarily about the cost of machining and the cost of materials, both relatively insignificant in aerospace quantities as compared to the cost of handling, sorting, storing, identifying, analyzing, inspecting, and assembling ***parts***, to say nothing of the accompanying paper blizzard. There are also at least two other adverse effects when material is forged or molded to something close to final dimensions:

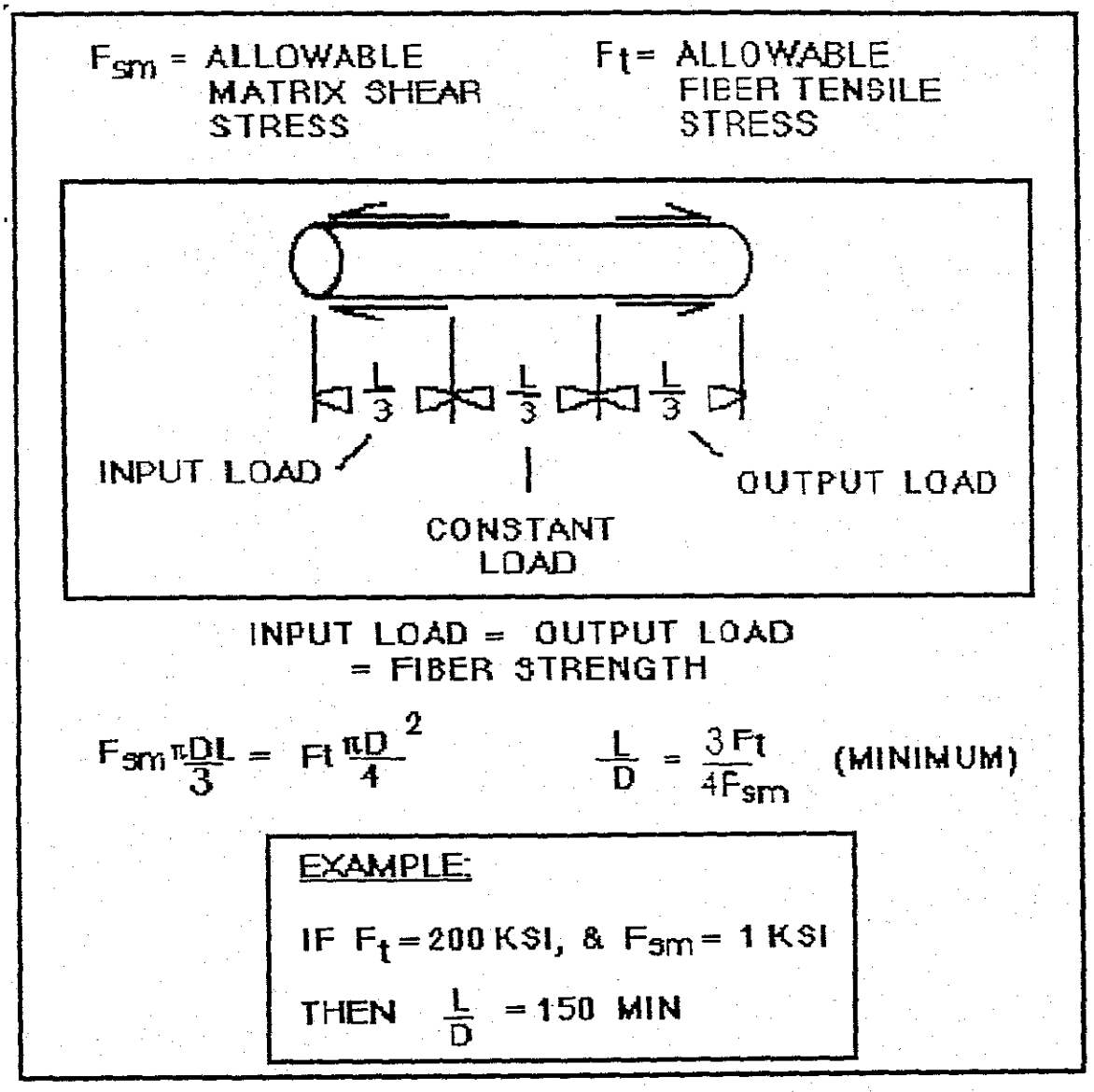


FIGURE V-2 - Working a reinforcement fiber imbedded in a matrix.

* Matched die sets are costly. The simple set shown in Figure V-1 which makes a part spanning about 7 inches cost something like $50,000 in 1976. Since R&D budgets for large tooling of this type are so hard to find, initiation of scale-up simply won't happen.

* The maximum load intensity the molded part can handle is determined by the cross-sectional area of the bars and their strength, much less than the capacity of a solid plate. Tailoring of a single piece to a wide range of load intensities becomes impractical, and the undesirable fittings and doublers reappear. The versatility obtainable by sculpturing a solid plate is lost.

In short, the simplest, most appropriate and easily made product is just a slab of uniform thickness. Since, after machining, it should at times be formable with heat and pressure against a contour fixture of some kind, techniques must be developed for machining an incompletely cured blank, extra consideration being given to holding it securely on the machine bed. Nobody claims this is going to be easy, but why deprive people of the drudgery they have already accepted as the price of making structures out of composites?

It should be apparent from the foregoing discussion that metal matrix composites, reinforced by randomly oriented whiskers and particles, are particularly suited to integral structural design, and require little change in practice other than major increases in scale. However, in accordance with the maxim of least density for least weight, none of them appear competitive with graphite/polyimide up to 600 degrees F.

To meet the performance demands of future launch vehicles, there will be an urgent need for light, strong, and stiff structures usable at higher operational temperatures. If the materials are composites, this will call for light, strong, and stiff reinforcement whiskers like graphite, in abundant concentration (say 60 per cent), imbedded isotropically in a metal matrix made of lithium, beryllium, magnesium, or some mixture of light metallic elements. With luck, the material may possess useful properties at about 1000 degrees F.

To summarize, materials which can be applied to successful, economical, efficient designs, need to be homogeneous and isotropic, reasonably strong and tough, of the lowest possible density, and available in very large stock sizes. A material which fails to deliver these characteristics is unlikely to be truly effective for mainframe structures, though it may have what is required for special - and limited - applications.

Manufacturing Methods

The basic ways of fabricating structural parts are forming, material removal (cutting, machining, drilling, etching, etc.) and material deposition (plating, for example). Casting probably belongs in this last category.

The material deposition process, alternating with chemical material removal and photo-masking, is what accounts for the remarkable versatility and miniaturization of modern electronic devices. It is also most effective in this case when applied to large scale production of extremely small units with precise and intricate details, not a situation found in aerospace structural frame production. However, there is at least one useful exception - electro-forming, a heavy plating of nickel on a mandrel which can later be etched away. For irregular, basically non-structural parts like inlet ducts, vents, and convoluted low pressure plumbing, electroforming is ideal in prototype or custom quantities - often more parts than expected in a "production" run for a Space Shuttle. It has been applied with great success for single-piece seamless bellows. It might also offer some interesting possibilities as a leak tight network of fluid cooling passages against the back of an actively cooled structural panel.

Casting is seldom found in airframe structure because the material strength is so low as to make the parts unacceptably heavy. However, it was the method shown to be a part reducer and cost saver in the fighter canopy comparison of Figure II-10. Even in this case, the quantity involved was something like 200 airplanes, many more units than space contracts normally entail. There are expensive patterns to amortize and molds to produce.

Investment casting, because it starts with a wax replica of the part to be made, seems a useful process for certain applications where a basic standard part needs to be customized in nearly every case. Modifying a wax pattern should be a lot simpler and less prone to distortion or local weakness than reworking the final hard metal part. Metallic high temperature shingles are suitable candidates for the process if thin enough walls can be made. This casting technique has already been used for a similar application - jet engine turbine blades.

Etching is a common way to remove large areas of sheet metal between shallow reinforcement ribs and where thick edges must be left for butt welding. A typical example is a gore for a large tank end dome. The technique is particularly useful where compound curvature makes machining nearly impossible - or, at least, impractical. The application must be cautiously adopted, however, because the large corner radii at the bottom of pockets often add unacceptable weight. Etching is also

applicable where parts designed for light loads become so fragile after material has been machined away that they can't be shaved down to the desired "minimum gage" dimensions. In this instance, the best course is to machine them oversize, chemically etching for final uniform reduction *without masking.* Masking is the most labor-intensive part of a chem-milling operation.

The titanium engine ducts in Figure III-8 were made by chem-milling. It is evident that there is a great deal of masking involved. In

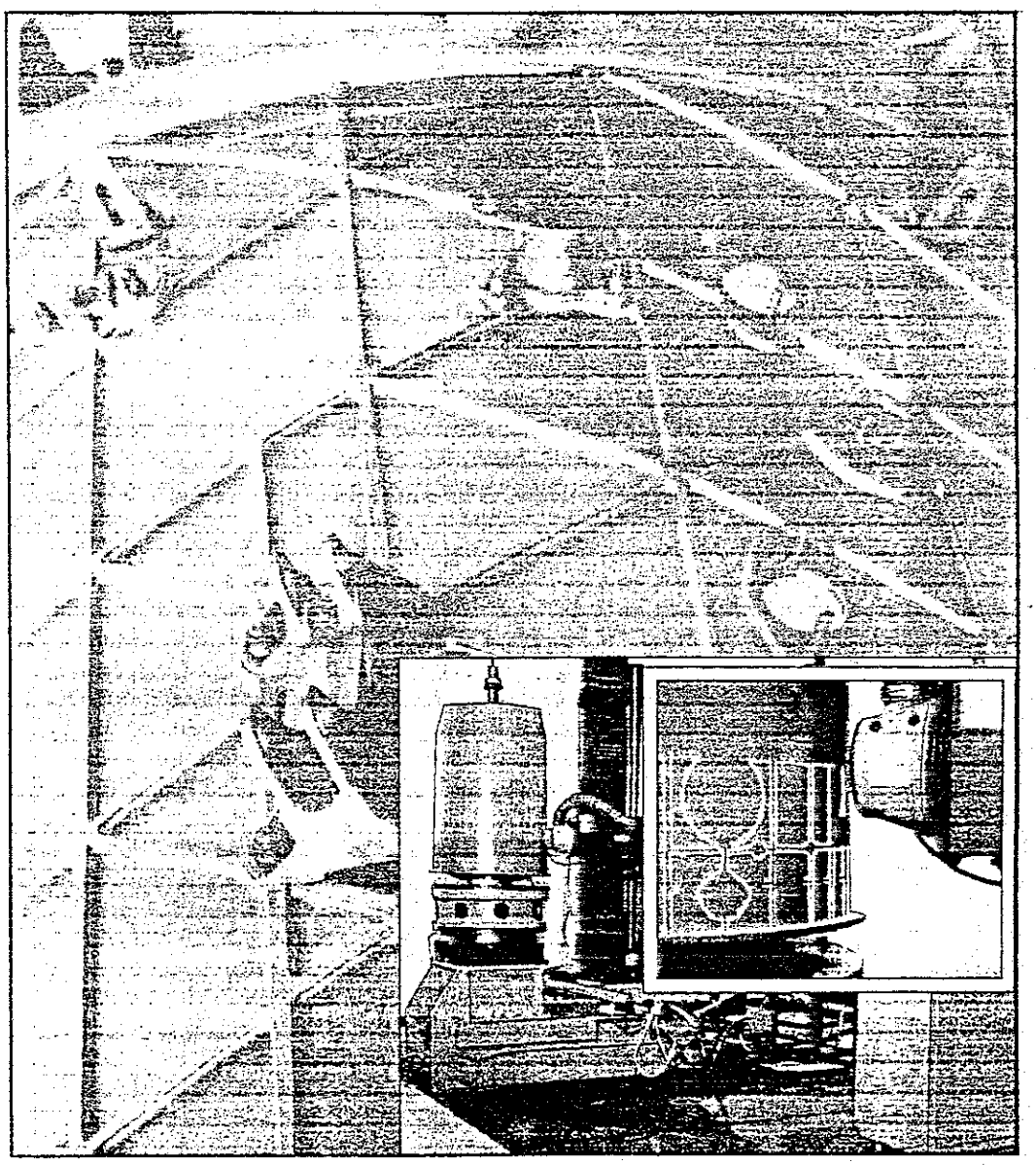


FIGURE V-3 - A 4-axis laser set-up for cutting a maskant coating in preparation for chemically milling a bypass duct assembly.

fact, the mask coating is cut by a computer guided laser beam in a sort of 4-axis milling machine set-up (Figure V-3). The maskant is then peeled by hand, great care being taken to see that it is all removed cleanly. Since the stiffening ribs are undercut, it is apparent that the cylinder is remasked somwhere in mid-etch. When asked why the whole thing hadn't been machined since the attachment edges and bosses and pads needed it anyway, a Chem-tronics engineer at an exhibition booth said that they had "run the numbers" and found machining to be prohibitively expensive. Since the duct requires about 200 hours for its production while the etching takes "only about 20 minutes", one must wonder how the remaining 199.66 hours are spent.

Estimators who "ran the numbers" on the S-IVB hydrogen tank cylinder before it was built turned out. in retrospect, to be off by a factor of 10. As mentioned earlier, they said the tanks would cost two and a half times as much per pound as the skirts.

Machining, admittedly a slow process for metal removal, has acquired a bad reputation in the auto and appliance industries where high speed and reduction of material loss are paramount considerations. For low quantity production, these attributes are essentially meaningless - ***chips are cheaper than paper.*** Machining large single parts which combine all the necessary features of many has been shown by cited examples to be the simplest and most economical method for building aerospace structures. There is no argument with the fact that machining is expensive; yet, when few units are made, the other piece-meal methods are much more so. To make the most of it, the individual parts must be as large as available material stock will allow. The work must be done on correspondingly large machines. Figures V-4 through V-11 illustrate the steps involved in making a fairly large test cylinder, a subscale representation of a much larger proposed tank for a launch vehicle. The steps proceed from pocket milling a large plate on a gantry milling machine to the finished flat part, from there to setting up and forming the part in a 40-foot power brake, then hoisting this part into a weld fixture, and, finally to the completed cylinder assembly consisting of three such parts. The unit is 8 feet in diameter and 16 feet long.

Chapter IV (Figures IV-18 through IV-21) described a large pressurized shell, in that case, a habitable module for a space station. Its fabrication would be much like that of the test cylinder just described, except that the conical ends, machined from curved flat pattern shapes, are a more challenging proposition for forming. The straight line elements converge, calling for special tooling and procedures to feed the parts into the brake. Note the adaptable features borrowed from Skylab experience.

Applying this construction to an airplane fuselage is not quite as

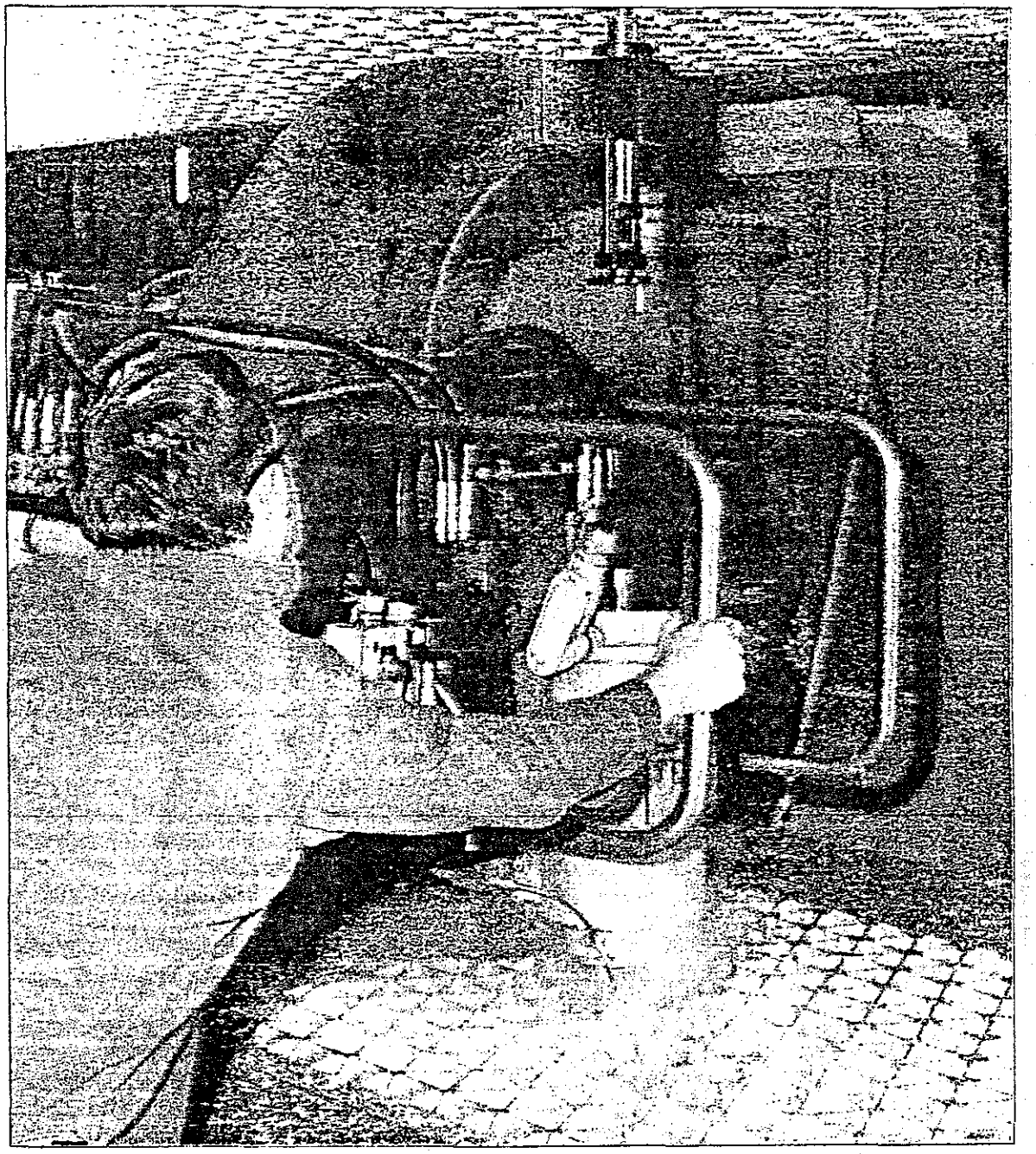


FIGURE V-4 - Machining a test cylinder panel. Numerical control (NC) is not always how it's done, though the master pattern overhead was made that way.

simple unless it is confined to a constant section, probably a short one. It would mean that the rest of the fuselage would be more conventional, losing the advantage of integral construction unless some method were devised to apply it where there is compound curvature.

One suggested approach is to start with an approximation of the final shape, converting lengths between body sections into semi-conical form. These straight-line surfaces can be developed into readily machinable flat patterns. How an F-16 fighter's shape would be modified for this purpose is shown in Figure V-12.

Following forming by a brake or power rolls, the final compound curvature would be achieved by shot-peening or heat treatment with applied pressure against contour templates. More development is needed.

Those concerned about the wisdom of making such large machined parts worry that a mistake would invalidate a large investment. There is also expected difficulty with changes once it has been made. In both cases, it becomes necessary to devise a salvage redesign which will work. It has

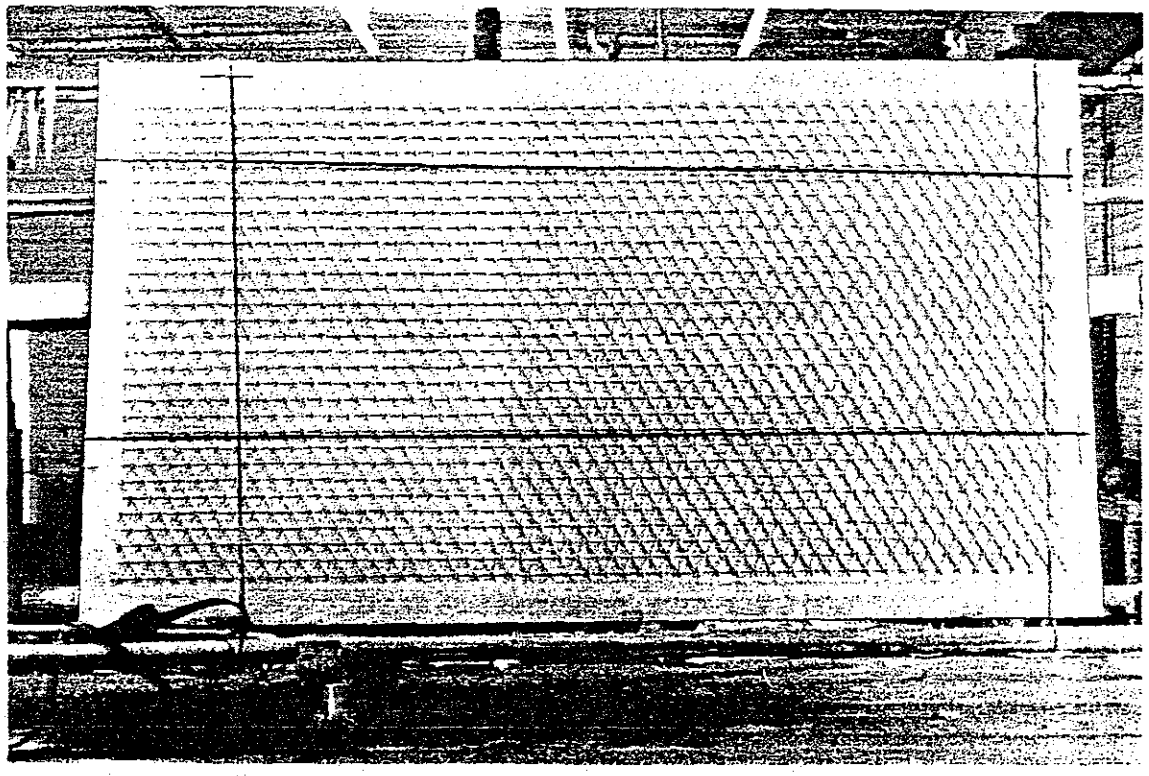


FIGURE V-5 - A completed flat cylinder panel. It is 16 feet long and about 8 feet wide.

been done before, each case being unique, and it does add parts, obviously increasing cost. The result is somewhat patchy, an undesirable situation, but not far from normality in built-up construction. It is still no excuse for starting that way.

Experience with programs like Delta has shown that occasional rework is necessary, declining as learning accumulates. However, the scrap rate is about half that encountered in sheet metal assemblies. Evidently, any machine operator is aware that a mistake in such a large part is a noticeable event, and he doesn't want to call attention to mistakes. On the other hand, the loss of a small sheet metal part is less noticed and scrappage a more routine expectation.

When it comes to making changes which reflect changes of mind rather than part spoilage in manufacture, that is the major thrust of design guideline B. If attachment opportunities exist in a regular and

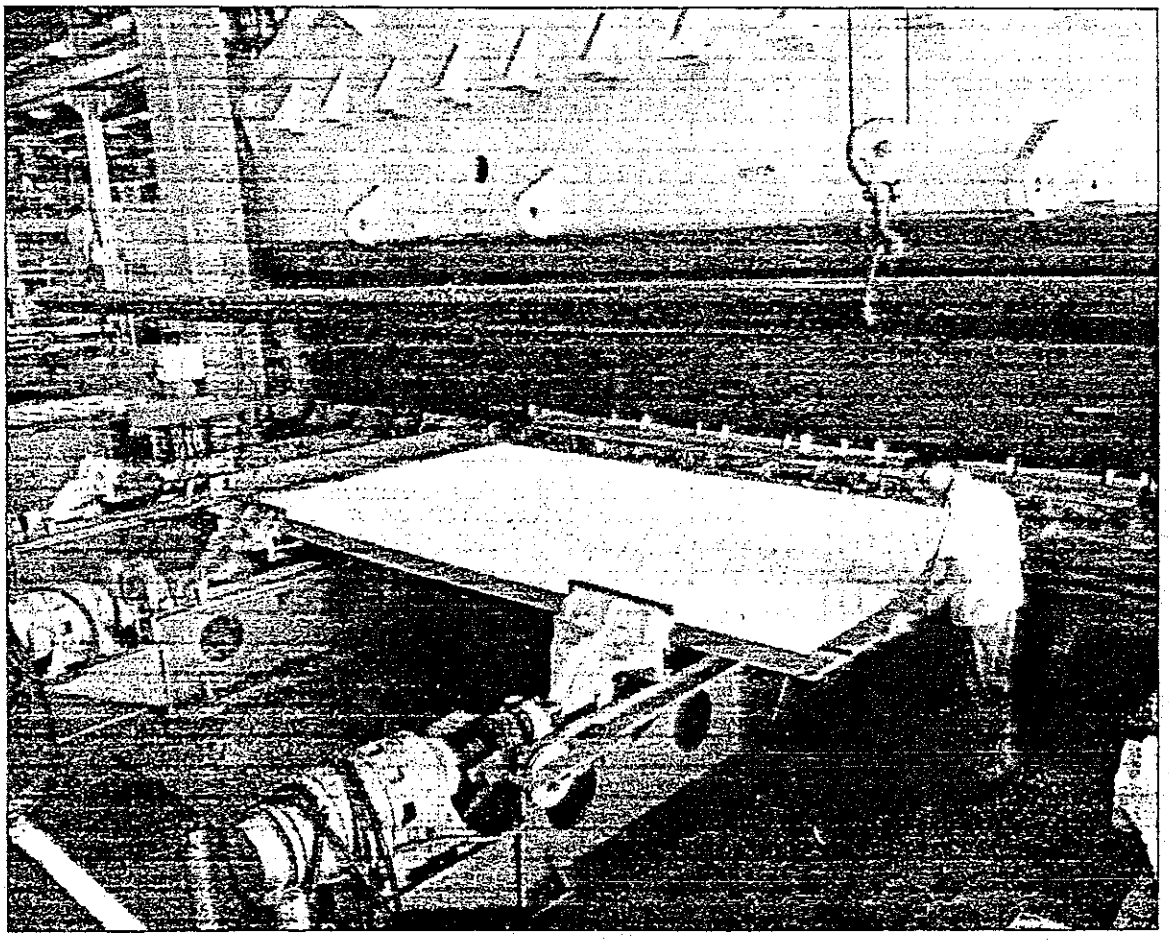


FIGURE V-6 - Applying edge shims to a completely machined panel before forming.

predictable way, as they did on Skylab (inadvertently) or the Delta isogrid payload fairing (intentionally), a botched installation can be remedied by moving the component a short distance away to nodes which have not been damaged. An afterthought, like added insulation, can be accommodated by picking up previously unused nodes. That occurred in at least one case where a payload under the Delta fairing needed acoustical shielding.

The standard stiffening pattern in the S-IVB hydrogen tank was of little help when installations were made by cutting down the stiffeners, interrupting the nodal pattern to machine a welding pad in the skin. This was initially the case on that program, but the standard pattern was still there when needed for Skylab. Having the pattern available is not always enough. It must be explained to installers that the pattern exists and that the hard points in it (the nodal intersections) are the **only** allowable attachment points. Installation design is much simpler and less time consuming when the patterns are exploited.

It must also be standard practice to recognize the pattern's existence when designing cutouts and access doors or windows. Much

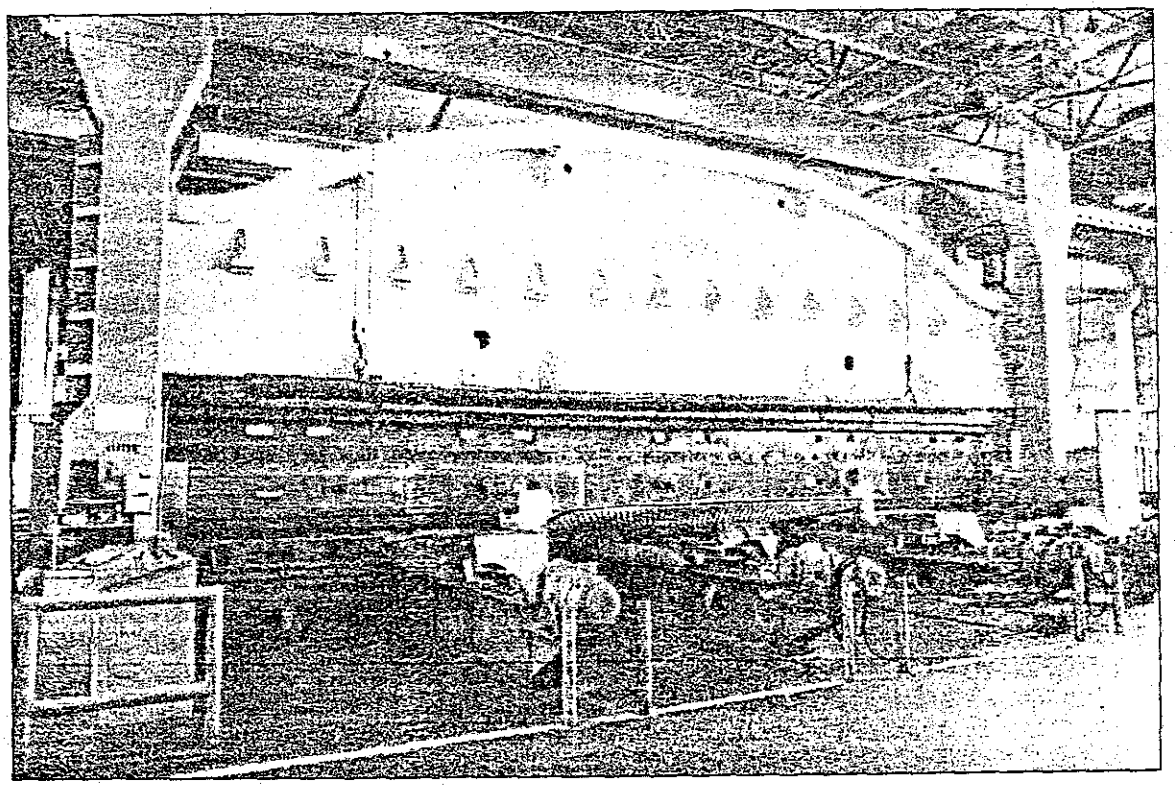


FIGURE V-7 - Forming the large integrally-stiffened isogrid panel in a 40-foot power brake.

mischief can be created when these are made of arbitrary shapes which fail to follow the reinforcement lines, as was done on the Delta program for access doors in the interstage structural barrel. There have been such misunderstandings in the past and probably will be in the future, unfortunately. It is one of the perversities of human nature to make extensive alterations when more amenable ones will do. The first order of business, then, is to make the intentions of such designs absolutely clear at the start.

When it comes to the manufacturing operation of assembly, probably the less said the better because the only satisfactory way to reduce the cost is by repeated exposure to the problem - that is, by learning, the cost descending with quantity along the familiar "learning curve". The only way to obtain this experience is with production. However, even the largest of aircraft contracts probably does not offer enough experience and learning to automate assembly and reduce its cost. Where companies try automation, it is likely to be as much a public relations ploy, to create the impression of "high-tech", as any real attempt to be economical. It is only human to be more interested in looking good than being good.

Just the same, there is one axiom of assembly efficiency worth remembering. It was stated by "Dutch" Kindelberger of North American Aviation after his visit to the Messerschmitt facilities in Germany just before World War II. He said, "Don't let it get too big too fast." The practice

FIGURE V-8 - Checking the contour of the formed panel with an accurate template.

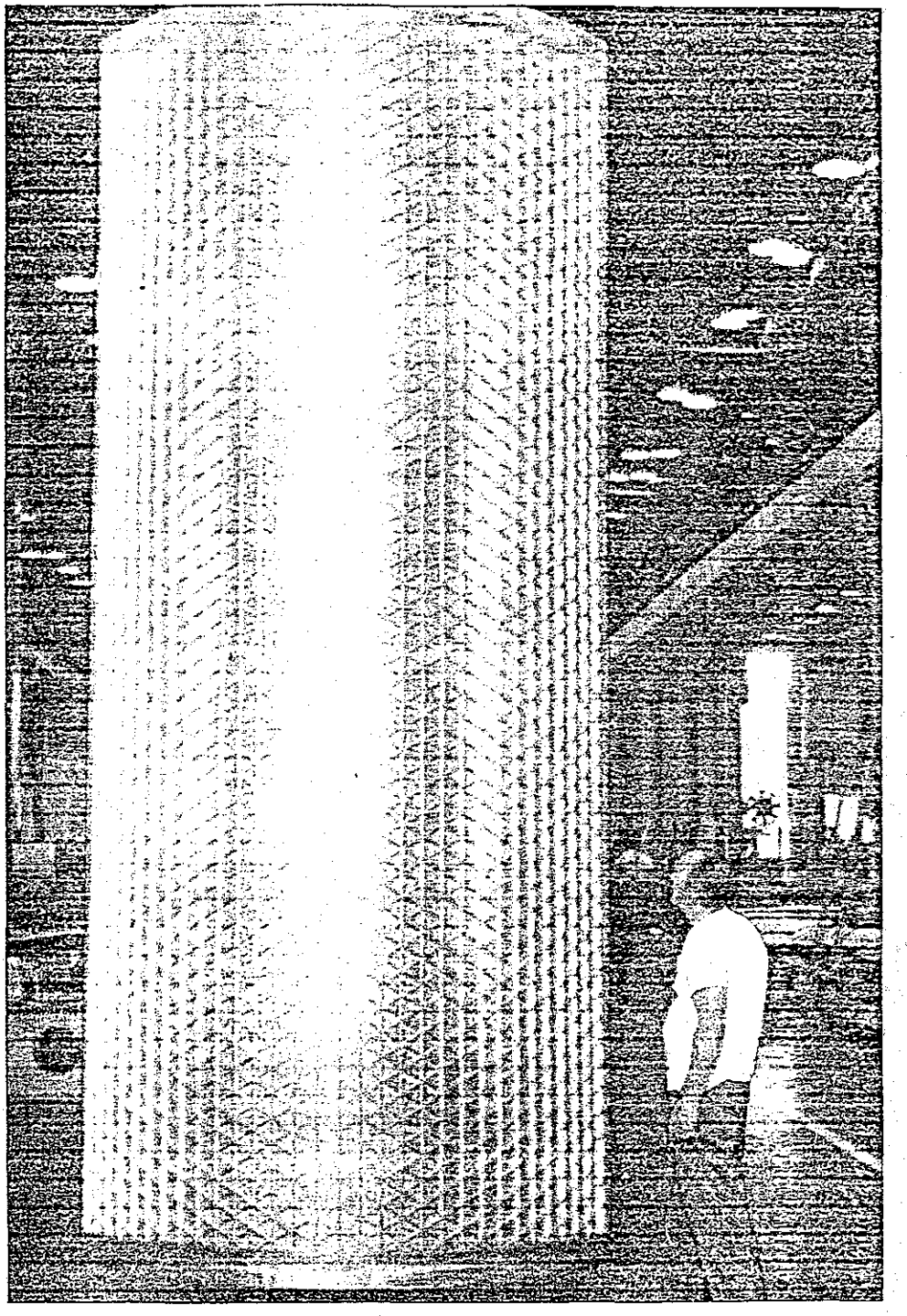


FIGURE V-9 - A formed isogrid panel, one third of a test cylinder.

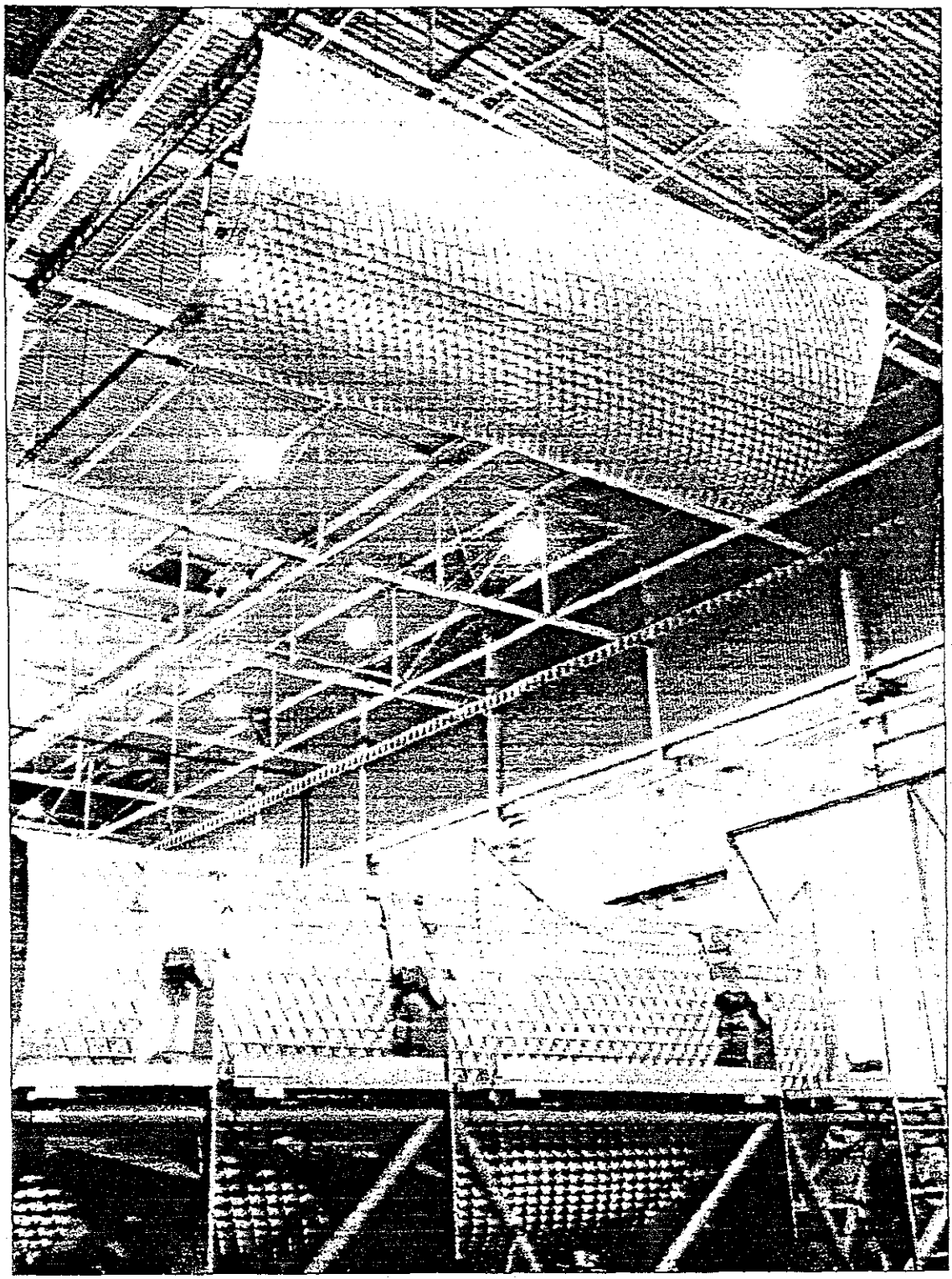


FIGURE V-10 - Hoisting the one third cylinder segment into position above the weld fixture.

followed by North American, leading to that company's early reputation for low cost efficient production, was to complete as much of the airplane as possible in the subassembly stages. That is, final assembly operations were performed on a very short final assembly line. Workers did not stumble over each other in overcrowded conditions.

This practice can only be followed if the design permits it. The design must feature well-defined margins and interfaces for separate units. Not much imagination is needed to see that one very effective way to accomplish this is the modular method described in the previous chapter. What is good for adaptability, maintenance, and repair, is also good for initial production, check-out, and, if necessary, replacement. At the **early** stages of learning, a phase never completed in the low production typical of space programs, the modular design habit should be most useful.

The elimination - or, at least, reduction - of assembly is one of the major benefits from fabrication of very large, accurate parts. ***Large*** and ***accurate*** are the key words here. They offer the prospect of eliminating assembly fixtures, serving in that role themselves. For example, the

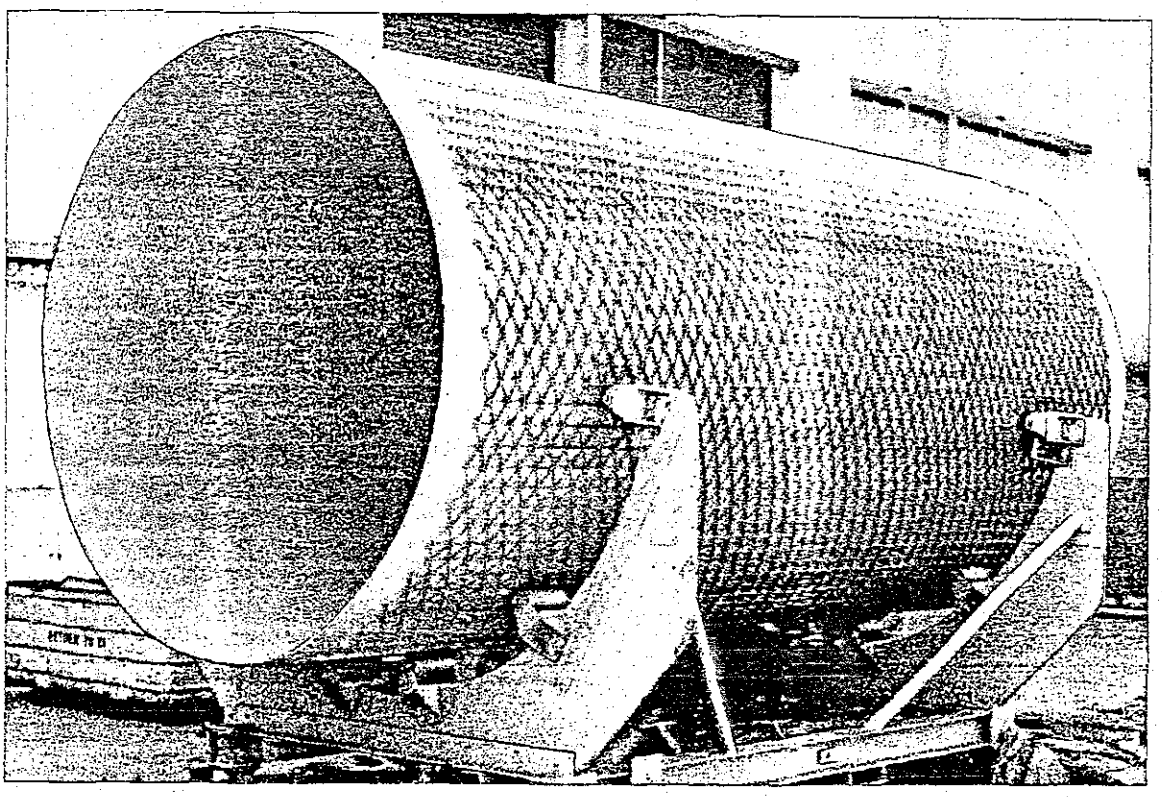
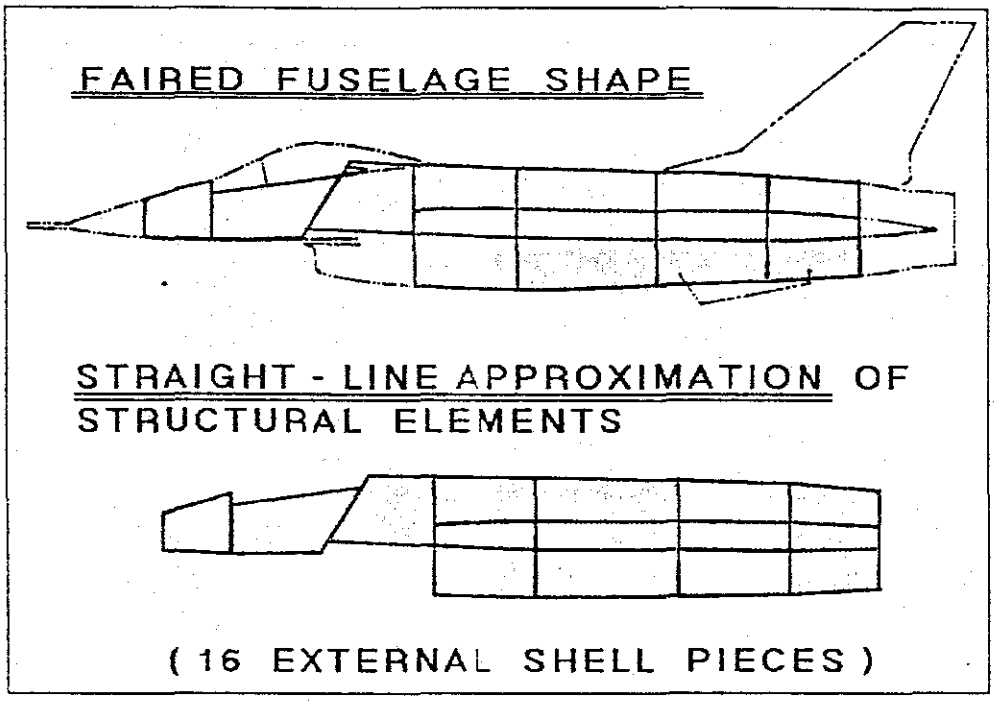


FIGURE V-11 - The completed test cylinder, 8 feet in diameter and 16 feet long. The propellant tank it represents would have been more than four times as large - 33 feet in diameter by 115 feet.

FAIRED CONTOUR APPROXIMATION



INTEGRAL SHELL DESIGN PROCEDURE

- DEVELOP FAIRED SHAPE APPROXIMATION WITH SINGLE - CURVATURE ELEMENTS — CONES, CYLINDERS, FLATS
- LAY OUT FLAT PATTERNS OF ABOVE SHAPES — STRAIGHT LINES BETWEEN SECTIONS JOIN POINTS WITH THE SAME SLOPE
- DEFINE STIFFENING PATTERN FOR FLAT MACHINED PART

MANUFACTURING

- MACHINE PARTS FLAT
- FORM SINGLE CURFATURE SHAPE APPROXIMATION WITH ROLLS OR POWER BRAKE
- PRODUCE GENTLE LONGITUDINAL CURVATURE BY SAGGING WITH HEAT, SHOT-PEENING, OR PRESSURE AGAINST A CONTOUR FORM

FIGURE V-12 - A suggested procedure for making aircraft fuselage integral shells with compound curvature.

forward face of an upper stage platform, shown in Figure V-13, is intended, like the invisible aft face of this same assembly, to be a single machine-perforated disc, roughly 13 feet in diameter, sculptured from 0.7-inch thick plate. All the parts between, and attachments at the edge pockets, are located by pre-drilled hole patterns in these parts. This sandwich structure assembly is the key element of the modular upper stage system discussed in Chapter IV.

Manufacturing laid-up unidirectional composite structures is more of an assembly than a fabrication process in the usual sense. In this case it is just about a thread-by-thread assembly job, something like the textile industry. That industry's product, mostly clothing, should be compared on a cost-per-pound basis with other manufactured goods before embarking on a large scale commitment to built-up composites for aerospace. While automatic machinery was first introduced in the textile industry and has enjoyed the longest use along with large scale production, the price is unusually resistant to the economic benefits of mass markets. Too many threads.

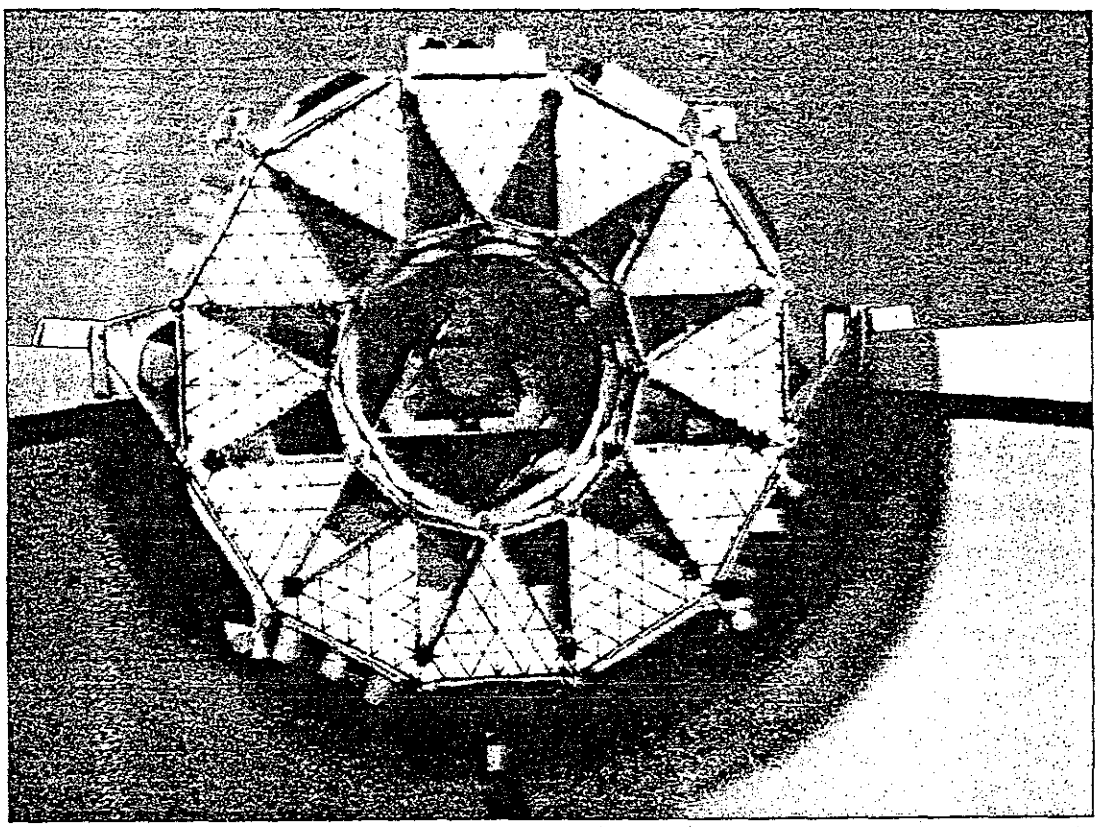


FIGURE V-13 - The front payload attachment face of a standard upper stage platform. It is intended, like the unseen back face of this 20-inch sandwich structure, to be machined from one aluminum plate approximately 13 feet in diameter.

This is why the cost of aerospace composite structure as currently built has almost no chance of being significantly reduced, even if the material were thrown in free. It is a repetition of the apparently forgotten mania for fiberglass which plagued the aircraft industry about twenty years ago. This time, though, the material does have the magical attribute of low density, a property which should be exploited for truly light structure. It is the form of the raw material, not its properties, which stands in the way. It's a little like developing a life-saving drug with lethal side effects.

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CHANGE OF STATE

Shortly after World War II, about 1946 or '47, Frank Whittle, the inventor,a prime mover of jet engine development in England, was in the United States, discussing his work at a meeting of the Institute of the Aeronautical Sciences (IAS, now the American Institute of Aeronautics and Astronautics, AIAA). His address was followed by the usual question and answer session.

One smart young fellow said, "All through your talk you've been referring to jet engine fuel as 'paraffine'. I suppose you meant 'kerosene', didn't you? I can't understand why you use a word which defines wax, a solid, when you must be talking about liquid fuel."

Whittle's reply was, "Yes, it seems we talk different languages, or, at least, dialects, on opposite sides of the Atlantic. On our part, we have equal difficulty understanding why Americans refer to petrol, a liquid motorcar fuel, as 'gas'."

VI - DESIGN ANALOGIES, MYTHS, AND HABITS

The art of design has not changed significantly for many decades, perhaps centuries. It is not noticeably affected by the level of technology. Technology may change the tools available, but not the process itself. It is the art of understanding and defining the problem, followed by trial solutions and the selection of an appropriate concept to solve the problem. It differs from a critical analysis in that it starts with a blank sheet, ready to benefit from the designer's experience and imagination.

How it often works was well described in a 1947 series of articles in the Saturday Evening Post by an experimental psychologist from Ohio State, Renshaw by name. His wartime contribution had been the invention of the tachistoscope, a machine which flashed whole airplane silhouettes for about 1/100 of a second to teach servicemen how to recognize the difference between friendly and hostile aircraft. Analyzing details hadn't worked. The British tried that in a system called WEFT (Wing - Engine - Fuselage - Tail) with minimal success.

The articles were about the workings of the subconscious mind and a characteristic he called "structuring". What happens, he said, is that the brain, when confronted by a problem, subconsciously sets up a framework - something like a spreadsheet computer program, but far more sophisticated. Into this framework it inserts facts, subroutines, and guesses to blend, prioritize, and compromise unknown conditions of the problem until a solution emerges. This explains the "Aha!" effect, a solution appearing, apparently fully formed, when least expected, often in the middle of the night.

He went on to say that this unrecognized talent, developed to some extent in everyone, accounts for the ability of people to remember the faces of others after many years, even after knowing them only slightly in the past. Names and the circumstances of previous meetings may vanish, but faces remain identifiable. At the same time, most of us are hopelessly unable to remember the details of eye shape or color, nose type, eyebrows, mouths, chins, hair, and head shape. Witnesses trying to reconstruct a suspect's appearance for a police artist are notoriously unable to bring out a recognizable likeness. They retain the whole picture but have little recollection of details.

Everyone has occasionally seen someone at a distance whose appearance seems so familiar that the observer has embarrassed himself by waving in recognition. The puzzled recipient of the greeting, on closer inspection, turns out to be somebody else. So, while we may form general relational images, we also retain enough memory of detailed arrangement to verify a mistaken identity.

Renshaw further demonstrated the "structuring" capability by having every student he taught learn how to expose all 52 cards in a playing deck one at a time and then, looking away, turn them up in the same sequence, calling out their identities correctly. According to the articles, while the time to master the skill differed, every student managed to succeed, and all in the same way. After slogging through the exercise in fumbling fashion for a while, the pattern suddenly fell into place, repeating unerringly thereafter.

While humans seem to possess this talent naturally, it is possible to lose it. One of the best ways, according to Renshaw, is exposure to formal education. Our educational system channels thinking into narrow formalized subjects, dragging the mind away from whole-concept recognition. Renshaw illustrated his point by showing a variety of people an out-of-focus black-and-white closeup picture of a Guernsey cow. Most adults thoughtfully analyzed the patterns of fuzzy black and white before finally giving up. Youngsters of pre-school age recognized it instantly as a cow.

In similar fashion, the formal procedural routine practiced on the job by working engineers, has been emphasizing "organized" approaches to problem solving, masquerading under the title of "system engineering" and featuring "trade studies". This activity has probably received much of its impetus from the existence of computers, their accurate and rapid computational ability, and the tabulations necessary to make their information storable and retrievable. Unfortunately, it has tended to make engineers think a lot like computers when, in actual fact, they are much more capable. This is not to say that computers are not magnificent working tools; it's just that their output must be interpreted with judgment.

While a computer can analyze with lightning rapidity, it is only able to perform as it was programmed. It lacks imagination. It cannot interpret unusual or unexpected relationships, the sort of thought that produces inventions, or even minor variations on familiar themes, what we know as analogies. It is equally incapable of recognizing the wrong analogy when it shows up. This is sadly becoming a characteristic of engineers who have been trained to follow "organized" procedures.

Skylab - the Protection Shield That Wasn"t

When Skylab was launched it met with catastrophe. A meteoroid shield was torn off by air loads, taking with it one of the "arms" from which the power-generating solar arrays were to deploy. It also jammed the other one, making the deployment mechanism inoperable. In one of the more

interesting space adventures to date. the first boarding crew was finally able to release the surviving solar array and rig a sun shade to keep temperatures under control. Ultimately, the mission was completely fulfilled and valuable information. not to mention experience, was obtained. Luckily, a recovery was possible and a shield for meteoroied protection proved to be unnecessary.

The main finding of the ensuing investigation was that the meteoroid shield was improperly sealed, that air under the shield, at higher pressure than the thinning atmosphere being traversed at the time, lifted the sheet metal blanket, allowing air to get under the leading edge and tear it off. The blame for this was placed on the design group charged with the responsibility for doing a spectacularly thorough job of sealing and venting to prevent such a failure. While all this contributed to the anomaly, it was not the primary cause.

The protective shield, also acting like a radiative insulation layer for the "vacuum bottle" surrounding the inhabited volume, was intended to stand off the tank wall a uniform 4 inches all around. Since there was no load on it in space, it was nothing but a 40-mil unstiffened aluminum sheet, wrapped snugly against the tank during launch. It was expanded by extension of a fold-over section and guide links at the ends after its release along a pyrotechnic "zipper". As originally conceived, it was to be rigged to a tightness approaching the yield strength of the sheet material so that it would resist expected pressure gradients. Control of the gaps around the edges, as later events proved, would be very difficult for about 160 feet of thin panel edges. To maintain a uniform edge seal for such a thin sheet against the tank cylinder would not be easy to assure or even to measure.

This is where the wrong analogy entered into the picture. While a tensioned sheet - or cable winding - wrapped around a cylinder causes hoop compression just as an application of external pressure does, it was also assumed by the stress department that the allowable compression stress would be the same in both cases. Of course, a snugly fitting wrap doesn't work in the same divergent way as external pressure does after the circular cylinder goes out-of-round under load. Apparently, cables wound on hollow drums can stress the drum far beyond the level at which collapse would occur from external pressure. However, very little information on the allowable load intensity was found, so a small-scale test was proposed to establish appropriate coefficients. The Skylab program, however, had established a "no test" philosophy to convey the impression of cost consciousness, the test was disallowed, and the flimsy meteoroid shield was carefully loosened to prevent collapse of the Orbital Workshop cylinder wall during launch. So it came off. Since none of this got into the official investigation report, it is one of the many "lessons" *not*

learned on Skylab to be available for future designers faced with similar circumstances - or perhaps avoiding them for the wrong reasons.

Space Shuttle - the Cargo-Carrying Bomb Bay

Analogy is always at work to some extent in the design business. It is useful to remember a previous design which approximates the device or system currently under consideration and apply it to new circumstances. For example, the Space Shuttle payload bay was assumed to be much the same thing as bomb bays designed into combat aircraft. The same kind of construction was adopted - a pair of longerons along the free edges at either side, stabilized by internal transverse frames which also stiffen the shear-carrying side panels. (Figure VI-1)

It seems to make sense until one considers that bombs are secured in place by bomb shackles up in the center of the bay, not along the door hinge lines, where Shuttle payloads apply the large inertial reactions caused by launch conditions.

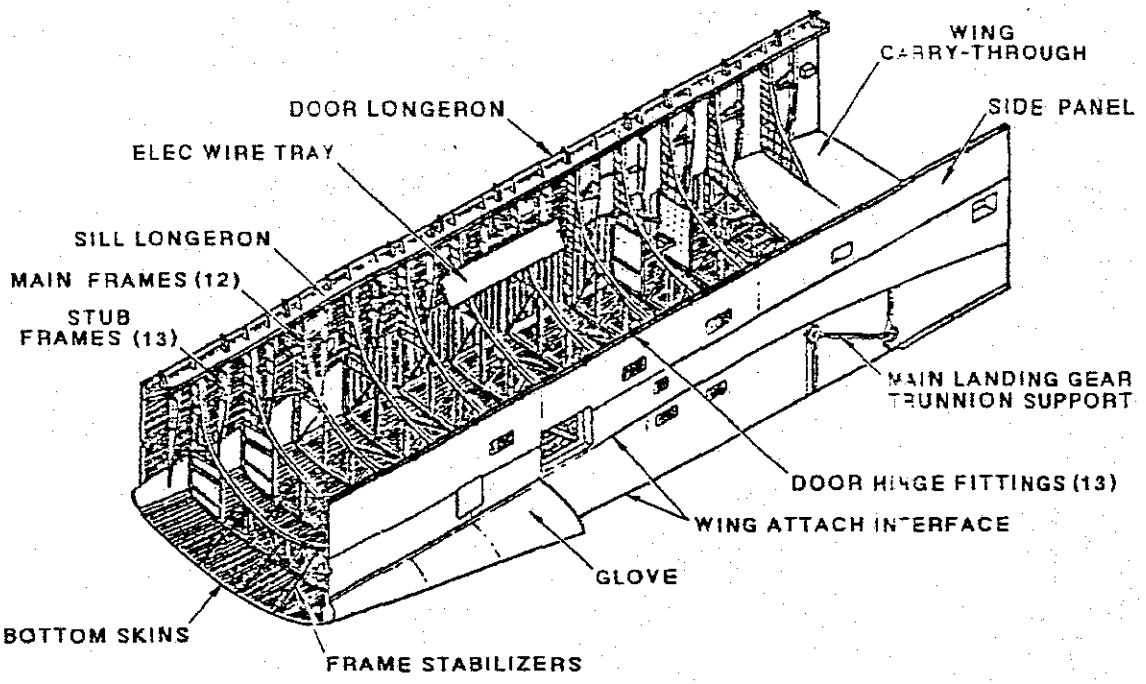

FIGURE VI-1 - The Space Shuttle Orbiter center body, a payload bay built like a bomb bay. Though unnecessarily complex, and based on an inappropriate analogy, it is probably the best designed structure in the vehicle.

When properly stabilized, the longerons can effectively handle thrust loads, but not side forces. Such long beams would be prohibitively heavy. Therefore, in the Shuttle, these loads are resisted at the keel on the bottom centerline of the bay, far removed from the center of gravity of the typical payload. The moments resulting from this eccentricity are then handled as a vertical force couple between longerons on either side of the bay. These bending moments exact their penalties in the form of structural weight in both the carrier vehicle and the payloads. The latter are the more heavily penalized.

The major thrusting loads, as mentioned before, are carried by the longerons at a pair of points 188 inches apart (15.66 feet) and 14 inches above the centerline of the payload envelope. Even the cradles supporting relatively small payloads must bridge this long span and take the load eccentrically at only two points. The bay was obviously designed to work with a full 14- or 15-foot payload weighing close to maximum capacity, originally advertised as 65,000 pounds.

So far, the only payload close to this size has been Spacelab and it, fortunately, weighs a lot less than the maximum. Meanwhile, for other delivered spacecraft and satellites, a typical penalty for an adapter cradle, the fixture allegedly "integrating" it into the Shuttle, is on the order of 25 per cent or more. No other carrier so heavily penalizes its payloads. What it means, of course, is that the unattained maximum payload (made unattainable since the Challenger disaster) was more like 75 to 80 per cent of the claimed 65,000 pounds - perhaps 52,000 pounds, at best. Actually, no Shuttle flight carried more than 50,000 pounds and delivered much less as useful payload, with future prospects considered to be much lower. It makes one wonder how valid the Space Station program estimates of flights to full operational capability really are. Has sufficient allowance been made for undefined adaptation hardware?

When it comes to the loads vertical with respect to the payload bay coordinate system, primarily the crash landing conditions which must be met even if never experienced, the situation worsens. These forces are applied at trunnions along the ***inside*** edge of the longerons, 11 inches away from the outboard side panels which eventually carry them. They can only be resisted at the frames, spaced non-uniformly about 5 feet apart, and the longerons are too shallow to function as effective beams between frames. Since the payloads, already penalized enough, cannot be expected to adjust their attachment spacings to fit the frame spacing, a set of removable bridges has been devised to fill the interframe gaps on an "as-needed" basis. They are not particularly light or efficient or standardized because of the non-uniform frame spacing previously mentioned. At the bottom center keel, side loads can also be accommodated only at the frames, creating a similar set of bridges, these

being further complicated by the inability of the keel attachments to carry thrust forces. There are other complexities, but the description is already complicated enough.

If all this sounds like a conflicting set of afterthoughts created by inadequate initial planning, it should. What should also be clear is that a bomb bay is a poor analogy for a cargo carrying space, that the more appropriate one would be the hold of a commercial airlifter where there are tie-downs all over the floor. This would suggest that the semi-cylindrical inner contour defined by the tops of the transverse frames, instead of being only a non-structural liner, should become load-carrying structure with means for support of payloads like a cargo-liner's floor. Instead of a payload bay cross-section like that shown in Figure VI-2, the existing configuration, it might be more like that in Figure VI-3. That is, the structure needs to be turned ***inside-out***, the cargo bay liner turning into an integral open isogrid array (equilateral triangles, like Skylab floors and partitions) without skin but with lots of anchor points built in at the grid nodal intersections. To minimize weight growth, these hard points, the inherent intersections of bars in the grid lattice, can be capable of receiving tie-downs but needn't be burdened with them initially. The compartment can be sealed off with a very thin liner film, if necessary, for

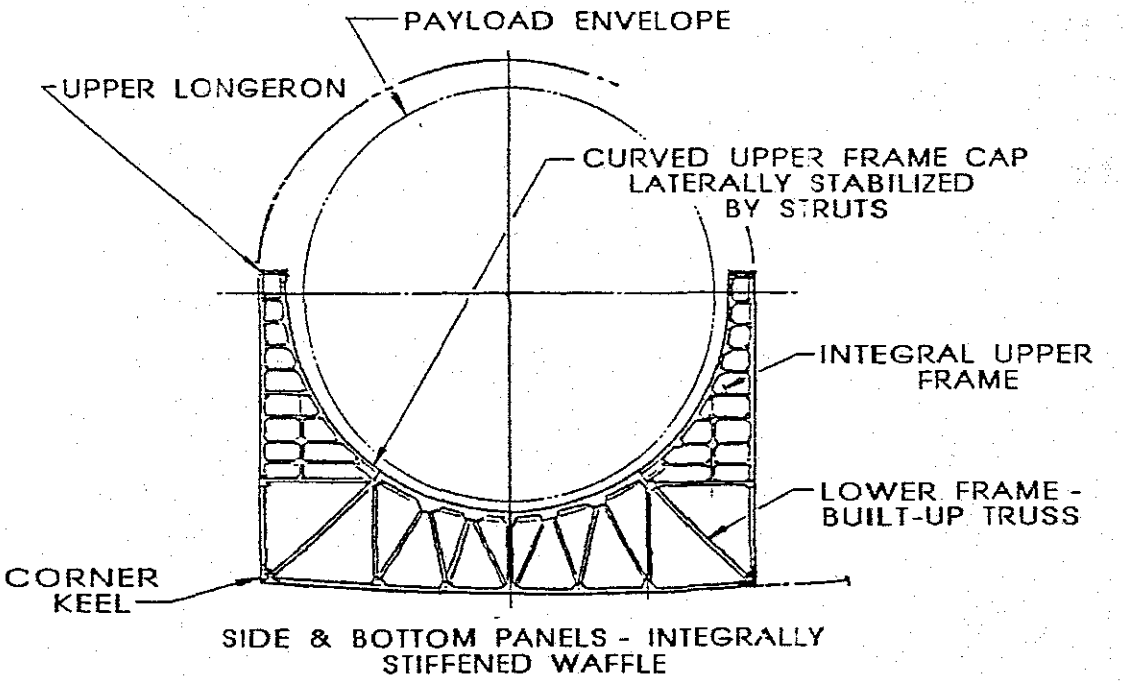

FIGURE VI-2 - A typical cross-section through the Orbiter payload bay, showing the jumbled mixture of construction philosophies involved. Payload inertial forces, applied at the inside edge of each upper longeron, make inter-frame bridges necessary.

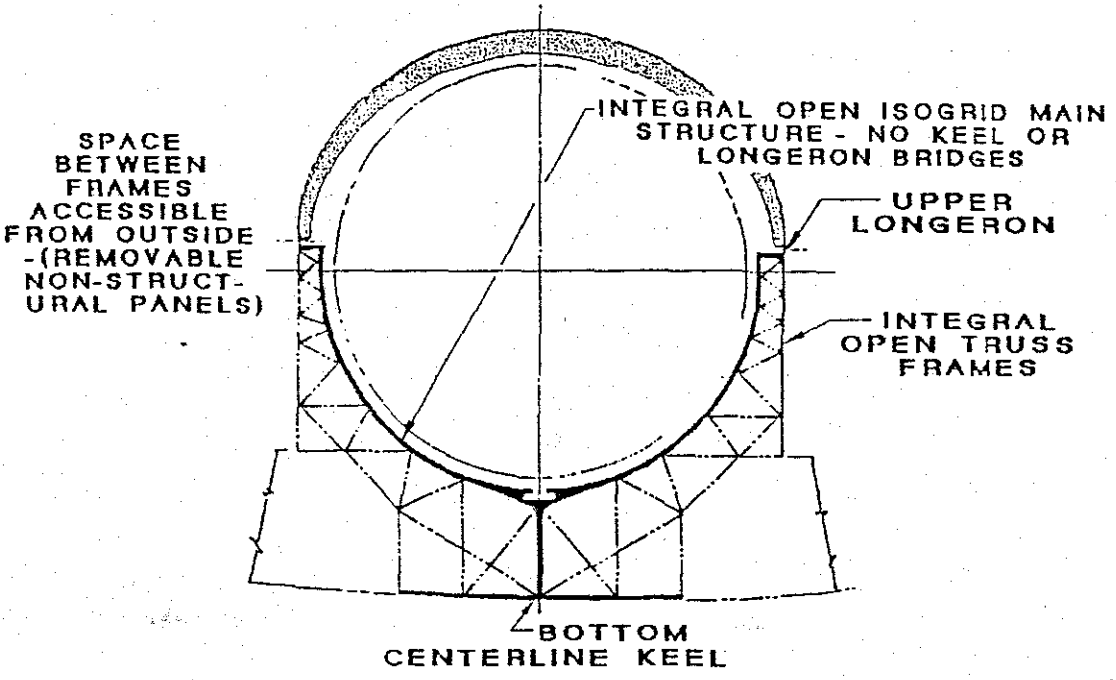

FIGURE VI-3 - When the structure is turned inside out, the main load path between upper longerons and keel is an internal integral open isogrid half-cylinder which is in line with the applied payload forces. No longeron or keel bridges are needed. Frames, fewer and farther apart, are also open integral trusses, providing passage for systems intercommunication without rework.

ventilation control.

When something like this is done, interesting possibilities emerge. First of all, the bridges can be eliminated entirely because the loads they were feeding indirectly to main structure can be put directly into the internal shell. Small payloads could then be mounted on this liner structure - not necessarily ideal, but an improvement over 15-foot cradle beams. Frame spacing could probably be increased and, with any luck, made uniform. Finally, the outer side surfaces, no longer structurally necessary, can become removable modular panels, carriers of accessible and replaceable subsystems, modules, as described in Chapter IV. It also permits access to the volumes under the cargo bay ***when a load is in place.***

The Shelvador

This name was bestowed on a package-carrying door for refrigerators made by the Crosley company. When first introduced in the early 1930's it was a novelty protected by a patent which earned for the Crosley company

a larger share of the refrigerator market than would otherwise have been expected. Besides, it made a lot of sense. As long as a refrigerator must be sealed by a door, why not use this structure as something more than a lid? By incorporating narrow shelves, it can be made part of the food storage volume in the box. More than that, as this space is swung open, it uncovers the in-box storage behind it, making both sets of contents accessible. At the same time, it permits the main shelves to be shallower and less likely to contain hidden packages in the back rows. In general, packaging can be both denser and more accessible - denser because no passages need to be reserved for withdrawal of the contents, and more accessible because part of the stowage volume swings away.

For some reason this ingenious idea seems to have found little application except in refrigerators where it is now universally the rule. The Crosley company's competitors lost no time adopting the practice after the patents ran out in the 1950's. Perhaps the hinges on most other doors are too flimsy to accept additional weight, although there are occasional signs that the idea is recognized. Kitchen cabinet doors sometimes support spice shelves, and house doors can be found with letter boxes attached.

Probably the only aerospace application of the storage door can be found on the Lockheed F-104 fighter, a machine which offered many other examples of design excellence. The central units of this airplane's hydraulic system are mounted on the inside of a door under the engine compartment. Electrically-driven pumps, regulators, and accumulators, with their interconnecting plumbing, are arranged like commonly used hydraulic system training units; the door even hinges on hydraulic swivel connectors. As this installation swings down for easy inspection, maintenance, or repair, it also exposes the underside of the engine for the same treatment.

In conventional stressed skin construction, where the stiffening patterns are rectilinear, large openings like this tend to cause weight penalties, setbacks which are accepted for the access they offer to critical subsystem units. Sometimes, the penalty is reduced, but not eliminated, by making the door load-carrying. Stressed doors like this, held in by closely spaced bolts around the perimeter, are removed with difficulty and not at all rapidly. They are also subject to damage like stripped bolts and nutplates when frequently opened. While it may not be possible to get something for nothing, much of this difficulty can be overcome if the basic structural stiffening arrangement is triangular or diagonal, automatically shear-carrying whether a skin is present or not. Where appropriate, the skin, if needed as an aerodynamic fairing or a thermal barrier, can be a quickly removable, possibly hinged, door panel. The back side of this plug can be designed as an equipment mounting surface, preferably with a standard "pegboard" pattern like isogrid which has universal application -

and is also strong and light.

To illustrate this concept, Figure VI-4 shows an access door on the Delta launch vehicle as it was actually built. The stressed door swings open to allow an electronic package to slide out on a track for access. This may look like a fairly neat idea, and has been so considered by some observers, but there are a few drawbacks:

The door, like all stressed doors, comes off slowly. Its jamb distorts so much if the door is opened when the tanks are full that it cannot be reinstalled. This has happened and has led to the production of a heavy removable frame to reinforce the opening for such events.
When the electronic package slides out for service, it completely fills the opening, making anything else in this intertank space inaccessible. That accounts for the other access door.

To position the electronic package so that it emerges in the right place, it is installed far inboard from the structural shell which must resist its inertial loads during launch. This creates a heavy set of beams and brackets to feed the load out. A major cause of overweight in flight vehicles is this practice of carrying load in long flexible beams - the cradles in the Space Shuttle, for example.

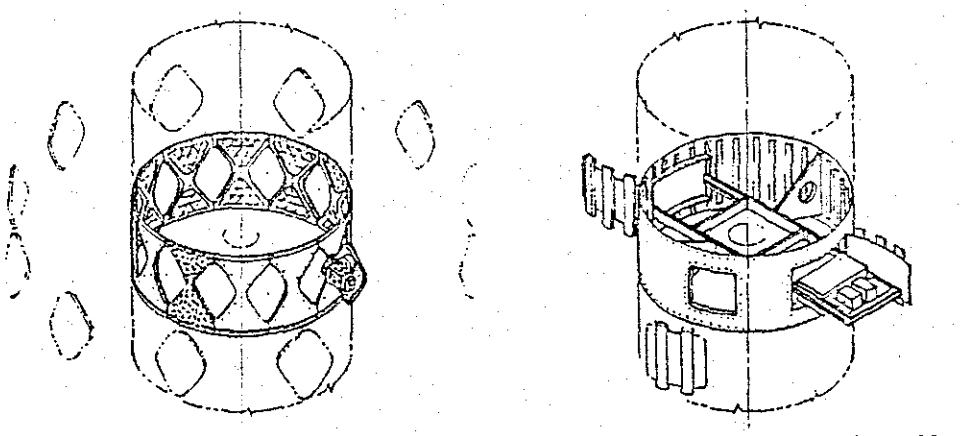

FIGURE VI-4 - A comparison of a simplified intertank structure for a Delta launch vehicle with the existing design. The anticipation of subsystem needs in the structure is typically lacking in such cases, the Delta vehicle being no worse off than most.

Then, of course, there is the long (and. consequently, heavy) wiring harness which must stretch to accommodate travel along the track without becoming caught in it and jamming the action. The track itself is another heavyweight like the supporting beams and prone to becoming jammed by little objects. Further, if it works freely it does not support its load very rigidly, making its survival in a shake test a bit doubtful. If the adjustment is too snug, the track can seize. Hinges are much more reliable and a lot lighter. Essentially, this installation has been considered analogous to a file cabinet or electronic rack, another example of the wrong analogy.

Alternatively, if the basic intertank structure consists of "X'-shaped integral panels, interspersed with diamond-shaped holes, as shown on the other side of the figure, equipment can be mounted accesssibly on the inside of panels covering these holes, feeding inertial loads directly into the shell, allowing rapid release because they are not needed as primary structure, and permitting easy access to the spaces behind them when they swing out. Panels like this can also, if made from dielectric materials, serve as antenna "windows". In other applications, the holes can accommodate umbilical panels or ventilation shutters. Of course, electronic packages of the present size wouldn't fit but also wouldn't be likely to grow as large under different circumstances, their place being taken by more and smaller units.

Perhaps the ultimate application of the "Shelvador" principle is the conversion of a Space Shuttle payload bay door into the cargo carrier, as mentioned in the discussion of modularity (Chapter IV). This permits cargo manifests to be installed and checked out while the Shuttle is in orbit, offering large benefits for reduction of ground time. It would seem also to permit a similar exchange at the other end of the trip if a first knocked-down unit can be assembled in orbit, ready to fill the payload bay gap for subsequent entry. Such units, in fact, could replace the "logistic module" now contemplated for a space station as long as berthing interfaces and, possibly, pressurized canisters were incorporated into their design.

The whole area of design with equipment-carrying outer panels held in an open skeletal structural frame is largely unexplored. Further examples, like the modular family of upper stages mentioned in Chapter IV, need to be examined in greater detail.

Accessible Engine Installations

An engine compartment urgently needs to be accessible because

there is so much equipment that must be examined, checked out, repaired, or replaced, and the engine itself makes a formidable obstruction. This is why jet engines are mounted on pylons, covered by removable panels. Reciprocating engines, for the same reason, were mounted on open trusswork ahead of a firewall and covered by easily removable cowlings. A further virtue of such installations is the ability to offer the same basic airplane powered by different engines in the same general class and to update with more efficient or powerful units at a later time.

Rocket engines are often out in the open with no cowling around them, though their accessories may be buried behind some form of heat shield. In the case of the Space Shuttle, the ultimate in inaccessibility seems to have been reached. The engines, a cluster of three, are supported by trusswork, closed off by a heat shield bulkhead, and surrounded by a heavy structural shell, as illustrated none too clearly in Figure VI-5. This is an attempt to show a very complex installation in simplified form. All of the equipment is omitted for clarity, but the pump supports where the feed lines meet the engines show that all three engine installations are different. It is hard to foresee any great improvement in turnaround time for this vehicle as long as such an inaccesible condition prevails. No amount of advice from airline experts can make the necessary design alterations, the cure which might work.

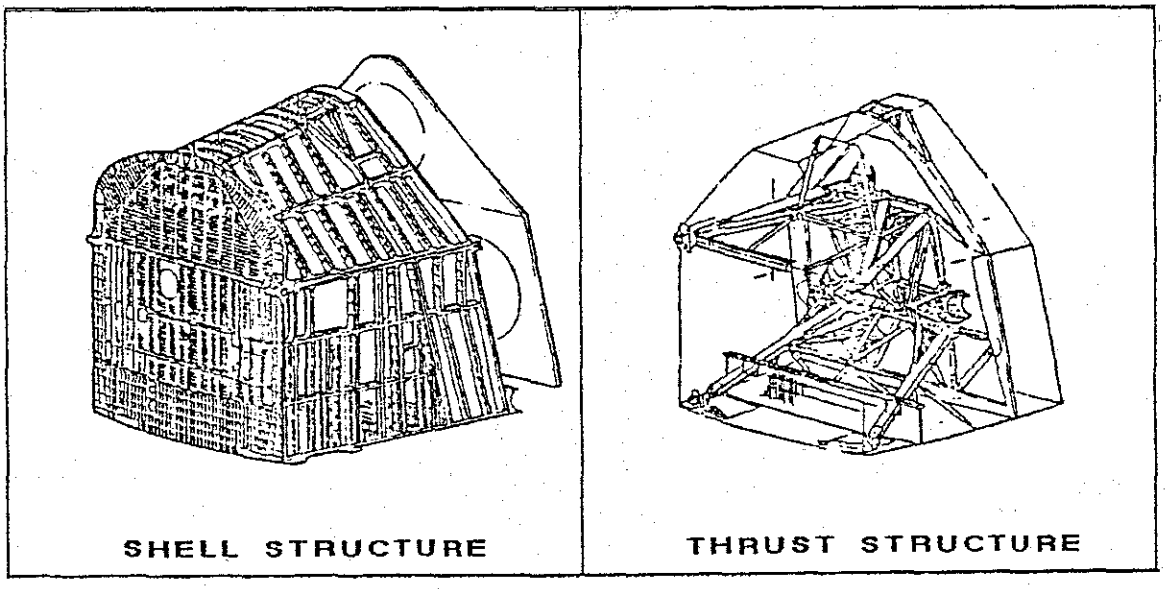

FIGURE VI-5 - The interdependent shell and "truss" structures of the Space Shuttle Orbiter aft fuselage. Because the "truss" is not a complete stand-alone structure, the outer shell is indispensable in this design, making ready access to the sybsystems in this compartment impossible without large weight penalties.

The trusswork should offer all the structural support needed in this area, except that it is not a complete truss. It is not stable unless it is connected to the shell. The inability of the members to handle the extremely large thrust loads comes from an arrangement that must leave room for six 12-inch propellant feed ducts as well as furnish hard points for turbine pump and gimbal actuator reactions. A geometric hodge podge is caused by a square gimbal pattern superimposed on a triangular engine cluster - thus the dissimilarities at the three mounting points.

Study of the situation reveals that the problem seems to have arisen from semantics; the gimbal axes which position the engines have been labeled "pitch" and "yaw" which have been interpreted to mean the pitch and yaw axes of the overall vehicle system. If these axes are recognized as mutually perpendicular directions which can be rotationally oriented in any appropriate way, the engine cluster geometry can be greatly simplified. The interface plane pattern, as shown in Figure VI-6, is basically symmetrical about a line between the gimbal actuator attachment and pump support points. In a triangular grouping of uniformly spaced engines, the symmetry lines can converge at the center of the pattern, creating essentially identical patterns at the corners (Figure VI-7). The mathematical rotation of gimbal motion components into the vehicle's pitch and yaw directions is a relatively simple algorithm for a

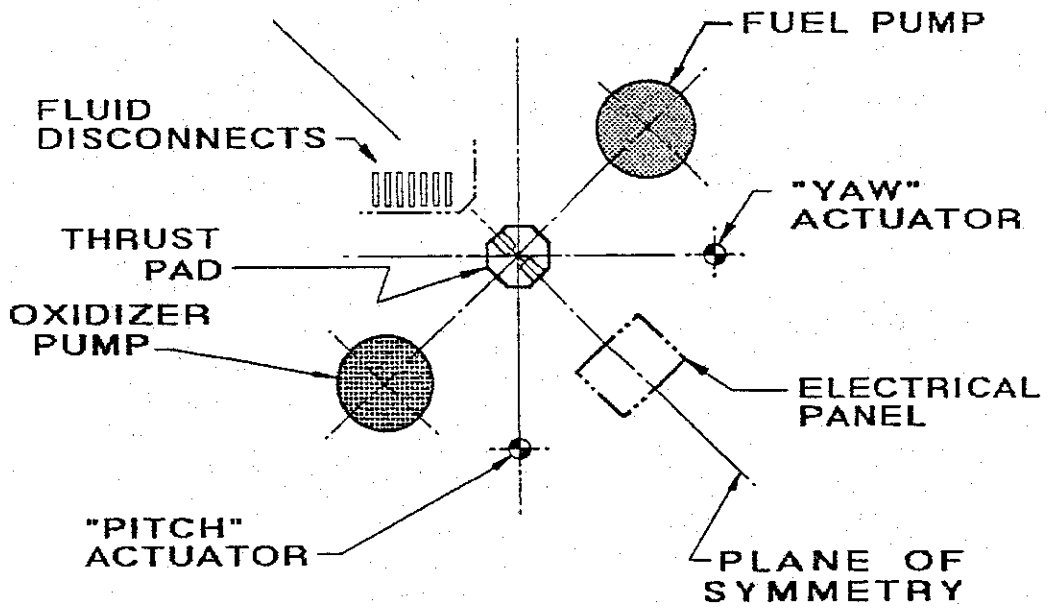

FIGURE VI-6 - The basic geometry of the Space Shuttle Main Engine (SSME) mounting interface, shown aligned with the vehicle coordinate system. The interface is essentially symmetrical about a line bisecting the angle between gimbal axes.

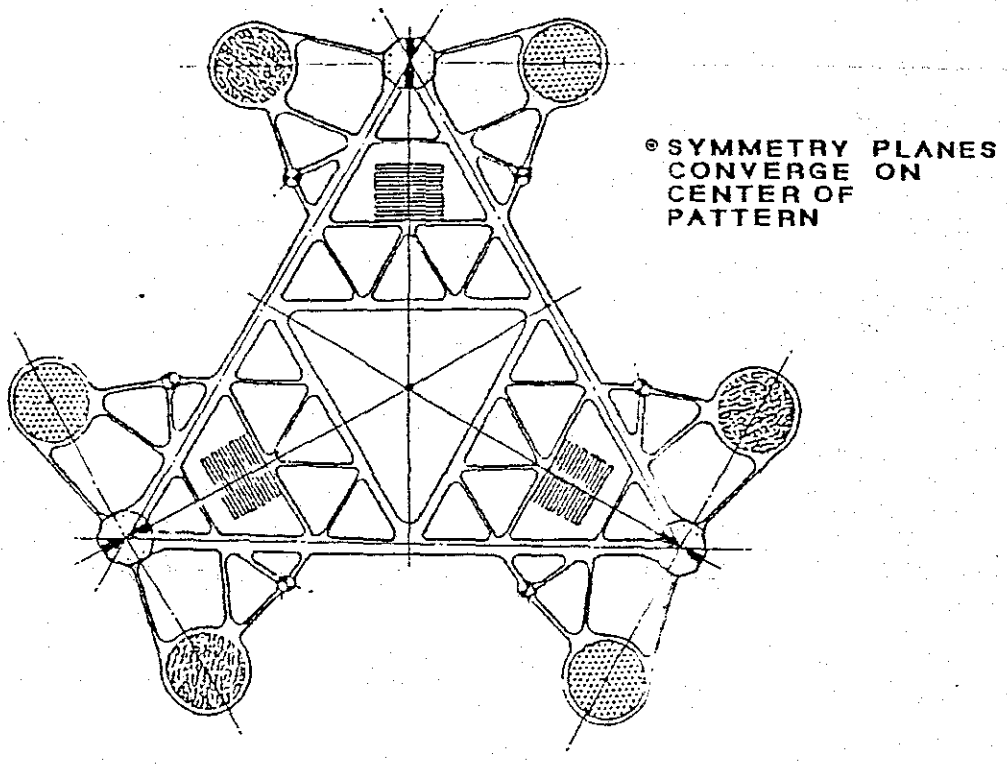

FIGURE VI-7 - How a three-engine cluster can be organized to offer identical installation for each of the engines by orienting the three interfaces so that their symmetry planes converge at the center. The integrally machined open truss-work at the engine mounting plane always contains the elements shown but can be extended to the outer surface as needed in different applications.

guidance computer, considering all the other computations it performs.

The canted plane defined by the three engine thrust points, contains a triangular face of an octahedron, its forward counterpart being a reversed triangle on the aft bulkhead of the payload bay. This geometric arrangement is shown in Figure VI-8. Figure VI-9 is a photo of a small scale model which more clearly, if incompletely, describes the situation. This distorted octahedral box is all the structure needed for the Orbiter's aft end, all the external panels being removable for access, serving as both equipment-carrying modules and as a heat shield to protect the enclosed volume. The engine support structure can be functionally (with appropriate disconnect provisions) and structurally isolated from the rest of the vehicle, facilitating its removal for replacement and updating for advances in performance or technology. Its adaptation for other vehicles based on the same system can also be contemplated, as illustrated in Figure VI-10 .

The "Quick and Dirty" Myth

It is too often assumed that something which looks crude is inexpensive. It is, to be sure, a "cheap" way to go if the word "cheap" is correctly interpreted to mean lower quality. However, if a one-of-a-kind test or demonstration article is made of a lot of pieces, such as a substitute machining blank built up of welded elements, cost will increase rather than decrease. This is what was discovered in the cost analysis of a prototype fuselage bulkhead in 1953, the case of the XF3D-3 mentioned in Chapter II.

In the welded blank example, the various pieces must be held in proper alignment to assure a reasonably sound weld; that means a tool, a weld fixture with appropriate stops, clamps, locating pins and holes, and probably partial dismantlement for removal of the finished part. Extra man-hours are incurred by designing and building the tooling. They are bound to cost a lot more than simply starting with a much larger blank and spending a bit more time making chips. Weldments, beside degrading the physical properties of most materials where least wanted, frequently

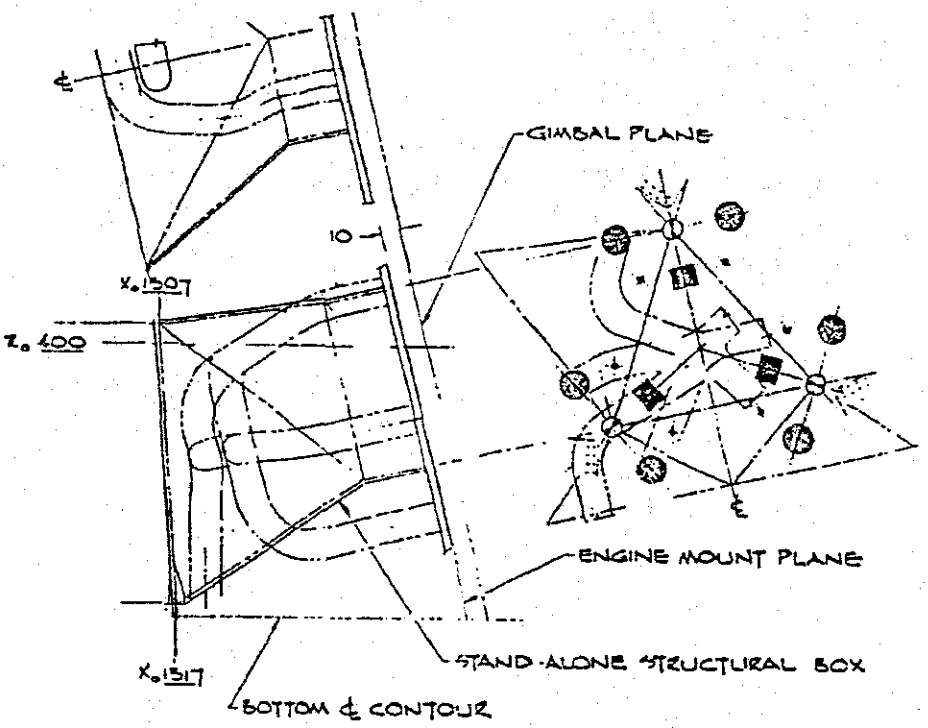

FIGURE VI-8 - The overall geometric arrangement of the tri-symmetric engine grouping as it applies to the canted thrust vector required by the Space Shuttle Orbiter.

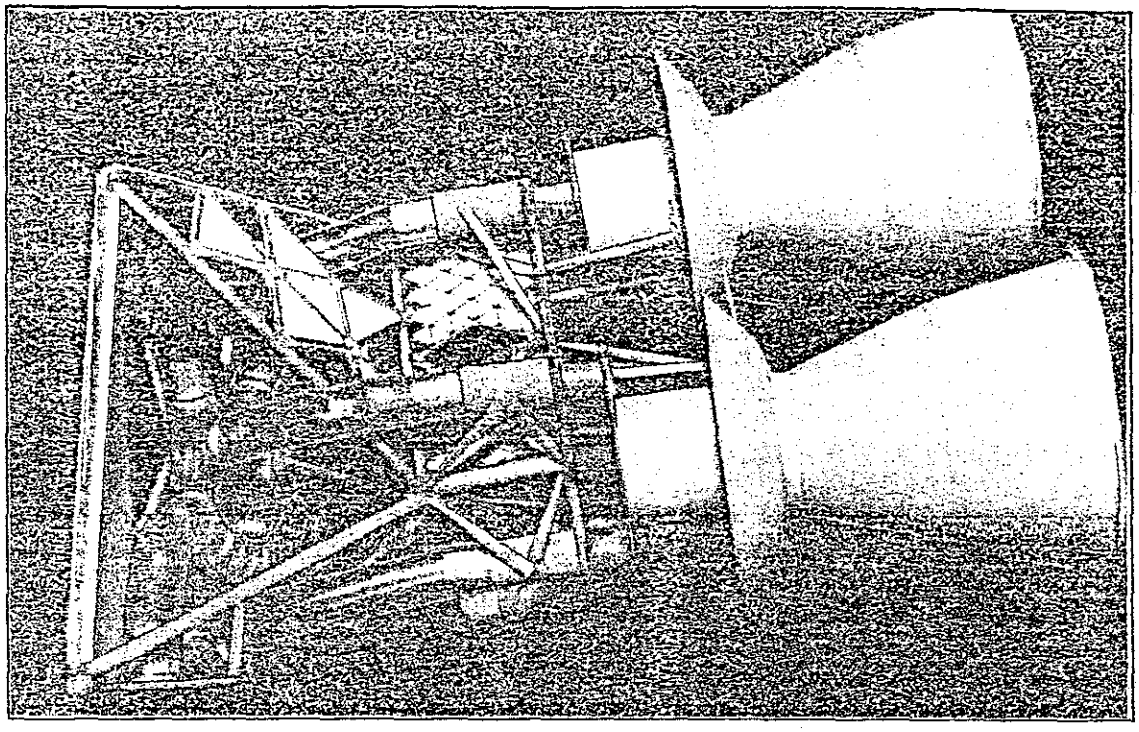

FIGURE VI-9 - A model photo demonstrating how the tri-symmetric geometry can be applied to a stand-alone truss system for the Space Shuttle. The outer shell can then be made entirely of removable panels, possibly with equipment mounted on their inside

distort out of shape, adding a straightening operation. This may be necessary both before and after machining, as internal stresses are relieved by material removal. Then, of course, there is the added paper work to keep track of the extra pieces, extra inspections, and extra operations, a cost which probably exceeds all the others combined.

Therefore, if a demonstration unit is part of a proposed design effort, it might as well be just like the ultimate finished article. The result is a much more presentable and authentic product, one which also will not need complete redesign for a working system.

The only problem is convincing a customer that he is really getting a bargain because the bidder knows what he is doing and can do it for less.

"Let's Do It the Old Way' - Another Myth

In a recent bit of brochuremanship put out by a contractor, the impression of economy was conveyed by a chart with the sheet metal details shown in Figure VI-11.

The subject was an expendable payload carrier for a Shuttle-derived launch system. The caption read "Conventional Construction Employed", as if that were the economical and preferred design for an expendable system as opposed to the more carefully sculptured machined metal design on the Shuttle itself. Not that the Shuttle design is completely satisfactory, because, as already mentioned, it seems to be inside out. A more appropriate and economical redesign for **any** vehicle, expendable or otherwise, calls for **more** integral construction, not less.

In a Shuttle-derived launch system, if the payload carrier is expendable while the propulsion module is not, too little of the present mid-body structure is appropriate. To begin with, it is not readily dismantled in flight. That is, a fairing, shroud, door, or similar payload protection should be ejected as soon as there is no more atmosphere to

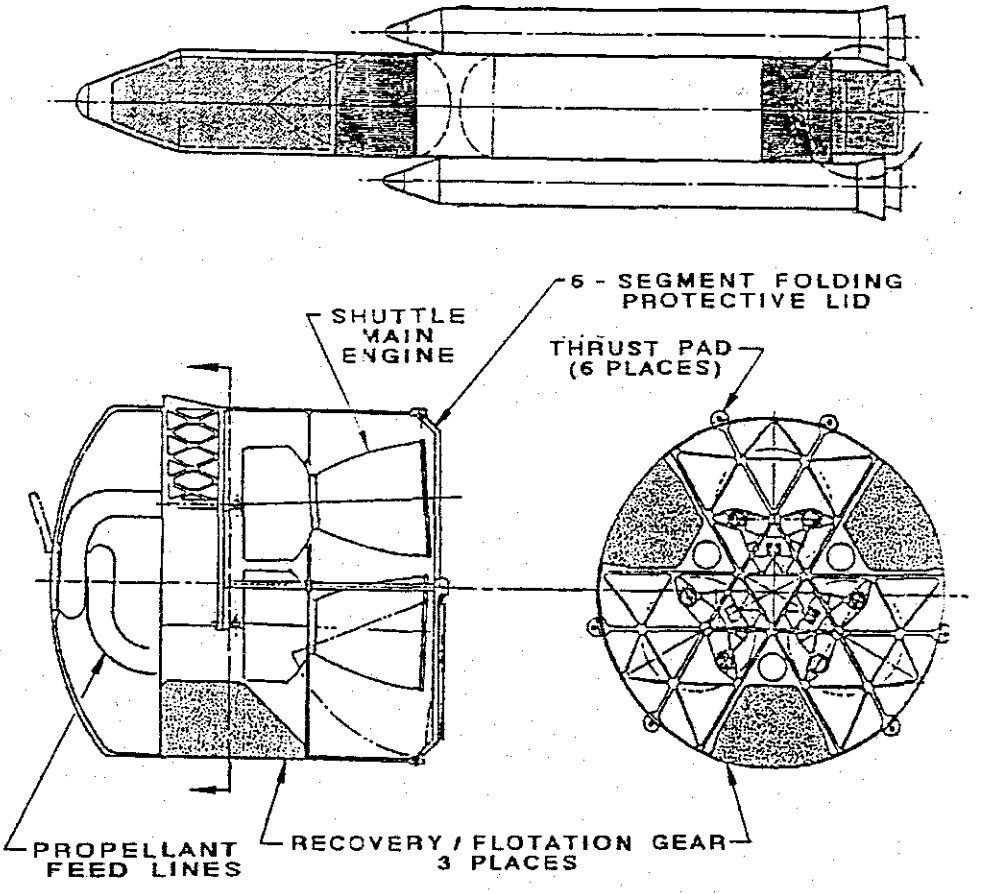

FIGURE VI-10 - How a partially expendable boost system, built from Space Shuttle components (modified in the case of the External Tank) can benefit from a recoverable engine pod which incorporates the tri-symmetric engine arrangement. The center portion of the engine mount plane bulkhead is identical to that found in other applications.

fight. Propellant is saved and payload increased when this can be done.

A design governed by these considerations is shown in Figure VI-12. Not having to fair into a wing, this carrier's cross-section (and weight) is reduced by undercutting the lower corners, leaving only a narrow strip next to the expendable external tank (ET). This strip must flare outward at the aft end to cover existing - and retained - Orbiter attachment points and propellant feed umbilicals. The basic load carrying section (Figure VI-13) as a result consists of the longerons (appropriately sized and shaped to accommodate payloads designed for Shuttle), an inner integrally stiffened open isogrid semi-cylinder, a keel element with integral payload support provisions, and a vertical longitudinal shear truss which connects to the bottom centerline strip. This strip, incapable of being discarded because it is trapped against the ET, is integrally stiffened to work as part of the basic structure. It is intended that the external sidewalls, the door, and the nose fairing all be ejected on ascent as soon as airloads and heating effects have sufficiently subsided. Since the structural shell attaches to the inside of the longerons where payload forces are applied, there is no need for the ever-present inter-frame support bridges and less need for the frames themselves. Consequently, the frames are lighter, more widely spaced, and external to the shell.

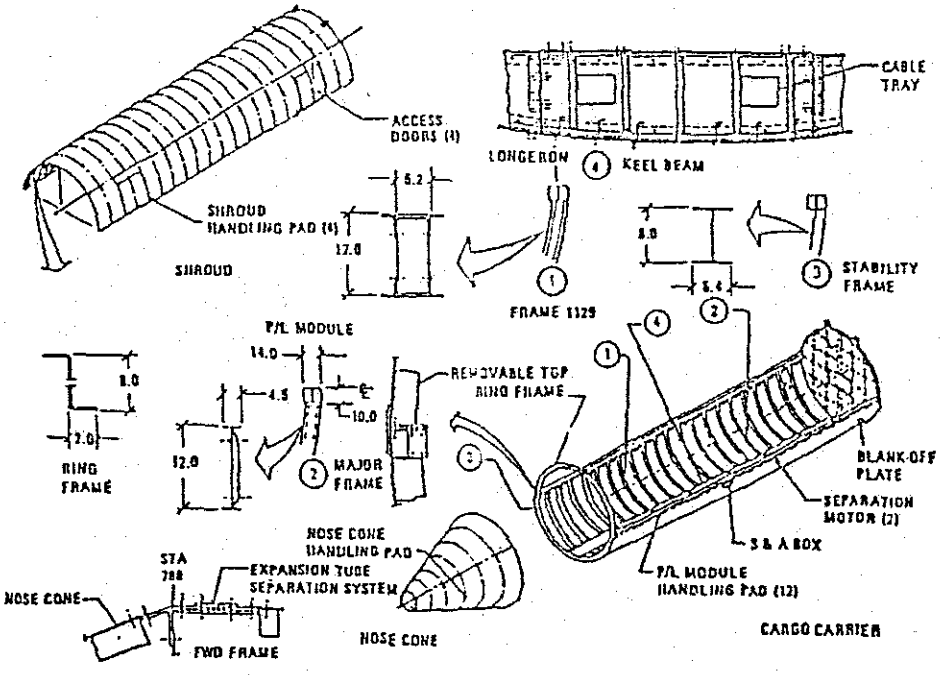

FIGURE VI-11 - Sheet metal details of an expendable payload carrier for a Shuttle-derived launch system. This "conventional construction" was offered to convey the impression of economy.

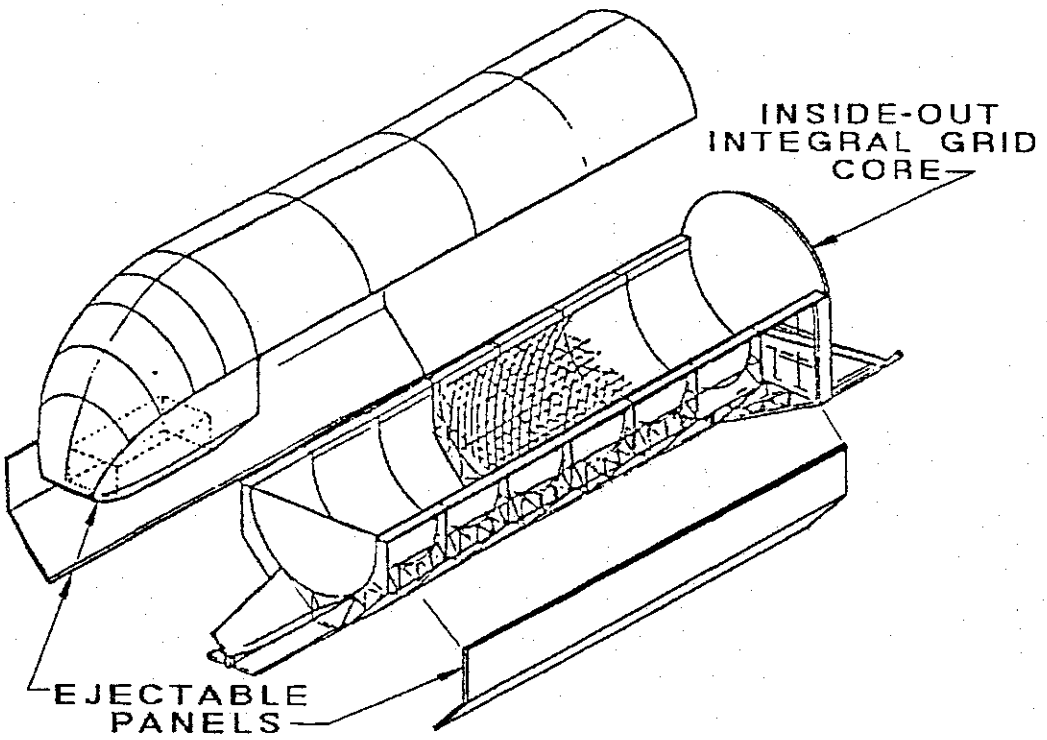

FIGURE VI-12 - A design for an expendable payload carrier applying the integral construction philosophy. Fewer but considerably larger parts are the key to real economy whether the vehicle is expendable or not.

Similarly, the central keel longeron is part of the basic structure and machined to shape like a wing spar cap. Containing continuous accommodation for payload keel trunnions, it also dispenses with auxiliary bridges.

Since the payload doors are ejected while the engines are still thrusting, it may be necessary to retain at least a part of the outer skin for a modicum of torsional stiffness. For the balance of the external area, the panels should be the largest possible ejectable units, made, if possible, of chopped-fiber-reinforced plastic foam, shaped by spraying against the inside of a mold. This construction method is also recommended for the nose fairing. The rest of the load bearing structure is machined from the largest obtainable aluminum alloy plates, it having been demonstrated already that the most economical airframes are made from the fewest parts, irrespective of the fabrication method.

It is true that the aircraft made of sheet metal several decades ago were less expensive than the ones made today, but that is also true of

everything that was made decades ago. Inflation has taken care of that. However, what is true today was true then, that reducing the number of parts reduces cost, although at that time there were not such large milling machines, there was no numerical control technology, and rolling and forging mills were not producing blanks of the needed size. In those times, the improvements in part count and handling of pieces were embodied in the sheet metal construction which was then supplanting the frail wood, wire, and fabric methods used for the airplanes of World War I.

The passage of time was graphically illustrated in a regular feature of the AIAA publication ***Astronautics and Aeronautics,*** now called ***Aerospace America.*** In one of the magazines published in 1983, the **50 Years Ago** page carried an item about the U.S. Navy's air arm budget for the year 1933. For the breathtaking sum of $9,320,000, the Navy planned to procure two aircraft carriers and their complement of 90 airplanes. Nothing was said about subsequent cost overruns, as likely then as now, but think of what could be done in those times for considerably less than half the price of a modern jet fighter!

So, if we want drastic cost reduction, we might hope to accomplish it by turning the clock back, something that present technology is still unable to do. All we can hope is that we are able to recognize what we have done right, and continue to do it in the future, perhaps in a modified form.

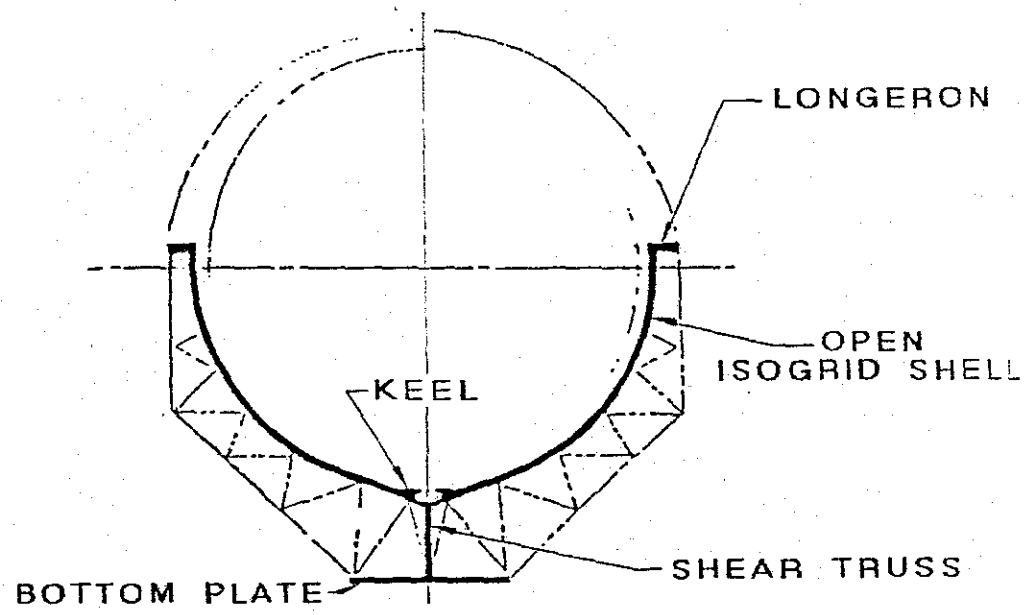

FIGURE VI-13 - The core structure cross-section for an expendable Shuttle-substitute payload carrier.

The Stressed Skin Efficiency Myth

Stressed skin construction was an improvment on trusses covered with fairings as indicated in Figure VI-14. It was efficient because it was a design compromise, but the stiffened semi-monocoque shell itself cannot rightly be called more efficient on purely structural grounds than the basic truss structure it supplanted. The advantage lay in more efficient use of internal space since the outer fairing was not a parasitic add-on dictated by aerodynamic considerations. Instead, it was the structure itself.

The new stressed skin technology spawned a completely new set of production machines like the hydropress for flanged flat sheet metal parts and stretch-forming machines for skin panels with compound curvature - also handy for shaping of extruded frame caps. Router blocks and blanking dies came into use to eliminate hand work, contrilbuting to the production miracles of World War II.

With these investments came the habit of building sheet metal shells and a reluctance to depart from this practice. A body of literature emerged to guide designers and analysts in the methouds to apply in designing such structure. At the same time, the conventional wisdom propounded the notion that truss structure was inefficient for all applications, even ruling it out for internal structure, which was a real mistake.

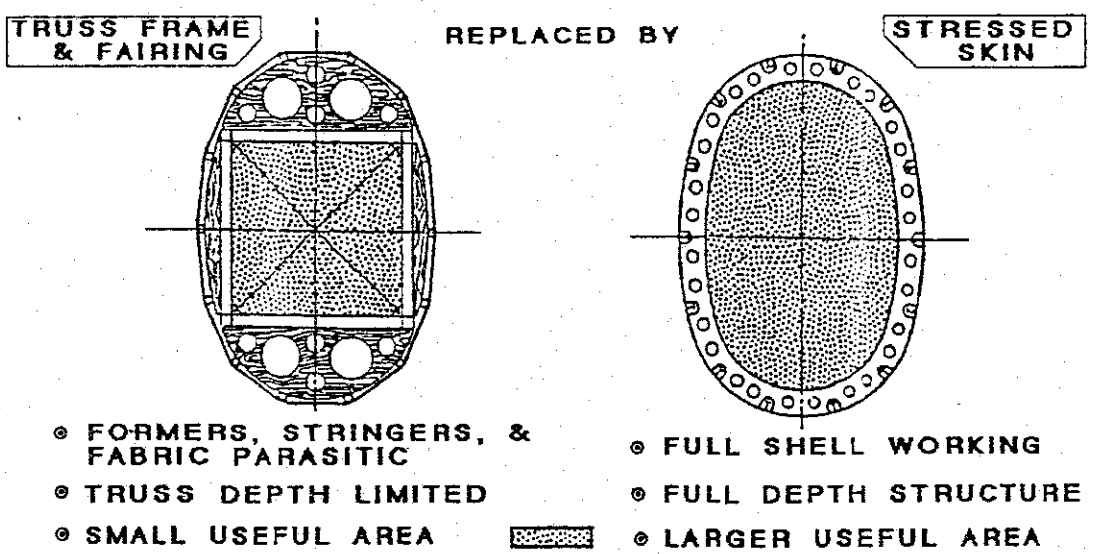

FIGURE VI-14 - Stressed skin construction successfully replaced the earlier construction method involving parasitic fairings added to a truss frame for the reasons shown. It is not superior structurally and is not appropriate as internal structure for that reason.

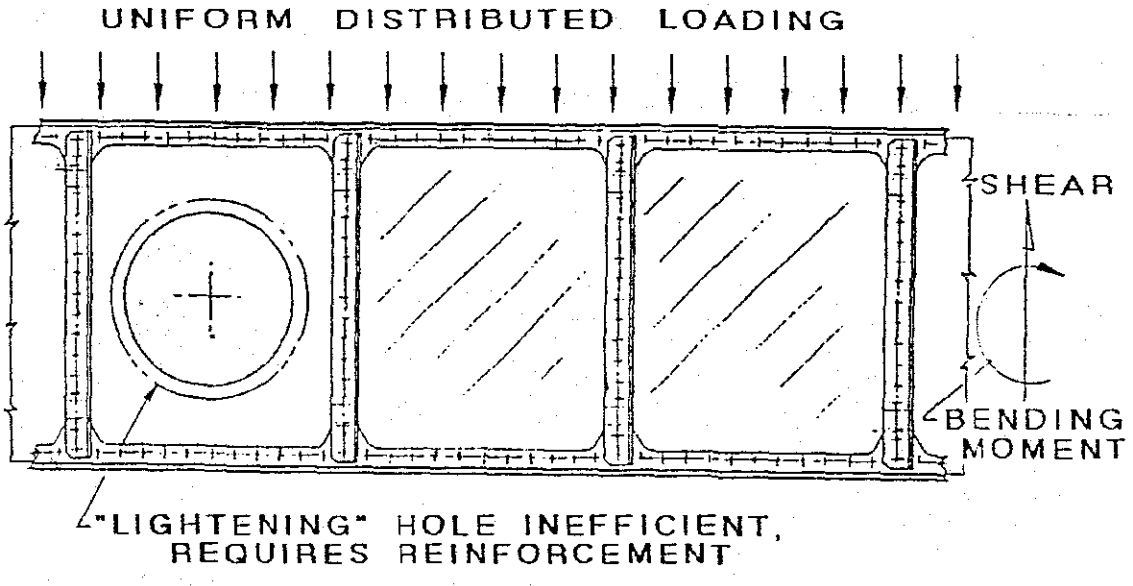

FIGURE VI-15 - A simplified sheet metal built-up beam sized to minimize weight by allowing the shear webs to wrinkle. The construction is obstructive, made of many pieces, and not very adaptable without substantial rework.

One effect of this design philosophy has been the orthogonal arrangement of structural elements. The old fashioned triangle has been forgotten. But it is still the **only stable polygon** provided by nature, in spite of the relentless march of technology. These ideas have led to some very inefficient ways of feeding load around penetrations, the misnamed "lightening" hole, for example. The curved path around its perimeter has an effect opposite to that intended by removing material.

Then there is "diagonal tension", another phrase to conceal the fact that nature is getting even by finding a diagonal load path when none has been provided. This adds to the load (and the weight) in the vertical stiffeners as they struggle to resist the tendency of the beam caps to pull together. An additional effect is secondary bending in the caps themselves from the distributed pull of diagonal tension, causing stresses which are superimposed on the basic tension and compression induced by bending moments. The situation is illustrated in Figure VI-15.

These effects stem from the inability of thin sheet to handle compressive loads well, if at all; it wrinkles, still carrying tension but

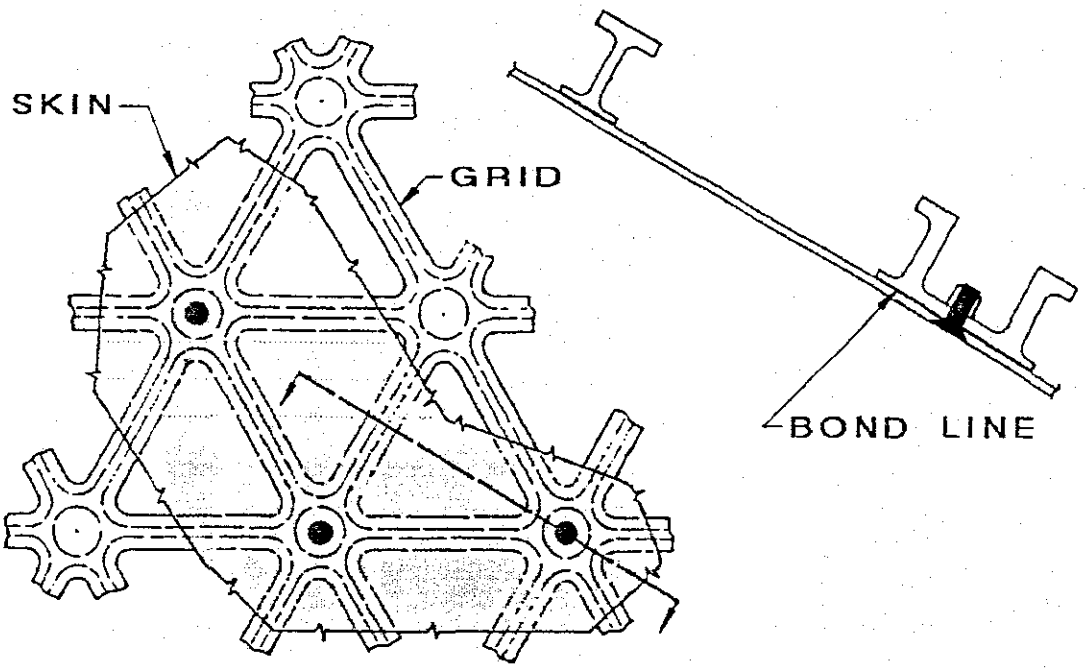

FIGURE VI-16 - A grid-stiffened sheet metal construction with a minimum number of parts. The skin and grid are separate to limit crack propagation. The attachments at grid nodes prevent the bond from peeling, the penetrations occuring only where there is good local reinforcement.

ineffective in compression. It can be stabilized for shear and compression resistance if stiffeners are closely spaced, but when these stiffeners are riveted angles or the equivalent, unusually close spacing means excessive weight in the attachment flanges. In the outer shell, this has led to the concept of an "effective width" of skin acting with each stiffener. There has to be some loss of efficiency because there cannot be an "effective width" without a concomitant "ineffective width". Then there is "inter-rivet buckling", the formation of transverse wrinkles across rivet lines when the rivets are not spaced closely enough, a situation which can pop rivet heads off as load increases, making the problems even worse.

The simple way out is integral construction. stiffener spacing being determined by elimination of skin buckling. In addition, the triangular arrangement of stiffeners called isogrid offers a secondary structure redundant to the skin it stabilizes while it remains strain compatible with that skin. Both "fail safe" and fatigue resistant properties are enhanced. In the fail safe case, the skin and stiffening lattice should probably be separate pieces, attached to each other as shown in Figure VI-16.

Misconceptions about Trusses

In keeping with "conventional" design philosophy, trusses have been pictured as built-up assemblies of hollow tubes and fittings, as shown in Figure VI-17. The wing spars of the Boeing B-17 bomber were made somewhat this way out of square cross-section aluminum tubes, including the caps.

They were a headache for manufacturing, involving a square cross-section bucking bar (called a "mouse) for riveting gusset plates to the tubes. The "mice", at the tips of long rods, were inserted at the spar cap ends, their position, in line with a rivet, inferred by measurement of rod length. The bucked end of the rivet, inside the tube, and thus invisible, could not be adequately inspected. To be on the safe side, the next larger rivet was indicated. These assemblies of tubes have given trusses a bad name and a not unfounded reputation for structural inefficiency in this form. The tube with its inaccessible interior is hard to attach to anything except by the mouse method or blind fasteners, and it certainly can't readily be attached to another tube without an intervening fitting or gusset - or both. In earlier truss construction, the tubes, made of high strength steel and welded directly to each other, made a somewhat more compact joint, but the material, an iron alloy, was about three times as dense as aluminum.

Tubes are appropriately efficient for long slender columns and if a beam assembly is deep their selection is justified unless intermediate support can be provided. As long as the the cross-section is tubular, round or square, breaking the span length to add such support is impractical because the joint weight and cost becomes unacceptable. It follows that there should be some other more suitable shape for a truss bar.

When the entire truss is a single piece machined from a single plate, the cross-section can be an "I" shape as shown in Figure VI-18. Bars then cross one another, those in tension stabilizing the ones in compression. To be sure, there are nodal penalties in such a case, but part of the extra weight can be reduced by properly placed holes. These, in turn, become rational points for attachment of equipment, eliminating or minimizing bracket weight. At the same time, any intercommunicating cables, harnesses, or pipes can snake through the construction without degrading the structure and without entailing more parts. Extended negotiation and argument, prompted by changes for equipment accommodation, is also avoided. As was demonstrated in the floor beam example of Chapter II, the design can, and should, be lighter.

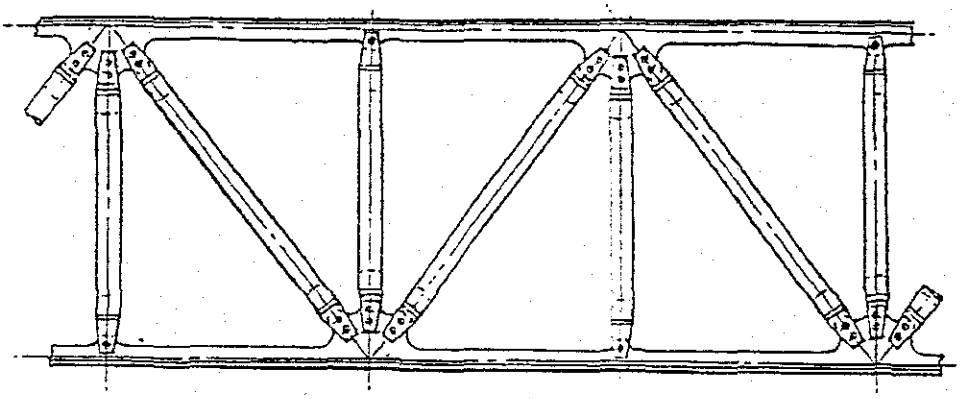

FIGURE VI-17 - A simplified popular conception of a built-up tubular truss beam. It is simplified by making the caps non-tubular, but each vertical and diagonal truss member consists of at least three parts.

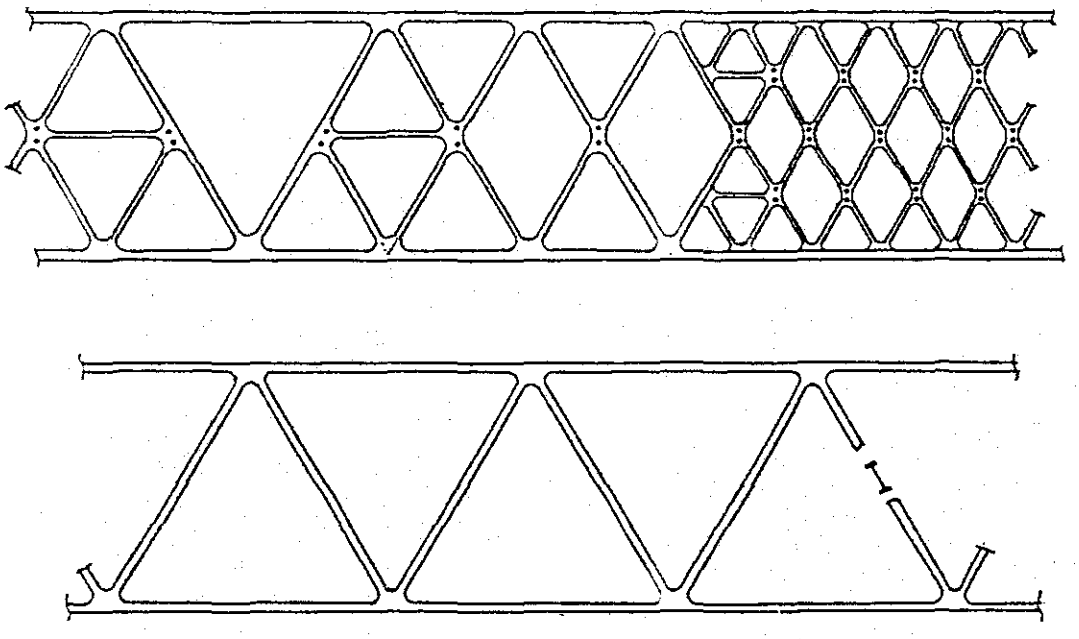

FIGURE VI-18 - Variations on the machined integral truss beam. All are producible from the same starting blank, a thick aluminum alloy plate. The number of pieces remains the same (one) regardless of the number of truss bars.

Trade Studies and "Optimization"

In these days of "systems engineering" it has become fashionable to conduct "trade studies". That is, various solutions to a design problem (too often, a large number of mediocre ones rather than a few elegant ones) are evaluated with the hope of selecting the "right" one. To some extent, this has become a tactic for reaching a foregone conclusion instead of achieving quality. It has also become a formal procedure which often selects one candidate without further pursuing answers to questions raised by the evaluation That extra effort in itself can derive a new and better candidate by combining features of the original ones.

If as much energy were focused on really grappling with the problem as is spent furnishing window dressing and justification, the results should be consistently better.

For some reason, formalized studies always seem to start at "square one", re-inventing unpromising ideas that should have been eliminated by experience. That, after all, is what experience is about - learning to eliminate false starts by directing effort down the right track.

Another shortcoming of the "trade study" evaluations, is the assumption that they must rigidly conform to a set of pre-ordained "requirements". The only real requirements are those dictated by the immutable laws of physics. Those that are made by people can also be unmade by people, and should be recognized as alterable, especially when they force imbalance in the design. The "requirements" should always be questioned.

In the early 1970's, when the Interim Upper Stage (IUS, now standing for Inertial Upper Stage) was being designed, a chart describing its trade study for the construction of skirts and interstage structures was circulated through the industry. It dutifully reported that three candidate schemes were investigated: unstiffened monocoque (boilerplate), aluminum honeycomb sandwich, and conventional built-up sheet metal skin, stringer, and frame construction.

The monocoque shell was identified as the most economical but heaviest alternative, and eliminated for its detrimental overweight. This candidate is always included in studies of this kind, apparently just to fill space, because nobody expects it to be a winner. Without any question, it is the heaviest choice, but it is not at all certain that it is economical; after all, it contains no provisions for installation of equipment or reinforcement around openings to gain access to internal spaces. By the time these unanticipated extras are added to the bill, the cost should not be far behind that of built-up sheet metal. As interpretation of the S-IVB cost

study showed, the basic structure of the aft skirt cost about a third as much as the afterthoughts begotten by inadequate initial planning.

Honeycomb was identified as the lightest construction, but was ruled out by assumed highest cost, a likely finding by any company having much experience with it. Again, its lightness, after it has been reworked support equipment not accounted for originally, is in question. The Shuttle-borne pallets for Spacelab are heavyweights which exemplify the high cost of reliance on honeycomb construction - and composites, too.

Skin, stringer, frame construction was selected as the happy medium for all the reasons that put it into the S-IVB, mainly familiarity. The candidate which could be expected to surpass all three, **integral construction, was not even mentioned.** Anyone armed with the information derived from the S-IVB experience could have made the appropriate selection for the IUS skirts without the benefit of any trade study. To put it another way, investigating past experience to develop sensible guidelines for future application could eliminate a lot of unnecessary labor and prevent loss of time spent wheel-spinning.

In another example, somewhat in the same vein, a 1972 study of a Shuttle upper stage called Space Tug, produced a design much like that depicted in Figure VI-19. Each element of the construction was carefully evaluated and optimistically sized (possibly to the point of manufacturing impossibility), whittling weight to the bone. When the result was presented to the cognizant center, the immediate reaction was, "It looks complicated."

The design shown in Figure VI-20 was the response to this criticism. Taking a 500-pound penalty in tank weight by using the same shape and size of end dome throughout, it was additionally simplified by extending the thermal isolation tank support struts to bridge the full gap between tanks, allowing the spaces between to be occupied by removable equipment-carrying panels. This change also eliminated two girth joints and a pair of ring frames. The weight estimate for this design turned out to be about 100 pounds **lighter** than the "refined and optimized" version. While such a small difference is well within the weight estimation tolerance expected for preliminary analysis, at least the design was not heavier, as expected. It proves that a sucessful design is not necessarily achieved by combining all the "winners" of individual studies. To strike a sensible and effective balance, some "winners" need to be combined with a few "losers".

Save the Hardware; Don't Redesign It

Often during the preliminary design phase of a program there is

scant attention paid to structural arrangement. It is considered almost insignificant, a mere 5 to 10 per cent of the total cost and therefore not worthy of careful attention. However, once the design has been "cast in concrete", the structure suddenly becomes inviolate, not to be redesigned except as a last resort if existing hardware cannot be made to work. It is the attitude that makes the "Shuttle-derived launch vehicle" (SDLV) appear attractive because it "saves" a basketful of tinware, inappropriate enough for its original purpose and much less so for derivatives. The term "Shuttle-derived" is sensible enough if that which is saved has meaning in a new program, but saving everything that has been "qualified" makes no sense at all. The point is illustrated in this quite distantly related example:

Pyrotechnic actuators and thrusters are a specialty of the U.S. Army's Frankford Arsenal. One of their thrusters was applied as the emergency power source for jettisoning the canopy of the F4D fighter. Its arrangement was roughly as shown in Figure VI-21. When the spring-

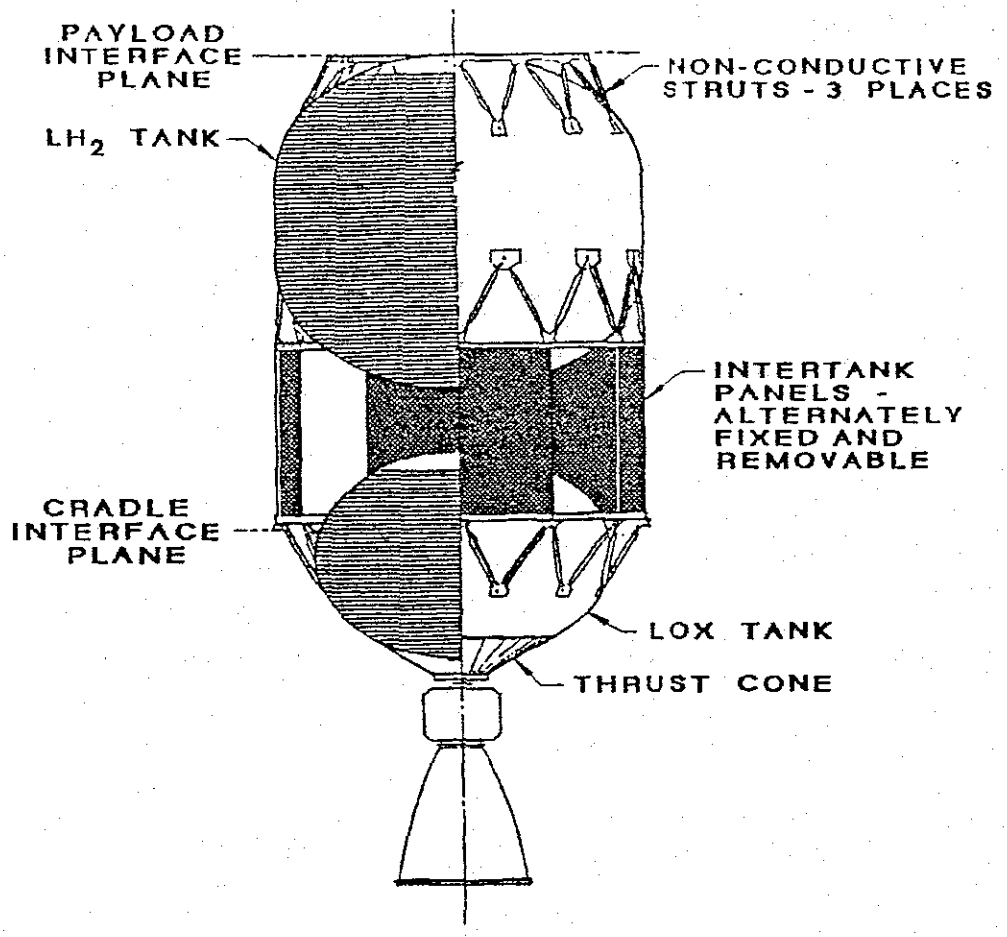

FIGURE VI-19 - The initial design produced by a study for a Space Tug which was judged to be "too complicated", though highly "optimized".

loaded striker was held back by the retention pin, the pin's early or inadvertent withdrawal was potentially catastrophic, threatening to explode the device during handling. A second cross pin was therefore provided, so that the main pin could be withdrawn for inspection or cleaning. It also meant that the extra pin, if forgotten, could still be in place, making the system inoperable in an emergency.

The extraction force was also somewhat unpredictable, relying on an accurate assessment of static friction which could increase as the "safing pin" slowly corroded before use.

It was therefore decided that a power extractor, another mechanical device, was needed. This extractor, incorporating a retention pin as an extension of its piston, was actuated by the gaseous products from an

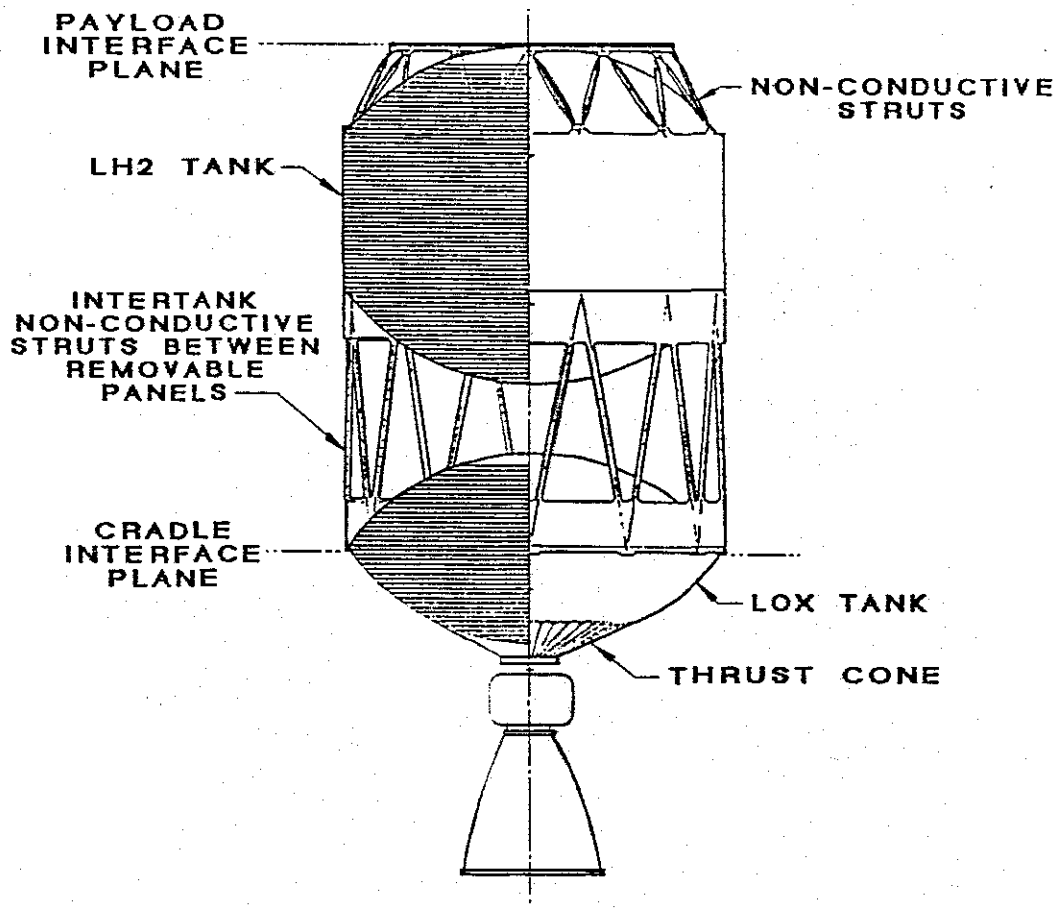

FIGURE VI-20 - The revised simplification of the Space Tug, while paying a 500-pound penalty for non-optimum tanks with standardized end domes, was still estimated to be slightly lighter. Extra members, particularly frames, and joints were eliminated to produce a more balanced design.

explosion in another unit, a gas generator. The generator, in turn, was set off by an initiator, a much more ingenious device than any of the others in the mechanical train. These gadgets are shown in Figure VI-22 and their relationship with the thruster in Figure VI-23.

The initiator firing pin was initially safe because its spring was only slightly compressed, just enough to prevent rattling, and the plunger weight was held away from the percussion cap by its connection to the pin through a ring of balls. The pin's withdrawal compressed the spring, adding energy just before the retention balls slipped outward into an expanded bore, releasing the weight which the spring then drove into the percussion charge. This set off the grain in the gas generator, much like that of a solid rocket motor, building pressure which, piped to the extractor, pulled the firing pin on the thruster. Rube Goldberg would have loved it.

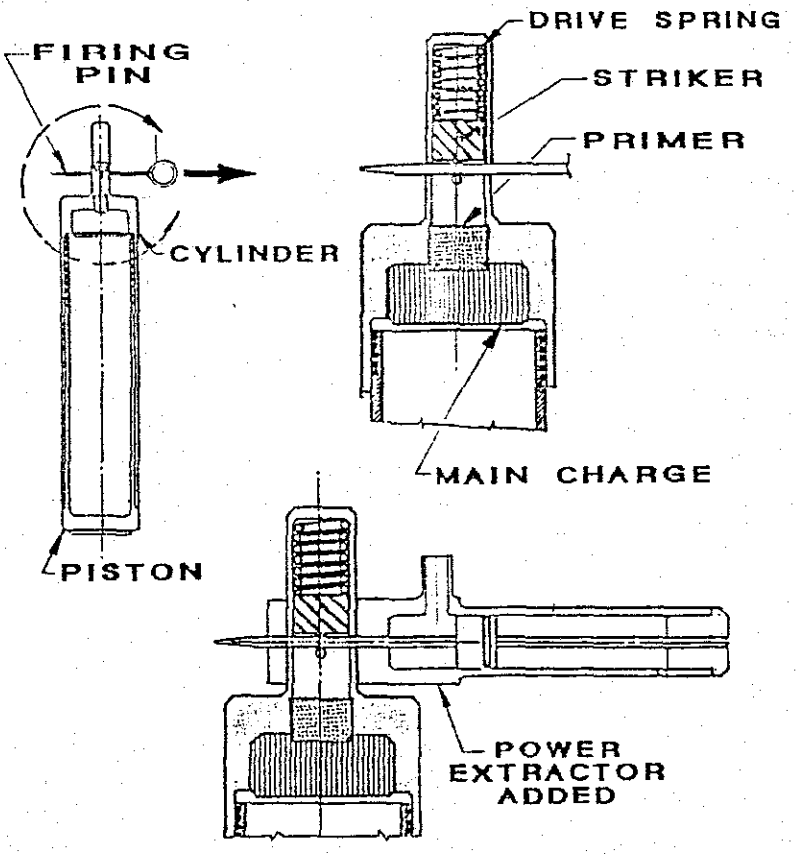

FIGURE VI-21 - A pyrotechnic thruster for such applications as ejection of aircraft canopies. Variable friction forces from withdrawal of the firing pin caused the modification shown, addition of a gas-driven power extractor.

The reaction of most listeners to this description of mechanical complexity has been, "Why not just build the ingenious little initiator mechanism into the head of the thruster and be done with it?" Why not, indeed! But this would mean redesign of the thruster head with consequent "requalification" of the entire unit. Evidently, such requalification was considered prohibitively more costly than the addition of three new units which themselves must be qualified. It's part of the illusion, so commonly embraced, that there is some economy to be realized by "saving" that which is worthless. Unlike wise investors, we are too often unable to recognize when the time has come to cut our losses.

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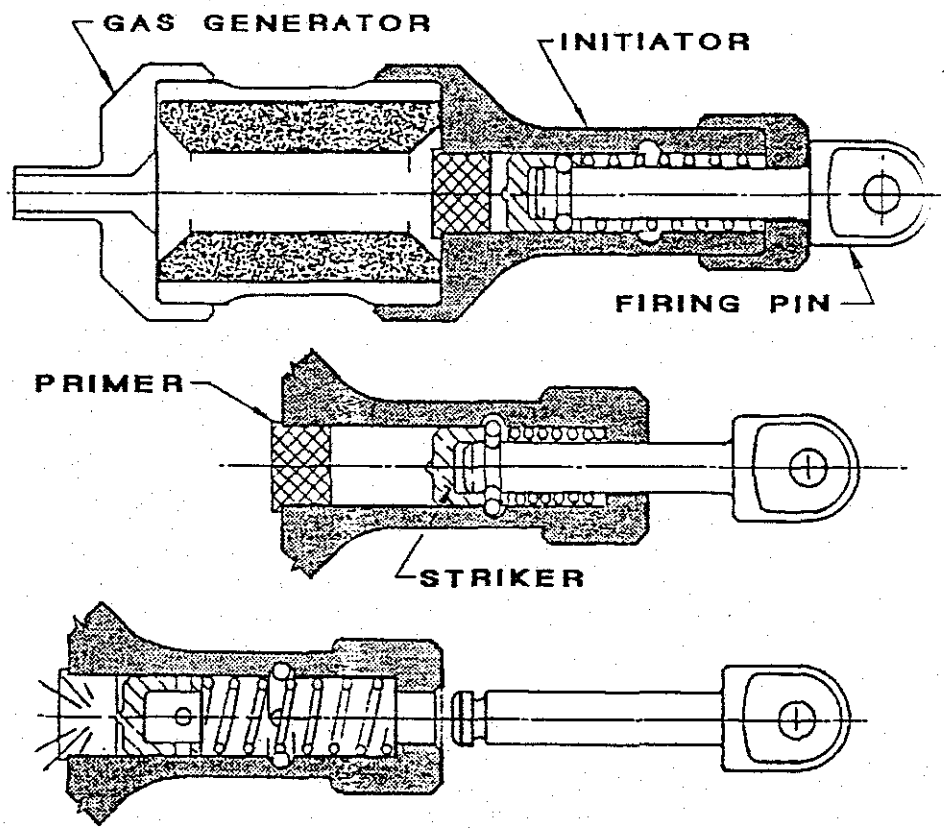

FIGURE VI-22 - To supply gas pressure to the power extractor, an explosive initiator and a gas generator like a small solid rocket motor were added to the system.

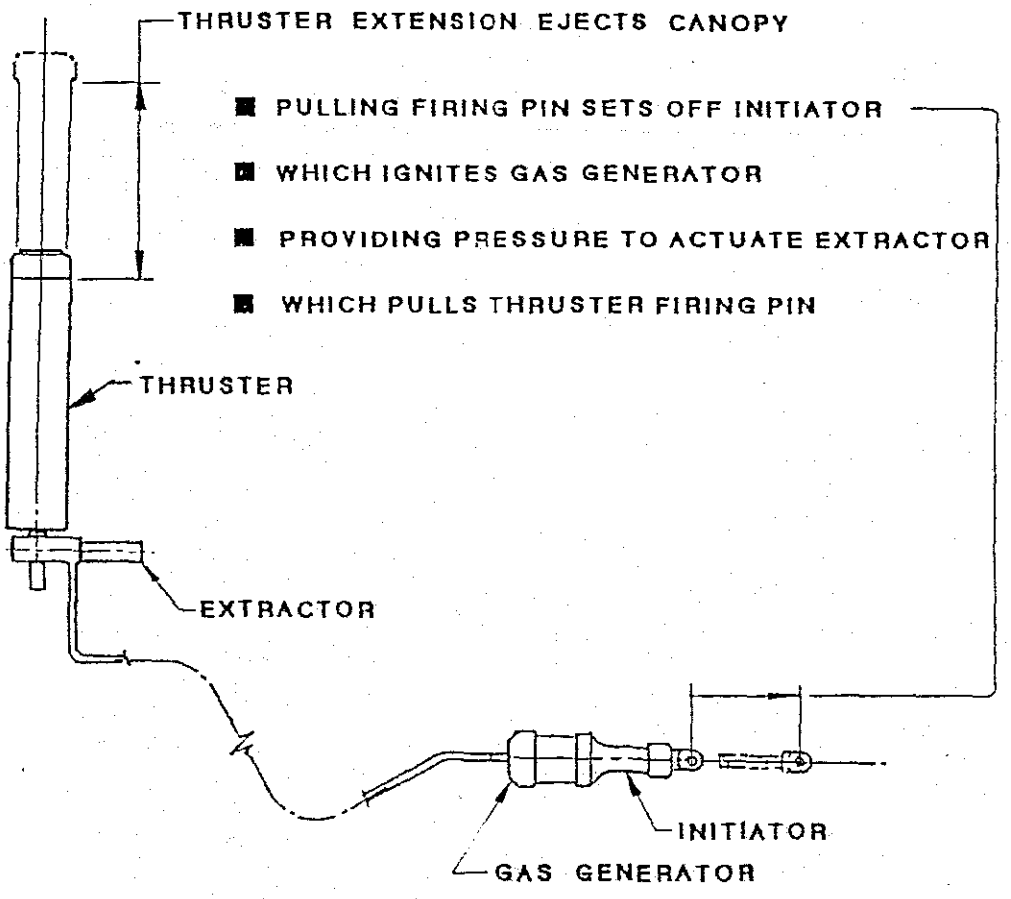

FIGURE VI-23 - Schematic diagram of the eventual pyrotechnic canopy ejection system.

If the content of this chapter conveys the impression that engineering design is not always an exact science, that is its intention. Mathematical analysis and calculation are essential for accurate, efficient results, but the arrangement as well as the interpretation of the analysis depends on people with judgment and experience. Unfortunately, as program duration increases along with cost, programs become fewer and farther apart, lessening the opportunity for designers to acquire experience and sharpen judgment. At least we must allow common sense to creep in once in a while to avoid being carried away on the tide of technical "sophistication."

MEMORY BOOST

My friend, Hal Linderfelt, one of the most creative designers I ever met, found employment in the field of his choice to be scarce in the early 1930's. So he settled for a job as a sales engineer with an aircraft equipment supplier, selling such items as Tinnerman sheet metal nuts.

The job entailed many brief encounters with a lot of people whose names were hard to remember even if their faces were not. Hal had difficulty, as most of us do, with name recall and developed an associative method of classification. For instance, anyone named Brown, White, Black, or Green belonged in the class labeled "color".

One day he arrived at a supplier's office to keep an appointment with an individual whose name had slipped away, apparently beyond recall. Entering into negotiations with the receptionist, he started out, " I have an appointment with one of your buyers but can't remember his name. Is there anyone here by the name of Paul, Peters, St. John, Matthews . . . . . something like that?"

Getting no favorable response, he settled for a list of names in the department he was involved with. "Well," the receptionist said, "we have a Mr. Johnson, a Mr. Jones, a Mr. Smith, a Mr. Bernard -"

"Aha! That's it," said Hal. "He isn't a saint - he's a dog !"

VII - SPECIAL DESIGN PROBLEMS

Structural mainframes, as mentioned before, are primarily concerned with lightness in conjunction with compressive stability. These characteristics must be achieved while, at the same time, the designer anticipates the subsequent arrival on the scene of subsystem components which must be accessibly fitted in, supported and protected. Interconnections between them, such as wiring runs and fluid pipes, must also be accommodated.

In the course of these design tasks, it frequently falls upon the structural designer to design some mechanical devices, primarily access doors and hatches, but occasionally some fairly complicated hinges, particularly those associated with devices like wing flaps, as well as release and separation mechanisms. These mechanisms are part of the main vehicle, not separable or replaceable subsystems. Since these problems are unavoidable, a few examples are in order.

In addition, there is that special class of structures which are designed primarily by tensile loads - control cables, seldom found since the advent of "fly-by-wire", and pressure vessels, which, in some cases, make almost the entire vehicle. Propellant and pressurant tanks and pressurized habitable spaces are the most prevalent forms.

Safe Access to Pressurized Compartments

Now that a U. S. manned Space Station is about to begin, with the prospect of permanent human occupancy in this interesting but unforgiving environment, it is timely to think carefully about safe passage between inhabited spaces and the hard vacuum of space. The consequences of opening ports at the wrong time, leaving them carelessly unsealed, or designing a closure which releases too easily can be catastrophic. Loss of life for everyone aboard is a distinct possibility.

The problems involved are not insurmountable and many of the needed capabilities are routinely demonstrated in airline operation. In fact, airline experience (and high flying aircraft experience, in general) is the kind to draw on for guidance in space operations. The total time of manned operations in space has been too short to reveal the weaknesses in designs which become embarrassingly clear during accident investigations. For the airlines, one such accident in perhaps a billion passenger miles, is one too many. So it is in space operations as well, though it may take decades to gain the experience.

Too many aircraft accidents have been caused by closures that opened outwardly too readily. Passengers and crew members have been sucked outside through improperly secured escape hatches, navigation domes, windows, and entry doors. It has led to requirements for internally opening doors on most of the current jet fleet. With the advent of the wide-body jets and modular cargo containers, this requirement was relaxed for belly cargo compartments, resulting in a DC-10 crash with loss of 355 lives near Paris.

After the Apollo fire disaster, the crew hatch was redesigned for rapid outward release. While this may have been considered necessary under the circumstances, it is the last option designers of airliners would choose. Fortunately, this hatch, and the Space Shuttle crew door since then, have been operated relatively few times and always by ground crewmen who were thoroughly trained and fully aware of the danger from improper operation. In retrospect, it is also apparent that the Apollo redesign was a somewhat hysterical reaction to a highly publicized event. The accident was mainly caused by an ill-advised ground test employing pure oxygen at dangerously high concentration and pressure, a circumstance which was not corrected. This Apollo redesign was only part of the "shotgun" activity but left its mark on the Space Shuttle, which appears to be undergoing the same treatment.

For a space station, particularly one assembled from modules, there will be many hatches for compartmentation as well as assembly in vacuum, at joints whose inadvertent release will be just as hazardous as an accidentally opened door or a blown window. With the passage of time, procedures will be relaxed or forgotten, mechanical interlocks and electronic warning devices will get out of order, and an increasing number of untrained or forgetful people will be operating the hatches. The consequences of carelessness will not be as simple as letting flies in or heat out, circumstances which have led to automatic door closers in homes and businesses. Here is where every conceivable shred of ingenuity must be exercised to circumvent Murphy's Law. Adding backup devices on top of preventive interlocks on top of special adjustments and procedures on top of safety devices is no way to get there. Simplicity should be much better.

The Right Shape

Notched panels which define a diamond shape and slide past each other to close an opening may provide a proper dramatic touch for a science fiction movie or television show, but simpler devices are a more reliable analogy for real operation in space. These are manhole covers - too large to slip through the openings they seal and thereby injure work crews

below. If inwardly opening hatches in space modules are to foil the insidious effects of Murphy's Law, they too should be incapable of passing through the openings they cover. The appropriate shape, in both instances, is round. There are other constant width shapes, some irregular, which can produce the same effect, but they introduce other problems : uneven distortion of doors and jambs which make sealing difficult and special orientation which complicates positioning mechanisms, to name two.

It may be argued (and has been) that such a door inside a closed volume cannot be removed for replacement when the need arises (or even installed after the sealed unit is built). True, but it should not be too difficult to design one which can be partially dismantled for this purpose. When fully assembled, it should still be incapable of passing through the hole.

As already mentioned, a round, regular door and jamb are unlikely to distort under pressure and cause leakage. This is the case when a round opening is at the end of a cylinder or cone or similar axi-symmetric shape, or anywhere on a spherical surface. A round opening does not work well in the middle of a square, some other polygonal panel, or on the surface of a cylinder. Nor does a polygonal shape in the middle of a circular panel. The consequence of this kind of inappropriate design are not necessarily serious, unless one is nervous about excessive structural weight or difficult mechanical operation. If the door designer finds himself faced with such a problem, it is probable that somebody working at a higher level of system definition has blundered.

Once again, it can be said that there is airline precedent for doors in the sides of cylinders, so why not? First of all, they all leak unacceptably for a space habitation where all the atmosphere must be imported. Secondly, they are never operated in flight while under pressure (except accidentally). Also, their jambs are not structural hard points where adjacent modules are connected . Besides, if they accidentally pop open, the results are not likely to be quite as serious in most cases. Airline precedent and experience are useful only up to a point.

The Right Size

As space vehicles, especially manned ones, and their components become larger, the appetite for larger openings increases. Devisers of requirements can always think of another larger object to pass through an access opening. In some instances, these objects are only used in quite specialized situations, making their accommodation an unnecessary penalty for all the openings in habitable volumes. In other instances, the

insertion of the equipment in habitable spaces may not be justified - consider control moment gyros in this category: they might as well be outside. Rather than size critical openings into a space station by the dimensions of existing hardware, it might be wiser to redesign or reshape the offending articles. After all, space stations can be expected to be around longer than most of the components which might shape them. The Manned Maneuvering Unit (MMU) is a good example which, with relatively painless redesign, could be brought into a pressurized space in three parts, two "arms" and a back piece. The same treatment can be given to oversized standard modules; they can be replaced with more sensibly sized units, like wall and base cabinets in the kitchens of homes on the ground.

Another difficulty in maximizing the size of apertures is that the lids which cover them must somehow be stowed in the internal spaces without blocking the passages. This is exactly what didn't happened on Skylab in the Airlock Module (Figure VII-1). These circular hatches became so large that, once they were lifted off the jambs, there was no place to stow them except back in the opening. The situation is illustrated in Figure VII-2 which shows that the ultimate door divides the opening like a butterfly valve. Why the airlock openings became so large is difficult to explain; there was little reason to make them any larger than the port in the top of the Orbital Workshop, a reworked S-IVB hydrogen tank. All the structural

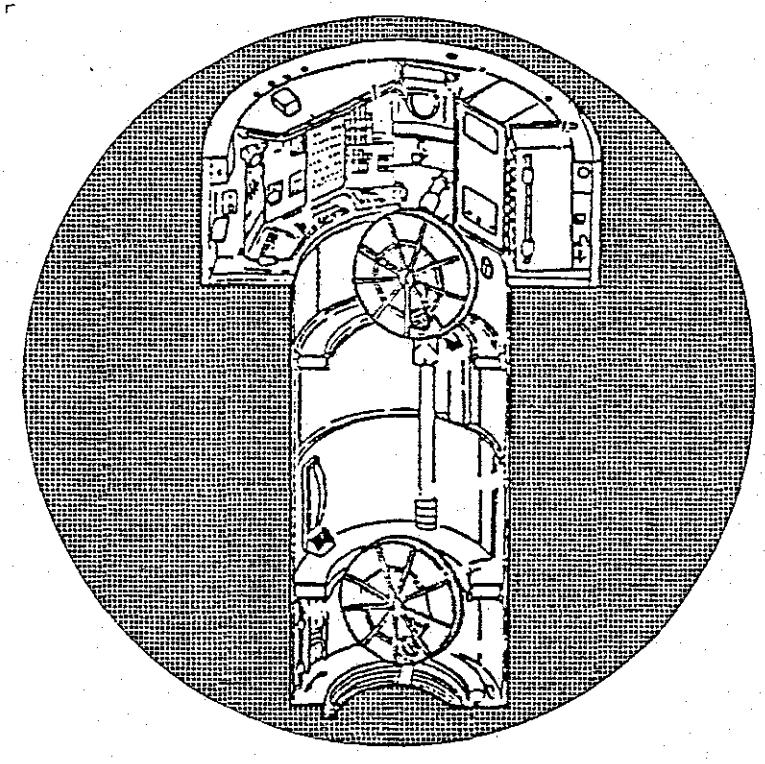

FIGURE VII-1 - Skylab Airlock hatches. They are so large that, when open, they can only be stowed back in the holes they cover.

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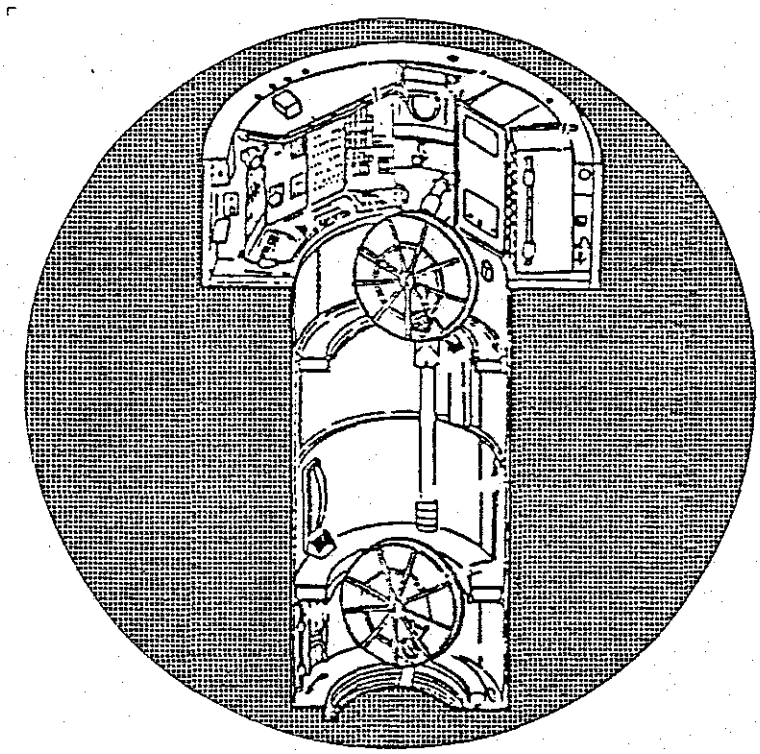


FIGURE VII-1 - Skylab Airlock hatches. They are so large that, when open, they can only be stowed back in the holes they cover.

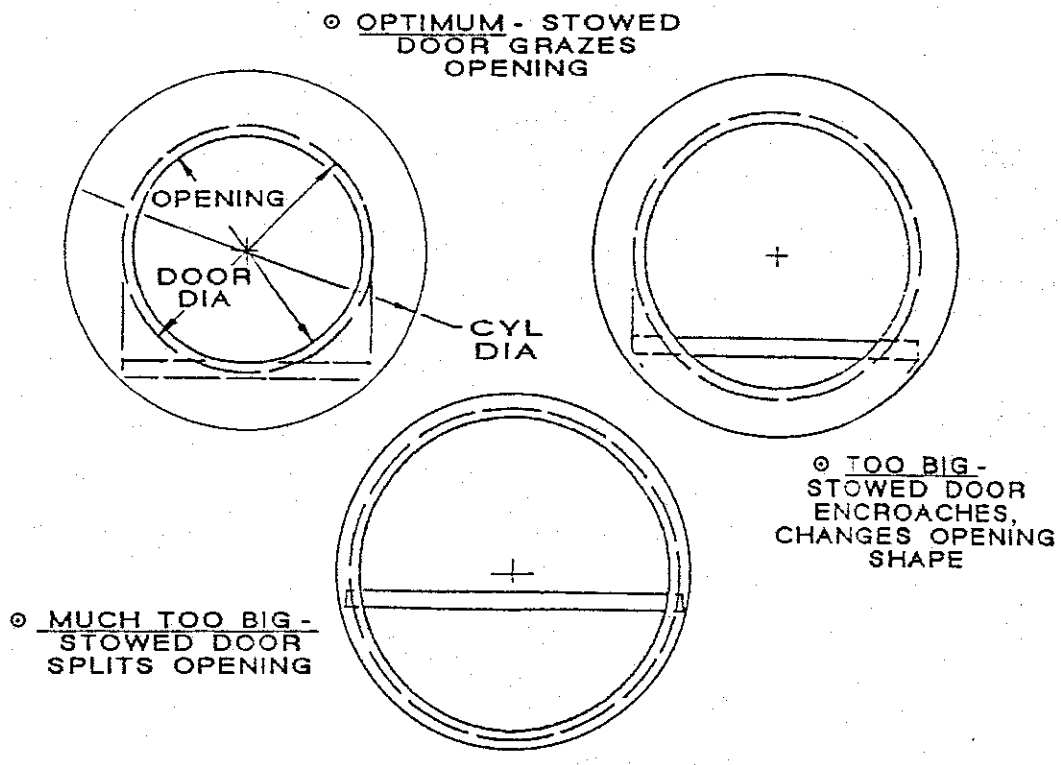


FIGURE VII-2 How to reduce the access passage by enlarging the opening. Doors in cylinder ends, enlarged beyond the optimum size, shown at top, increasingly encroach on the opening when stowed. Ultimately, the door, almost as large as the inside diameter of the cylinder, can only rotate about its center, splitting the opening like the vane of a butterfly valve.

pieces making up the Workshop were required to be small enough to pass through this 40-inch opening. Once the restriction was known and accepted, it created no great hardship. A similar size of round opening seems reasonable for a space station, particularly when door weight, which is approximately proportional to the square of door area, needs to be controlled like all weight transported to orbit. At any rate, a careful study which takes into account all the previously mentioned factors and further considers the long term effects of any space station decision may reveal that the appropriate size for standard ports may be considerably smaller than originally specified.

The Right Mechanism

The design rules for airliners may specify internal plug doors without introducing any confusion, but for a modular space station or similar compartmented space habitation, it must always be assumed that a barrier between two pressurized volumes can be subjected to pressure from either direction. The plug principle may work adequately in one direction, but, in the other, the door would be hanging on its latches. Perhaps it wouldn't be flung into space if the latches let go, but, with pressure behind it, it could become a very hazardous battering ram. The situation can be likened to an outward-opening canopy on a fighter or a cargo door which cannot be allowed to swing into a cargo container's space.

One solution to this problem has worked quite well in at least one of these cases. That is to make the door itself (or, in this case, the canopy) the latch, suspending it on a compound hinge mechanism (See Figure VII-3). A similar concept is found in the inward-swinging, outward-opening

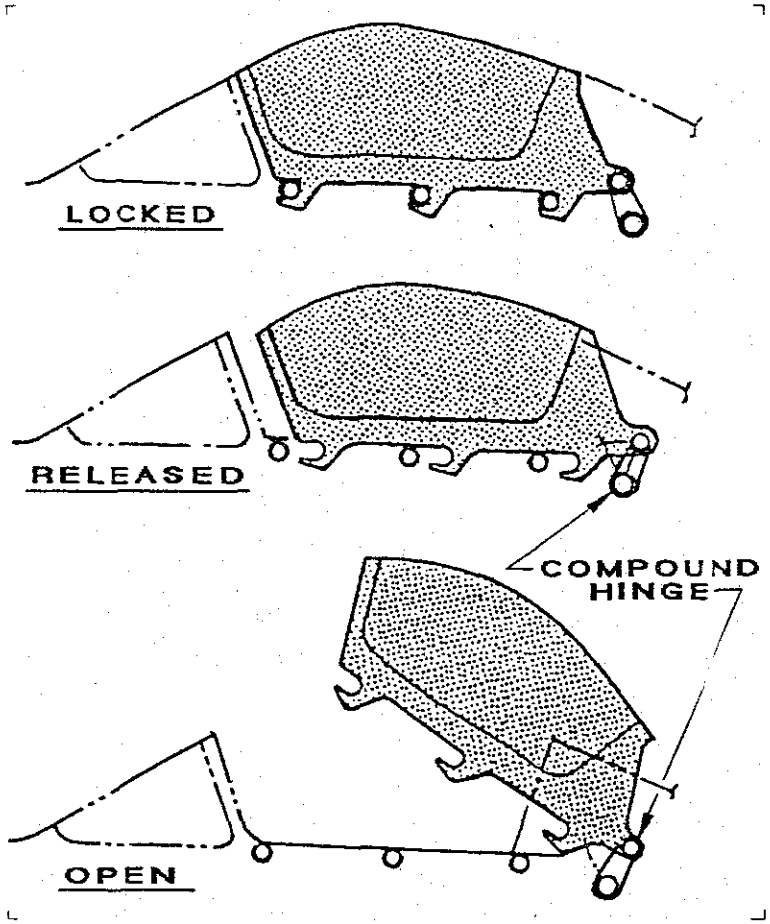


FIGURE VII-3 - A compound hinge allows an aircraft canopy to move as a single unit to engage locking pins or lugs on fixed structure. The mechanism is the same for one attachment point or a dozen. No system of individual interconnected latches offers as much safety as having fixed parts of the cover behind fixed elements on the structure.

passenger doors on DC-8 and 707 transports. No system of interconnected latches, however cleverly devised or accurately adjusted, can offer the safety and reliability offered by having fixed parts of the door behind corresponding fixed parts of the jamb. Another advantage of this technique is that the number of attachment points between door and jamb is independent of mechanical complexity. A closer spacing, that is, more attachment points, can be obtained without redesigning the mechanism.

While the closure acting as its own latch works well for doors, it is quite impossible for connections between assembled habitable modules. No way has been devised to rotate a pressurized module at one end to engage it without, at the same time, unfastening the opposite end (unless there's a heavy, possibly unsealable, swivel joint in the middle). In this instance a separate, probably redundant, latching system is indicated. Here again, it is not wise to be overly clever with mechanical gadgets. One mechanism which should be applied with utmost restraint, preferably not at all, is the overcenter toggle latch.

In 1951 this writer had the assignment of designing a latch system for the F4D-1 fighter (at the Douglas El Segundo plant which used to make Naval combat aircraft). The initial product of the exercise was a double-action double-overcenter bundle of mechanical complexity which was duly, and with some pride, presented to the U.S. Navy for routine review and expected approval. It was flatly turned down with the comment that "no 'hair-trigger' devices like overcenter toggle latches are acceptable for closures on pressurized volumes". Back to the drawing board.

It's unfortunate that this gem of good design practice was not heeded in the design of the DC-10 belly cargo door. At least, if learning is to be gained by avoiding the repetition of mistakes, such experiences are worth remembering.

It is recommended, in light of this knowledge, that the appropriate mechanism for joining separable pressurized modules which cannot serve as their own latches is something more humdrum and conventional like a set of interconnected jack-screws. If thoughtfully designed, they can slowly open without sudden release. The attendant leakage should be warning enough. In any case, it is prudent to design a mechanism which, while opening, can back off without abruptly (perhaps, treacherously) letting go.

One Way to Design a Hatch

From the standpoint of accurate fit, economy, and leak tightness, it is desirable to make a hatch from a minimum number of parts, preferably one. However, since something must be removed to get it through the hole, no less than two pieces will do. An arrangement which fits this requirement is shown in Figure VII-4. Integrally machined from plate stock, both the door and the removable segment can be very accurate, assuring snug and consistent fit. Permissible leakage can and should be minimal.

As indicated, the perimeter of this round door incorporates equally spaced lugs. To assure the mechanical simplicity and reliability achievable in no other way, the door is its own latch. In the case illustrated, with 18 external lugs alternating with an equal number of

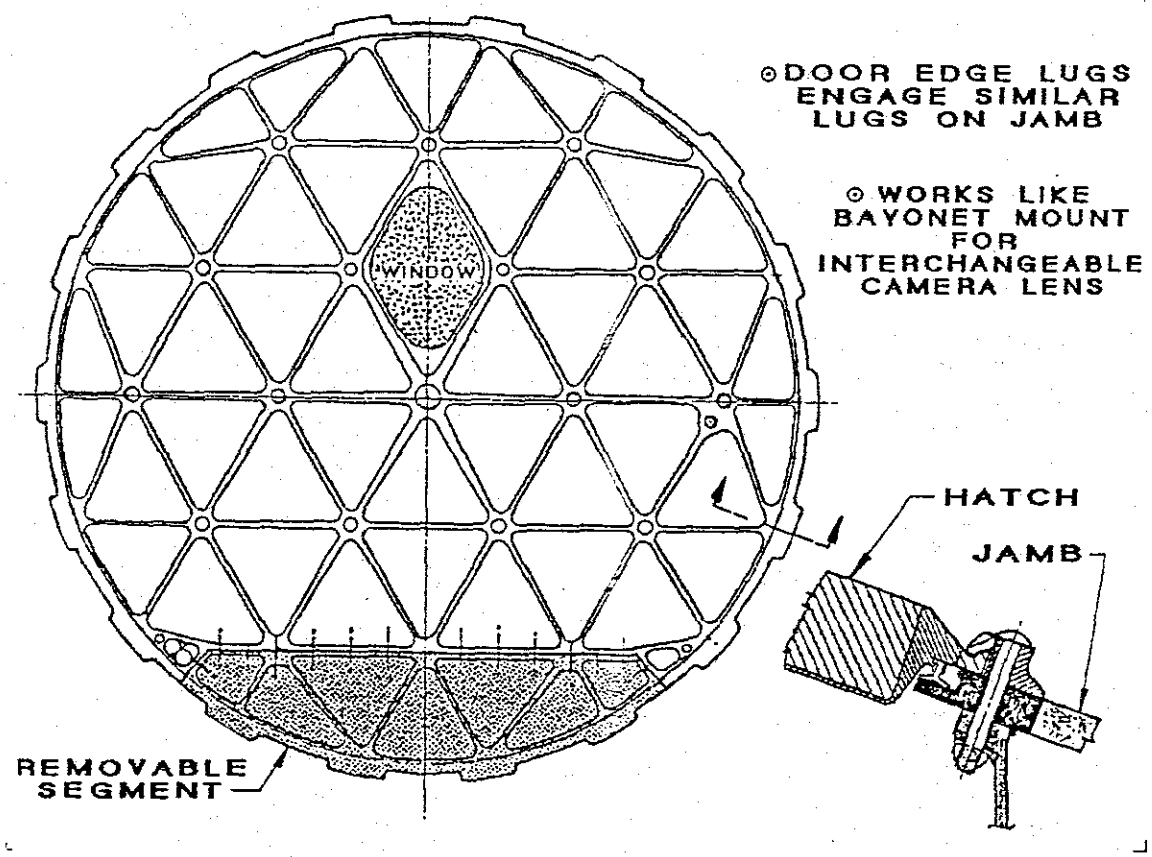


FIGURE VII-4 - A round hatch with uniformly spaced lugs around the edge can be locked by rotating it so that these lugs are under corresponding fixed hooks on the structure. It is released by rotating it to place these lugs between the elements on the jamb.

spaces, the rotation between the ***open*** and ***locked*** positions is 10 degrees. Door lugs, fitting under jamb lugs, carry pressure with equal safety in either direction.

Figure VII-5 shows the edge relationship between door and jamb in greater detail. The seal, though small to minimize overlap, is double-flapped to seal in both directions with enough allowable travel to maintain contact during any expected and controllable relative motion. A bulb seal would require high contact pressure to work, possibly demanding a pressure system, another potential failure point. When the only force available is the differential pressure across the closed port, a flap seal is a better choice because its edge is flexible, conforming more easily to irregularities, and it offers more area for pressure to lay it down.

Since the seal must slide lightly along the sealing surface when the door is operated, it cannot be allowed to move laterally for fear of tucking under. When the seal is circular, the motion during operation is always tangential without lateral components. This is another major reason for making the door round.

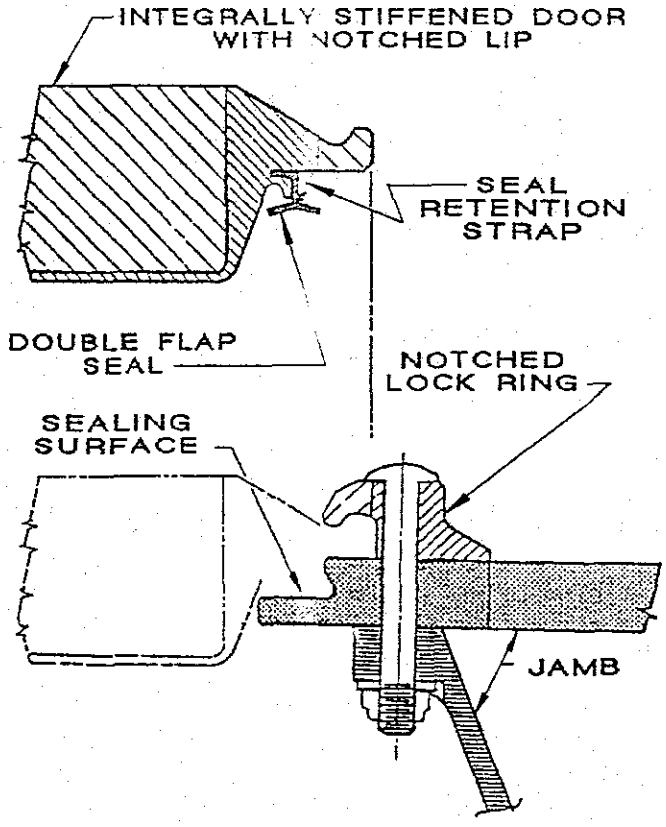


FIGURE VII-5 - A detail of the round door edge and adjacent jamb, showing the relationship between them and the means of sealing.

Note that the sealing surface is part of a step in the jamb edge. By being so located, below two projecting corners, it is protected from damage by objects bumping the edge as they pass through the opening . The seal is similarly placed in an edge concavity, although, being flexible, it can move unresistingly away from a damage source; in any case, it is also replaceable. As intended, it would be made as an accurate, continuous-loop molding, slightly undersize to fit snugly against its retaining shoulder. Its retention strap would also be continuous like a bandsaw blade, slightly oversize and heat-shrinkable. The shrink temperature must be lower than that which would damage the seal.

Many positioning (or latching) methods can be adopted for this door design without involving much risk as long as the door lugs lie between the jamb lugs when the door is opened and closed and behind them when the door is secured. The mechanism can include an overcenter link arrangement but, in this case, it is only for establishing and maintaining position, not directly involved with resisting pressure. The pressure load, in fact, acting as it does on the peripheral lugs, makes this hatch difficult, if not impossible, to open when there is any substantial pressure across it. Since it is unsafe to open the door when a pressure differential exists, anything which prevents it should be considered a safety feature. An added elaboration like an "emergency" over-ride creates its own emergency - an instant need for survival in a vacuum.

No hinges or stowage guide links have been shown because they are likely to be different for different applications and would only serve to confuse matters. In any case, it will be desirable to keep such devices to a minimum - if possible, none at all. As one corollary of Murphy's Law states: "You can't make anything foolproof because fools are too ingenious." However, it might help to counter such ingenuity by keeping airlock hatches as simple as possible, leaving minimum scope for mischance, misadjustment, and operational mistakes.

Bubbles and Barrels

Pressure vessels and propellant tanks (not necessarily the same things) offer recurring design problems. The purpose of this discussion is to sort out some of the main problem elements and gather some useful information. While the background theory must be kept in mind, there are other factors, such as the compromises necessary for balanced design, access and installation considerations, and manufacturability, which govern the design of these containers.

Generally, pressure vessels are unstiffened membrane containers designed almost entirely by the requirement to remain intact (with appropriate margins) while resisting uniform internal pressure at the highest prudent stress level. Propellant tanks, on the other hand, are often as much affected by pressure "head" gradients exerted by dense fluids under acceleration. They are also affected by dynamic slosh loads, requirements for venting and draining, and the basic vehicle loads resulting from their integration into the structural frame. So, while they may be influenced by the theories governing pure pressure vessels, their evaluation cannot stop there.

Pressure Vessels

The minimum attainable weight of a pressure vessel relative to the volume it encloses is expressed by:

$$\frac{W}{V} = \frac{KPd}{s}$$

P = pressure, pounds/square inch
d = material density, pounds/cubic inch
s = membrane working stress, pounds/sq. inch

and K is the shape coefficient. The ratio comes out as pounds of pressure vessel per cubic inch of volume contained.

The minimum value for the shape coefficient is 1.5, that of a sphere or a spherical lobe assembly, the lightest known pressure vessels. A coefficient of 2.0 defines a headless cylinder (that is, a section of circular cylindrical pipe), a multi-lobed cylinder, or a perfectly designed and built torus (see Figure VII-6). The equation applies only to ideal pressure vessels, those without joints or penetrations whose elements all work at the same high stress - in short, animals as mythical as unicorns, Easter

bunnies, or corporate images, suitable only for reference purposes. In a study comparison, it boils down to the credibility (or position in the pecking order) of the individual who assigns the "fudge factor" to account for realities. Note that the size or number of pressure vessels is not involved. In other words, a hundred little spheres weigh no more than one big one with the same capacity - and the same values for the other variables in the equation. Of course, there are some differences in the penalties from the number of connections, occupation of space , joints, brackets, and penetrations which deter anyone from testing this theory in actual practice.

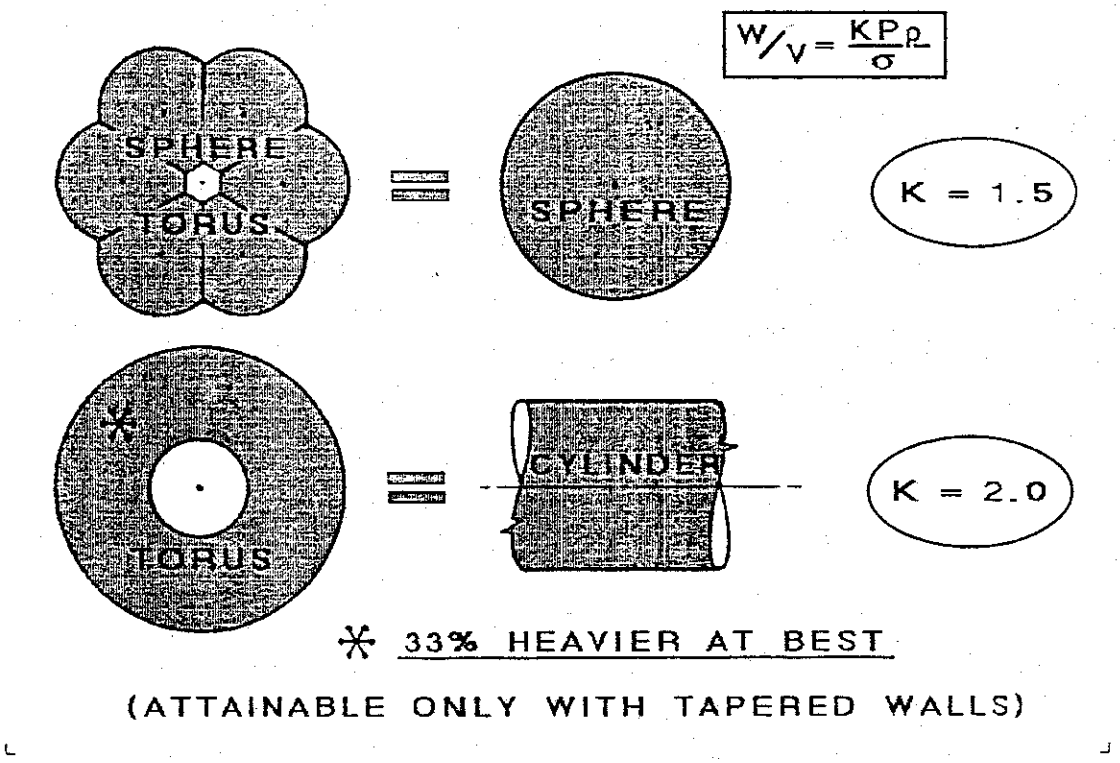


FIGURE VII-6 - As shown here for typical cases, the weight of a pressure vessel relative to its volume is determined by its shape factor, 1.5 for a sphere and 2.0 for a cylinder.

Spheres and Spherical Lobes

While a sphere is the lightest form of pressure vessel, it doesn't fit very comfortably into many of the available spaces in typical aircraft or space vehicles. It is also an inherently slippery object to hold, requiring special necks, saddles, or straps which are sometimes quite heavy and impose large eccentric moments on the back-up structure. Just the same, for minimum pressure vessel weight and minimum surface area where heat transfer must be minimized, spheres are often the logical choice.

The whole subject of sphere installation can fill a book. However, the main point to remember, for spheres as well as all other pressure vessels, is that membranes possess in-plane or tangential strength and stiffness, paying large weight penalties when resisting forces - or components of forces - are applied normal to the surface. Loads, particularly local ones, should always be applied tangentially or at stiff corners where surfaces intersect.

Efficient high-pressure metallic spherical containers are generallly made in two hemispheres (mostly, of titanium) with an equatorial girth weld. They are usually made from thick-walled forgings which, while supported on precisely shaped mandrels matched to a precisely machined interior, are machined down to minimum thicknesses on the order of .030 inch, sometimess less. All inlet ports, mounting pads, and weld lands are integrally incorporated. The halves are joined by welding in a sealed chamber filled with an inert gas, usually argon. They receive individual solution heat treatment before welding after which the assembly is stress relieved by a heat soak.

It is evident that a lot of expense is incurred to gain efficiency. Besides, qualification testing is lengthy and rigorous. As a result, programs usually look for qualified "off-the-shelf" hardware from previous programs, items on a listing of "available" pressure vessels. Usually, these are unavailable containers made for some long defunct program. A re-order is much like starting from scratch; the manufacturer probably has no tools or drawings left and can't obtain forged blanks from the material supplier.

Such experience is typical. No standardization is achieved because the industry loses interest between major programs. Vehicle designs continue to be compromised for non-existent "available" hardware which is often radically altered, but not improved, after the wrong choice has done the damage. There is need for standardization but no program seems willing to shoulder the cost "burden" and nobody seems interested in the general problem. It is a relatively minor (even if constantly irritating) subject which fails to interest a researcher who is bent on stemming the

tide of progress.

One particular variation on the sphere offers some interesting possibilities as a standard module. It is a part of a spherical lobed pressure vessel, which, as previously indicated is theoretically as light as a sphere. The derivation of its shaoe factir is shown in Figure VII-7. This module has already been described as a standardized building block in Chapter IV, the general subject of which is modularity.

Analysis indicates that arcuate forms of such tanks will not straighten out under pressure as toroidal arcs will; tests are probably needed to confirm this. At any rate, it's not difficult to see how standard vessels which can be made to different curvatures can readily be fitted to many of the odd shaped volumes in space vehicles. Good examples are the annular crevices between intertank cylinders and the tank end domes jutting into them. These tanks also are endowed with good natural "handles", the stiff and stable inter-lobe creases where spherical membranes and disc membranes intersect.

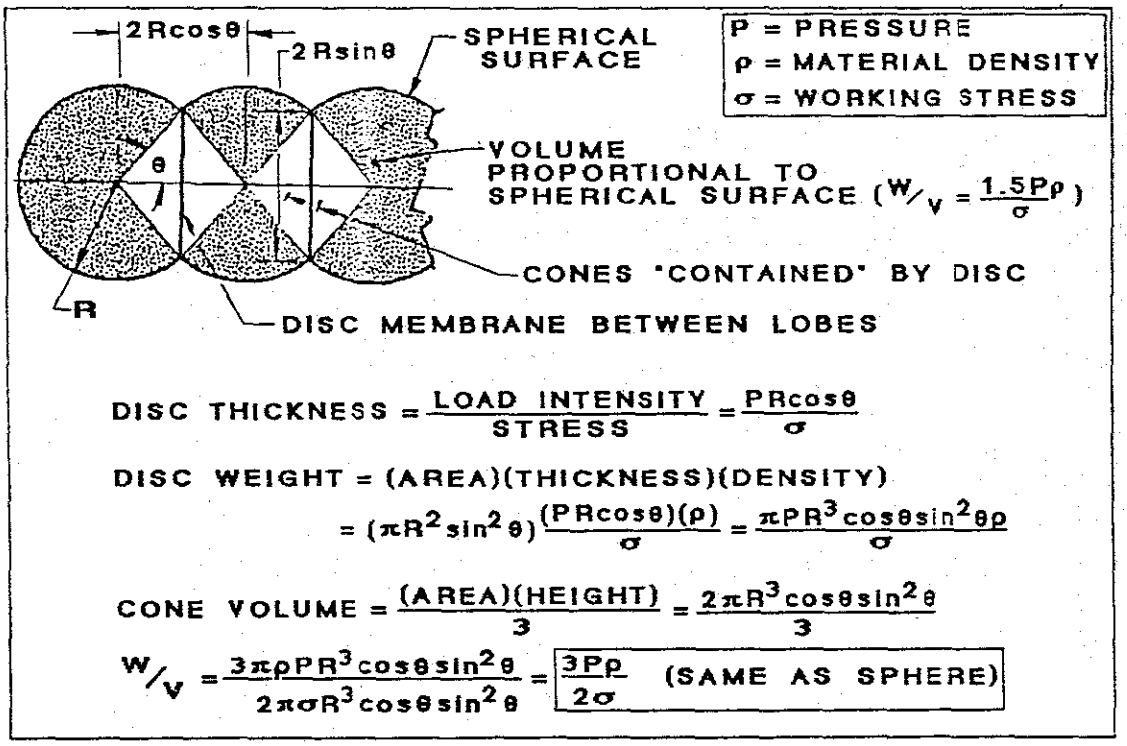


FIGURE VII-7 Derivation of the shape factor formula for a spherical lobe of a multi-lobe pressure vessel. The weight/volume ratio is not affected by the number of lobes.

In the actual application of this unusual but promising pressure vessel, certain cautions must be kept in mind:

◊ As the number of lobes and inter-lobe discs increases, the membranes become impractically thin and, therefore, unbuildable; the penalties of "minimum gage" apply.

◊ In the same situation, the number of equatorial welds also grows with corresponding joint weight penalties.

◊ Similarly, the theory assumes sharp corners where membranes intersect; in actual practice, there are fillets at all these corners which entail weight penalties - with careful design they can be kept small.

◊ When such a vessel becomes a propellant tank, the increase in numbers of sumps and vents with accompanying penetrations, lines and so forth can very rapidly outweigh any improvements in so-called "volumetric efficiency" which, after all, involves other things than propellant containment.

On the other hand, any other pressure vessel (such as a sphere) must also be penalized by girth welds, penetrations and mounting hardware before it can be put to practical use. This is where design judgment comes in.

Cylinders

While a cylinder is at an inherent disadvantage as a pressure vessel with its shape factor of 2.0, it has many applications for combined resistance to internal pressure, bending, and axial load. It is the logical shape for integral propellant tanks in launch vehicles - Thor/Delta, Atlas, Titan, and Saturn, for a few examples.

As shown in Figure VII-8 , when a cylinder is sustaining pressure only, the critical tensile loading is hoop tension:

N_h = hoop load intensity, lb/in = PR
P = differential pressure, psi
R = cylinder radius, in

The axial load intensity, N_a, is half as high:

$$N_a = \frac{PR}{2}$$

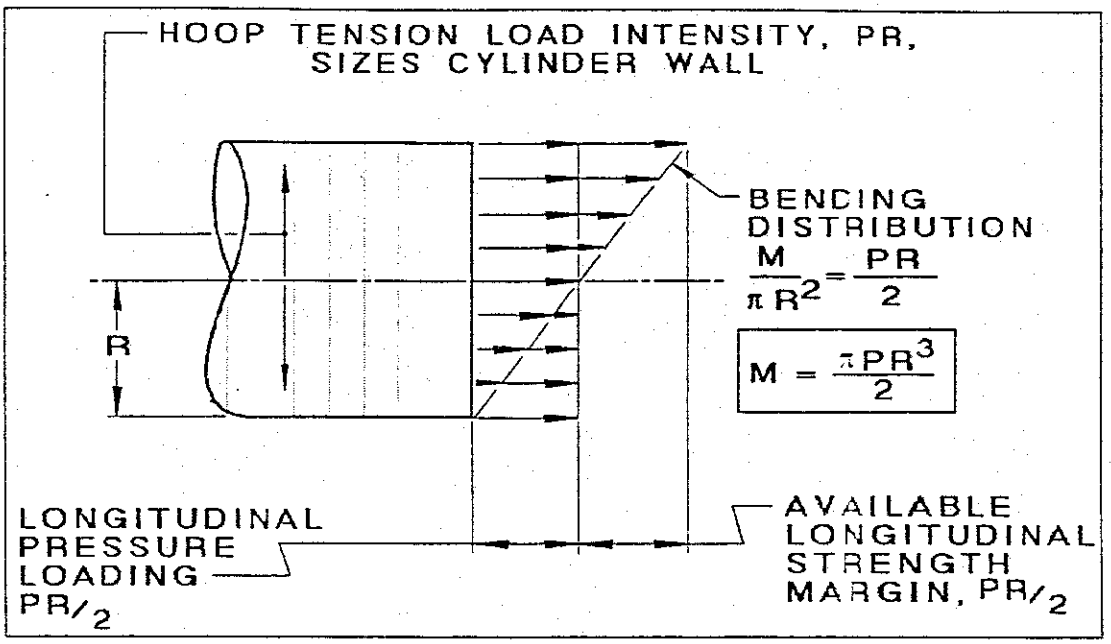


FIGURE VII-8 - While a cylinder is not the lightest pressure vessel, the difference between hoop and longitudinal stress (a 2:1 ratio) allows it to sustain large bending moments while pressurized.

This means that a pressure shell made of isotropic material like a metallic alloy plate or sheet must be sized for hoop tension and therefore possesses residual strength for axial forces chiefly from bending. If the maximum axial compressive stress from bending is equal to the axial tensile stress from internal pressure, the net axial stress in the membrane at that point is zero, as much force as an unstiffened membrane should be expected to sustain without buckling, and:

$$\frac{PR}{2} = \frac{M}{\pi R^2} \qquad \text{or} \qquad M = \frac{\pi PR^3}{2}$$

That is, if an unstiffened cylinder 10 feet in diameter is sized for a 20 psi pressure differential, it can carry wihout additional penalty a bending moment of 6.79 million inch-pounds, the moment generated by hanging 28.3 tons on the end of a weightless 10-foot boom.

Fluids under pressure can accomplish quite spectacular results like the example just cited and, occasionally, explosions. Since the principal task in designing aerospace structure is resisting compressive loads efficiently, it's always a temptation to let compressed gas handle the job. Blimps do it this way, maintaining rigidity in the buoyant gas bag with a

pressure of only 4.5 inches of water head - about .18 psi.

The Atlas ballistic missile tank is an unstiffened welded stainless steel cylinder, lightweight but fraught with operational difficulties. The trouble is that loss of pressure from improper seals or leaky valves and regulators means collapse; overpressure means disaster. Consequently, Atlas must be handled with a stretcher strongback during fabrication while the ports are open and with an attached pressurization kit during transportation and erection at the launch site. Centaur has been designed with the same philosophy which may partly account for the lack of enthusiasm in some quarters for its adaptation as an upper stage for the Space Shuttle. Other booster systems like Titan, Saturn, and Thor/Delta reflect a reaction to the problems of Atlas. Their shells are stiffened to carry the weight of any upper stages and full fuel while on the launch pad, unpressurized. In some instances, there are no flight conditions which can cause compressive loading in the pressurized shell.

Most cylindrical tanks are round tubes, but they can also have multiple lobes with the same weight/volume ratio as a single cylinder, as shown in Figure VII-9. This is analogous to the spherical lobe vessel with

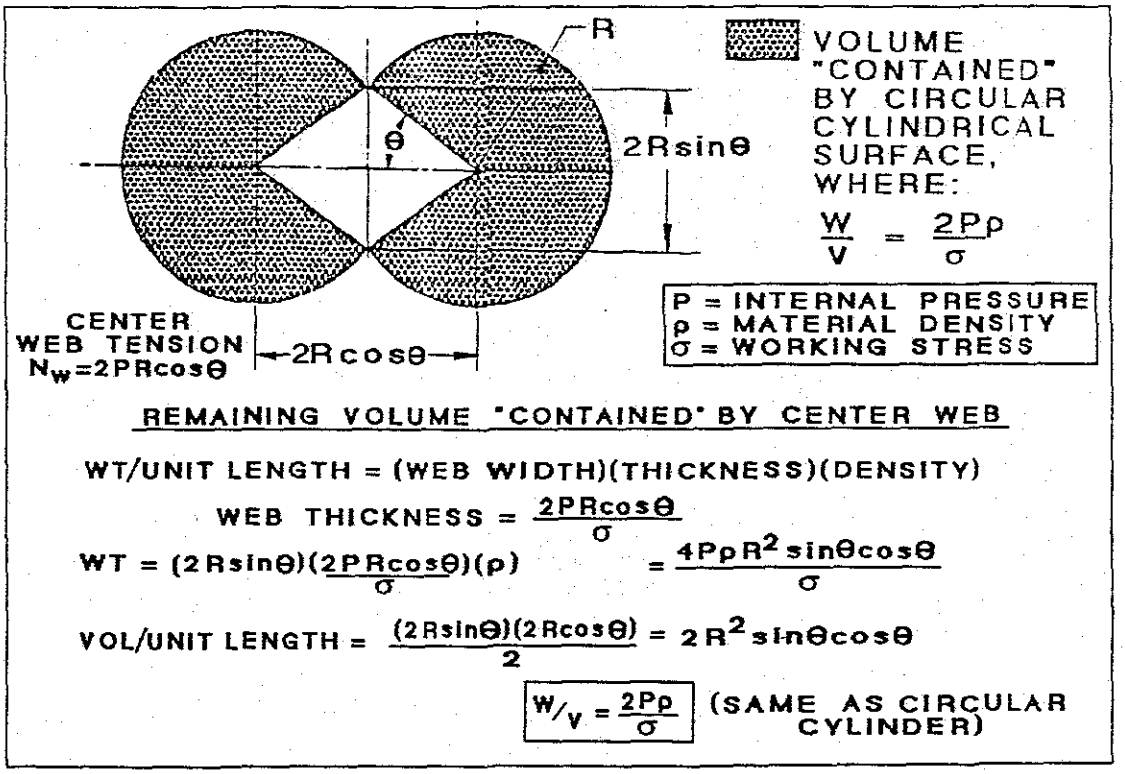


FIGURE VII-9 - A lobed cylinder is theoretically as light as a single round cylinder, as shown by this derivation of its shape factor, 2.0.

one important difference; the tank end domes become quite complex. In the late 1960's, General Dynamics built an experimental two-lobe tank of this type. It was a technical success because it carried pressure, but it was complicated and costly, with the weight penalties that complexity engenders. No urgency to repeat the job seems to have arisen since.

One other cylindrical variant is the torus, which can be described as a cylinder turned around on itself to make a loop without ends. Elimination of the end dome problem is an advantage which is soon offset by the problems of manufacturing saddle shaped pieces and joints and penetrations in them as well as the inability of such a tank to contribute significantly to the general structure. Where liquid propellants are contained, there are additional penalties in added sumps needed to minimize residuals, and slosh baffles which are difficult to design and build. A problem which refuses to go away is basic structural inefficiency. At best, the shape factor is 2.0, achievable only with walls of tapering thickness because the meridional load intensity (equivalent to hoop loads in the straightened cylinder) is higher inside the "doughnut hole" than at the outside perimeter. This difference is reduced as these two diameters approach the same value, that is, when the doughnut is thin with a large central hole. However, this kind of a tank is very inefficient volumetrically. Tapering the wall thickness of this vessel is formidable enough to have been avoided in real practice. This means that weight penalties, even disregarding penetrations, are higher than for cylinders. The shape has repeatedly been considered since space vehicle design began, but each time the discouragement of closer inspection has shelved it until the next round.

Cylinder Ends

The trouble with straight cylindrical tubes is that they cannot contain anything without ends and these ends are a perennially controversial issue. The issues are weight and volumetric efficiency - as measured by overall vehicle length. A long tank end not only takes more space but requires a longer and heavier skirt structure extending from the tank cylinder in a typical rocket vehicle.

The lightest end dome is a hemisphere since it has the same shape factor as a sphere. However, its height is equal to the tank radius and its strain is incompatible with that of the cylinder. A hemisphere is uniformly stressed in all directions so that its bi-axial stress ratio, as measured along any pair of mutually
perpendicular axes, is 1:1; the cylinder's longitudinal-to-hoop stress ratio is 1:2. As a result the cylinder's hoop deformation is higher than that of the sphere (or hemisphere) at the same stress. The hoop contraction from

longitudinal stress caused by Poisson's ratio is less than the equivalent contraction in the hemisphere. This strain mismatch, or discontinuity, requires some extra material at the joint, material that is almost always present for the dome to cylinder joint or for skirt attachment in most cases. Quite often, the physical requirements for space and structural depth in the vicinity of such joints make the attachment rings much larger than would be dictated by theoretical strength or stiffness. The weight penalty, if any, is not readily expressed mathematically.

A shorter and more strain-compatible end dome shape for a cylindrical pressure vessel is an ellipsoid. The special case which works best in theory and practice has a dome height equal to the cylinder radius divided by $\sqrt{2}$. This shape requires a thickness equal to that of the cylinder (or twice that of a hemisphere) where the two shapes join. At its apex, the radius of curvature, twice that of the hemisphere, also requires twice the hemisphere's wall thickness. The same holds true all over the surface of such a dome. A uniform thickness is optimum. Other proportions of ellipsoids and similar shapes are only optimum when the skins are tapered, a manufacturing task difficult enough to be generally avoided.

The $\sqrt{2}$ elliptical dome plus the length of cylinder added to bring its capacity up to that of a hemisphere weighs twice as much as a hemisphere and is .9 times as long. It's a considerable weight price to pay for a length reduction of only ten per cent, but a price which has been willingly paid in most cylindrical tank applications. The shorter cylindrical skirt needed to extend the structure evens the weight; if this skirt is inefficient enough, the ellipsoidal domed tank installation can be lighter.

Another form of end dome, one which appears heavier for a tank as a pressure vessel only, is a spherical segment, the shape defined by a sphere of larger diameter than the cylinder. The intersection corner is in circumferential compression but is well stabilized by the membranes on either side. The extra material required makes a relatively heavy but conveniently rugged "knuckle" which can easily include attachment provisions. This configuration is common in such cases as pressure bulkheads at the ends of transport airplane passenger cabins. It is also found in one of the more successful expendable space boosters, the Thor/Delta (Figure VII-10).

The rigidity of this corner is particularly advantageous for attaching discrete elements like truss strut ends in inter-tank and skirt areas. This improves both access and thermal isolation. While it will always appear to be heavier in a purely structural evaluation, the overall effect on a complete configuration is usually favorable - often in intangible and initially unmeasurable ways. In one study which comes to mind, the

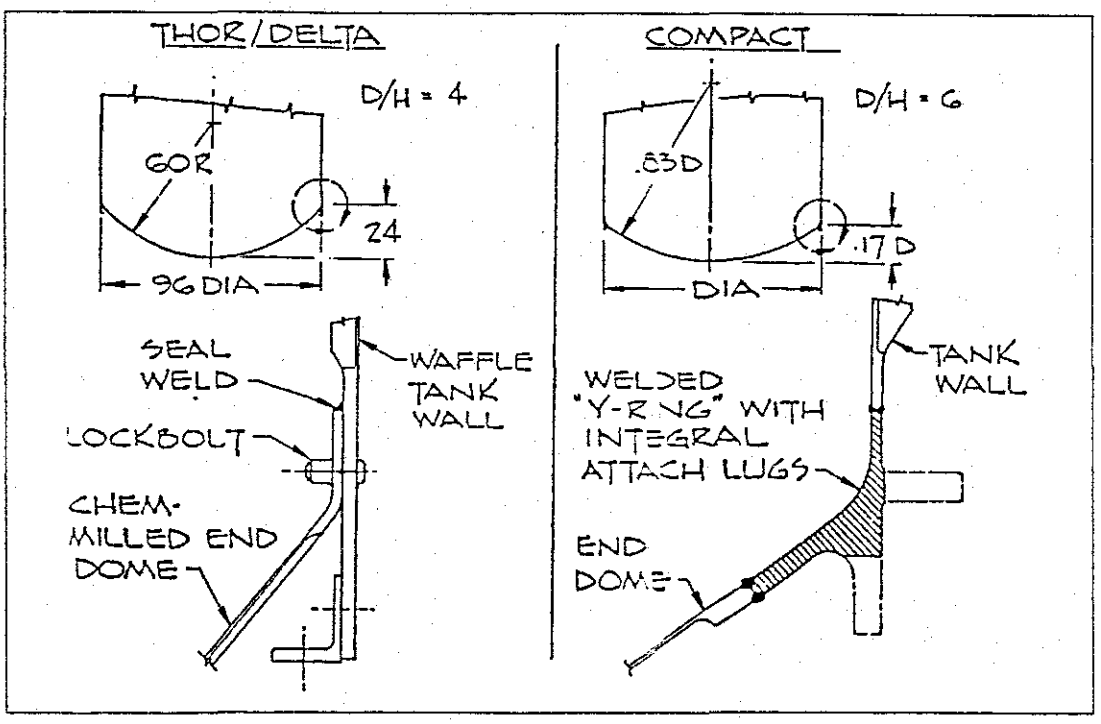


FIGURE VII-10 - A tank end made from a spherical cap, as shown, is not theoretically efficient but in practice is simple to build.

propellant tanks alone were 500 pounds heavier on paper than carefully sized ellipsoidal ones (out of a total 2500 pounds of structural frame) but the overall weight was slightly lower. The reduction came from the elimination of ring frames in skirt and intertank areas. Ring frames, like all curved structural elements loaded primarily in bending, are excessively heavy and well worth eliminating wherever possible.

The non-tangential intersection of dome and cylindrical wall makes an open angle where skirts attach, easing space restrictions in the attachment area and permitting structural depth for stability where the skirts need it. The more open crotch is also less likely to trap loose parts like nuts and washers during fabrication. The spherical surface of the dome, since its radius of curvature is constant in all directions, is simple to make and measure and allows standardization of penetrations.

Probably, no discussion of end domes for cylinders is complete without at least a mention of the Cassinian dome. It offers little, if any benefit, being useful mainly for demonstrating one's technical footwork. While it may not save any weight, it will at least offer a number of manufacturing challenges like tapered skins, irregular reinforcement at penetrations, and tricky geometric form. These shapes (a whole family of them) are the outlines of slices taken through the edges of toroidal doughnuts as shown in Figure VII-11.

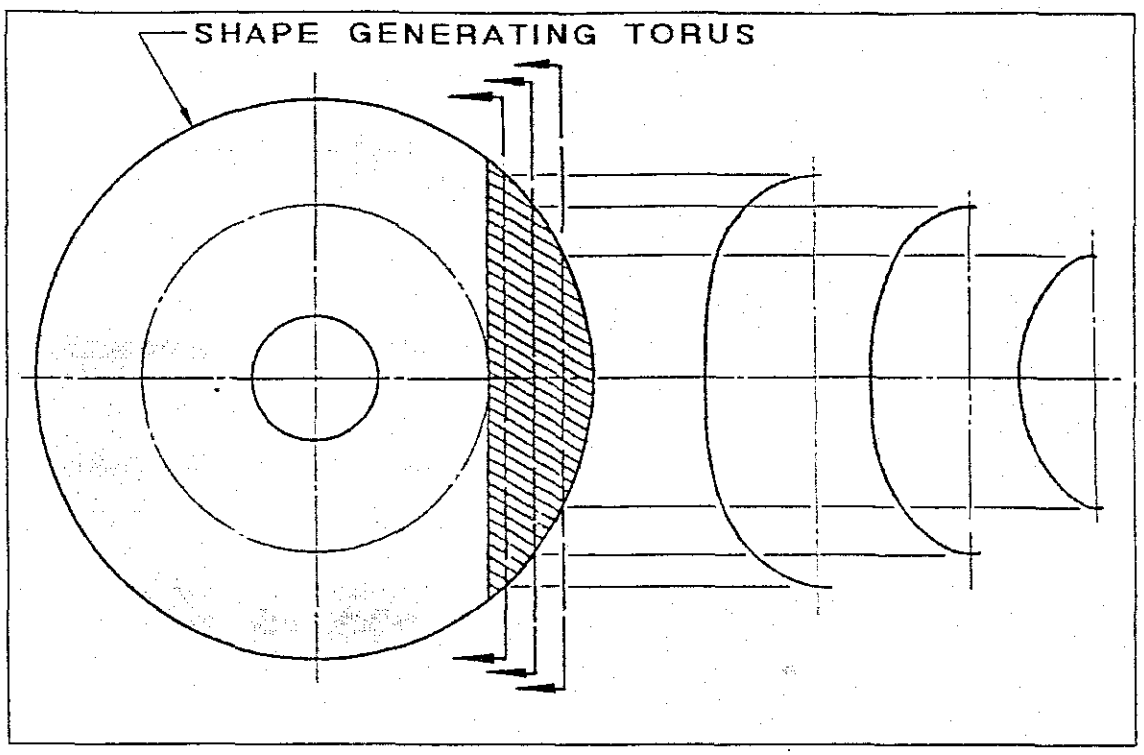


FIGURE VII-11 - Cassinian tank end domes, interesting but not particularly advantageous, are derived from the shapes of sections cut through a torus as shown.

Similarly esoteric possibilities can probably be extracted from the shapes of super-ellipses. These are mathematically defined by variations of the familiar equation for ellipses with the exponent being any number larger than 2. A favorite mathematical recreation of a Danish designer, Piet Hein, the shapes have so far been useful mainly for generating the forms of coffee tables and traffic "circles" in Copenhagen.

Propellant Tanks

Liquid containers are, as previously mentioned, subject to non-uniform pressures from the gravitational head of dense fluids, adding considerable material in the sump region. This pressure head is exploited to deliver fluids to pump inlets. However, dense propellants like LOX (71 pounds per cubic foot) or nitrogen tetroxide (90 pounds per cubic foot) can cause quite steep gradients at accelerations of 3 or 4 g's, gradients too steep to be simulated effectively in hydrostatic tests of full-scale tanks, particulary in routine acceptance tests applied to every vehicle. Suggested partial solutions to the verification problem include giant cetrifuges and dense, muddy slurries hard to clean out after the test. No program has yet

paid for such elaborate measures, so tanks are hydrostatically tested with plain water which has been treated to prevent reaction with the tank walls. Since the worst case situation must be demonstrated in the test, upper parts of the tanks will be subjected to higher pressures than seen in service (Figure VII-12). Weight penalties incurred by this practice must be taken into account.

Penetrations, Reinforcements

The theoretical pressure vessel without penetrations or reinforcements for local load is fictitious, as previously mentioned. Inattention to good practice in the design of these inevitabilities can make liars out of optimistic weight estimators.

A very important consideration is the difference in local shape between the pressurized and unpressurized conditions. Excessive and uneven distortions will raise stress levels, increasing the weight of reinforcement to prevent this, or increase the probability of leakage where the joint is required to open. The one type of penetration which can be expected to work reliably is that which is defined by the intersection of two spheres or a sphere penetrated by a cylinder whose axis passes through the sphere's center. This intersection is circular and lies in a plane, remaining flat and round whether the container is pressurized or not.

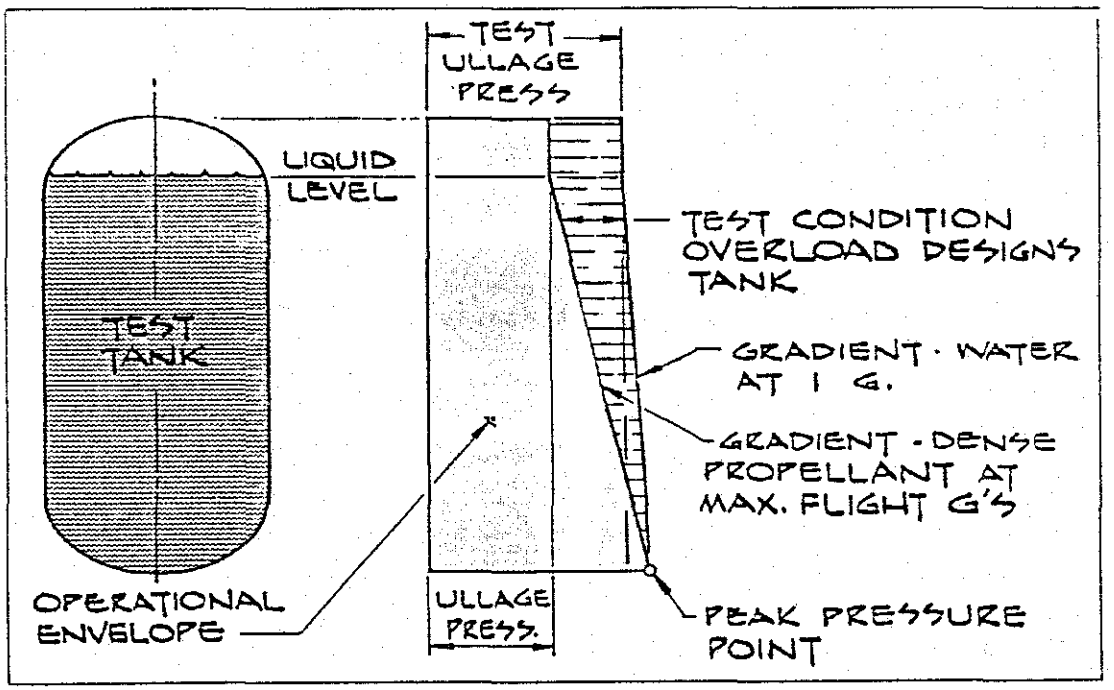


FIGURE VII-12 - A typical tank for a space vehicle pays a weight penalty for being designed to meet an achievable test rather than the real conditions of flight.

Even in this ideal situation it is important to align the centroid of the reinforcing ring with the pressure resisting membrane (Figure VII-13). The local rotations induced by the eccentricity when this practice is not followed cause non-uniform stresses, especially undesirable in welded joints. For similar reasons it is desirable to locate the stepped reinforcing lands at welds on the ***outside*** of a pressure vessel so that the secondary bending caused by bulging of the membrane between straps creates relieving compressive stresses in the notch of the step.

Intersections between cylinders or between spheres and cylinders or cones which are ***not*** on coincidental centers are not round and do not lie in planes. The shape distorts under pressure causing either leaks at disconnectable joints or extra weight and testing to avoid them.

Figure VII-14 shows the original design of one of these troublesome intersections, the fill and drain line into the LOX tank of the Saturn S-IVB stage, the modification which came about because the weld could not be made successfully, and the redesign proposed to relieve the problem. The original weld had to be produced on a 5-axis positioning machine capable of following the distorted elliptical intersection while changing torch angle to bisect the continually changing intersection angles around the path. The operation, which also called for control of electrode feed, torch advance rate, weld current and gap, required automatic programming. The redesign was proposed after the canted weld repeatedly cracked during proof pressure testing of new tanks. Because only 5 or 6 more

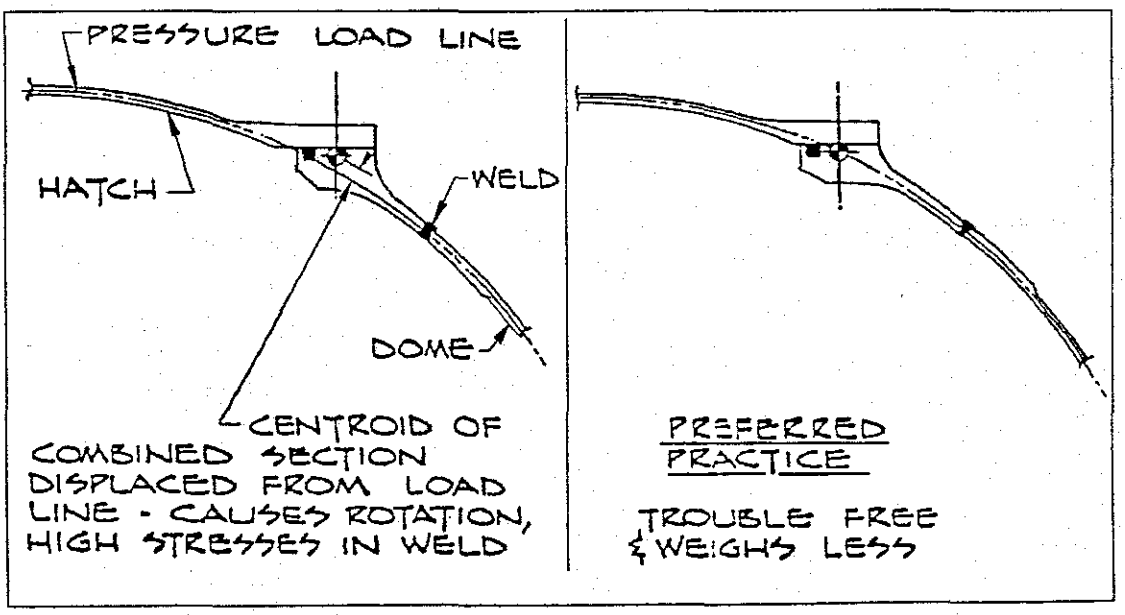


FIGURE VII-13 - Eccentricities in local reinforcement around holes in spherical surfaces can cause trouble and should be avoided.

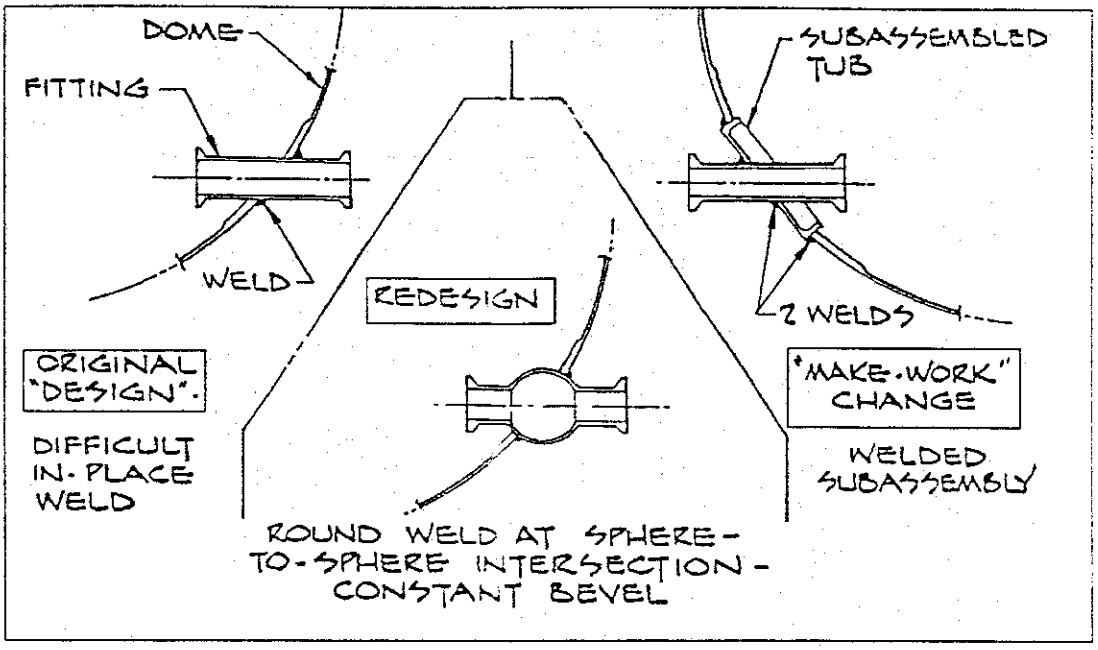


FIGURE VII-14 - The fill and drain line for the S-IVB LOX tank penetrates the end dome at an angle, creating the assembly problems indicated by the subsequent redesigns shown.

vehicles were scheduled to be built under an existing contract and all the parts were on hand, the proposed change was vetoed by the project office. Eventually, all the available parts were destroyed in unsuccessful attempts to build the assembly, each part having to be re-ordered at least once and, in some cases, 2 or 3 times. This joint was described by manufacturing engineers at Marshall Space Flight Center (MSFC) as one of the 10 most annoying "show stoppers" in the Saturn program.

Surfaces and Volumes

Finally, because this is supposed to be a brief dissertation, not a pressure vessel textbook, some useful area and volume relationships are offered.

A simple but too-often unfamiliar relationship between cylinders and spheres of the same diameter is shown in Figure VII-15. Knowing this can save a lot of time and computation. Figure VII-16 relates ellipsoids and hemispheres, a fairly simple exercise when volumes are compared, but quite a different matter for surface areas. Figure VII-17, showing how the volume of a spherical cap relates to its height, is useful not only for calculating the volumes of spherical segments but for determining the volume of liquid in a spherical tank as its depth varies.

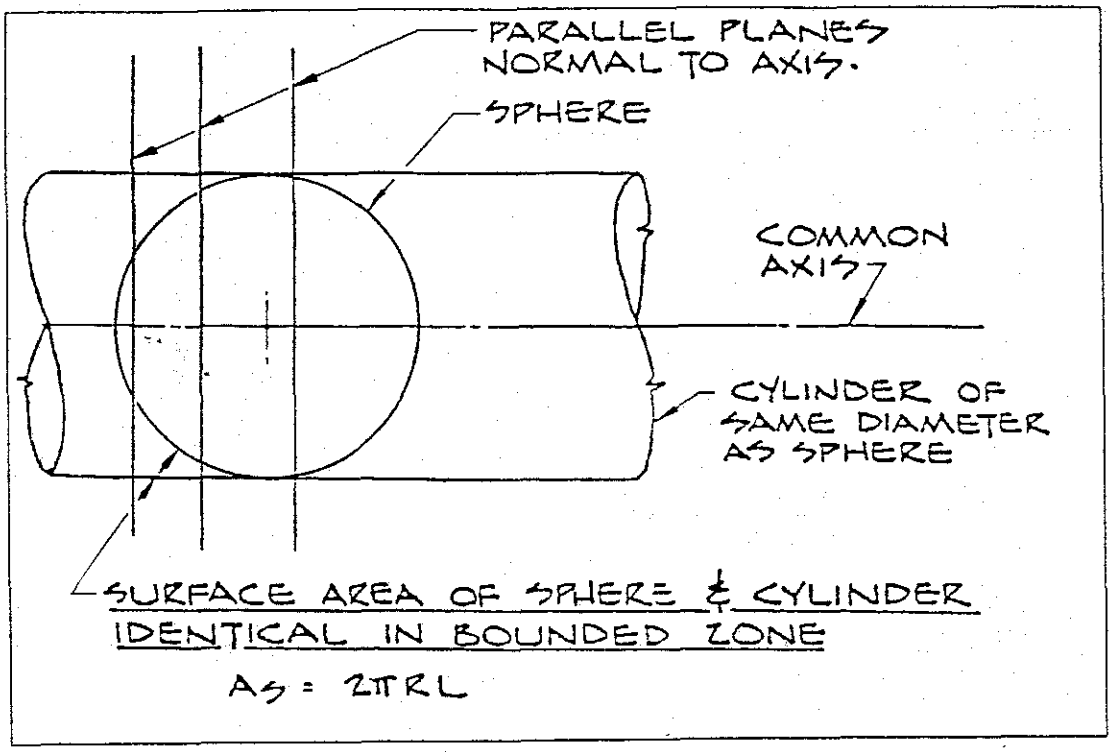


FIGURE VII-15 - The surface area of a spherical slice is the same as that of a circular cylinder of the same diameter with the same distance between boundary planes.

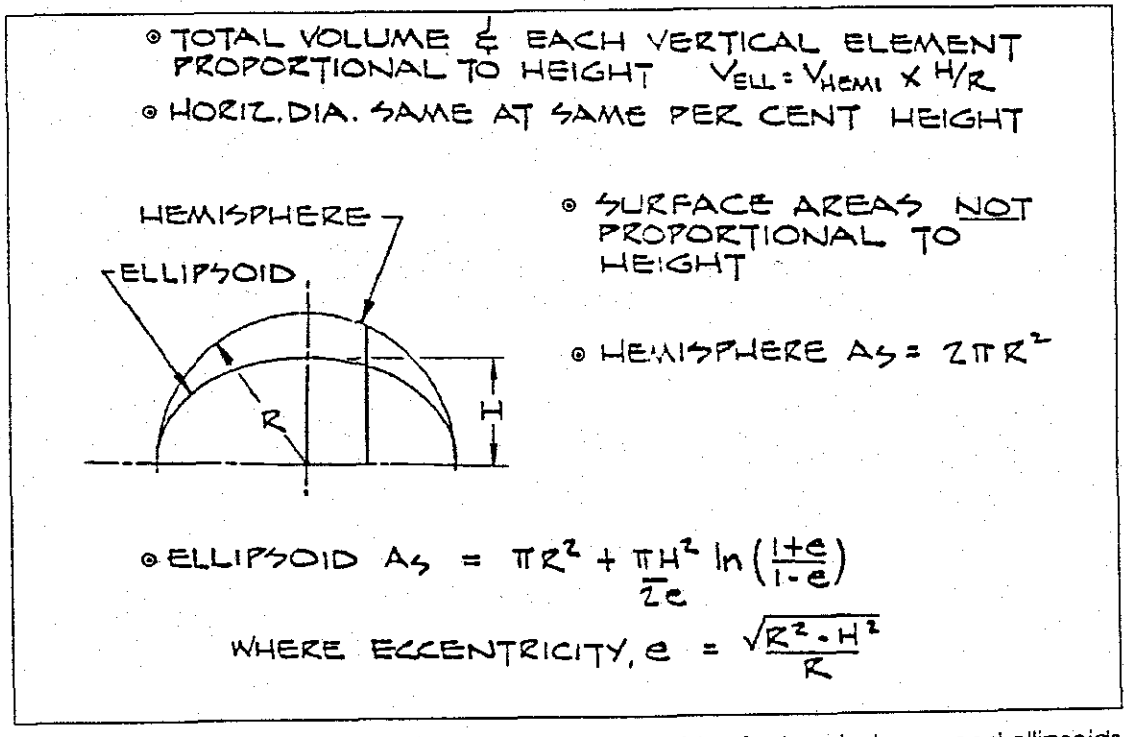


FIGURE VII-16 - Volume and surface area relationships for hemispheres and ellipsoids.

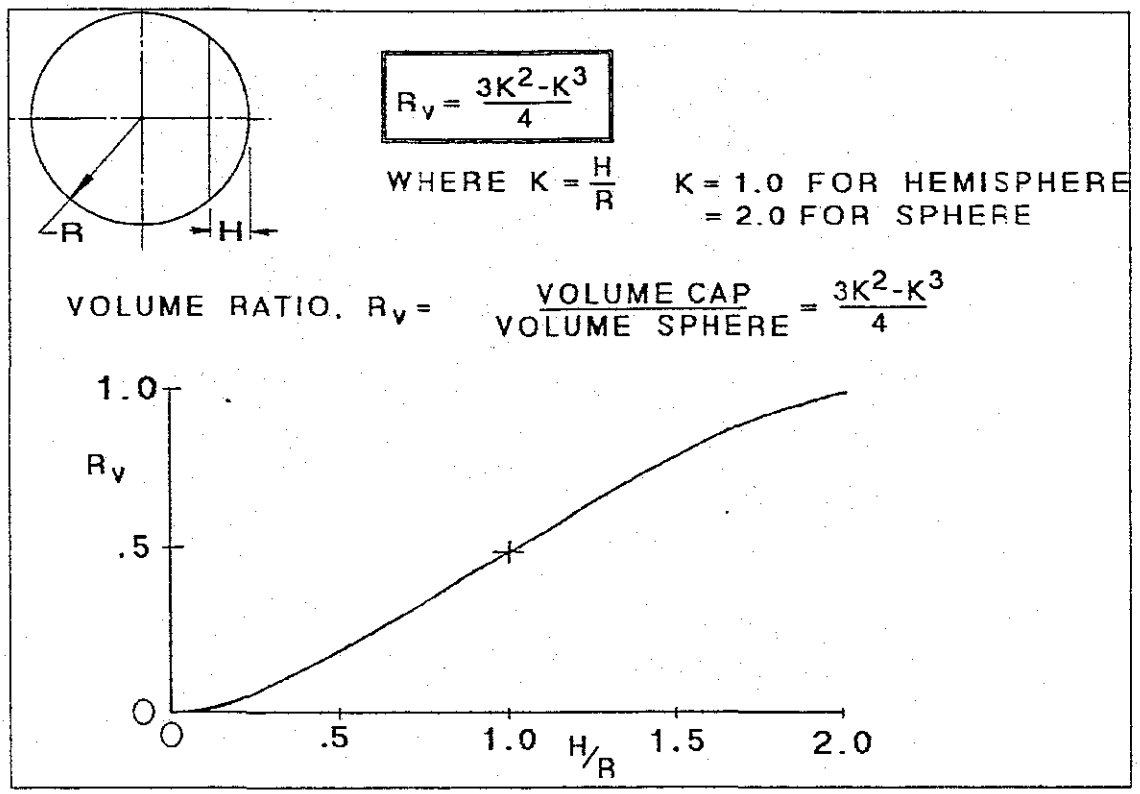


FIGURE VII-17 - Volume in a spherical cap as determined by its height and the sphere radius.

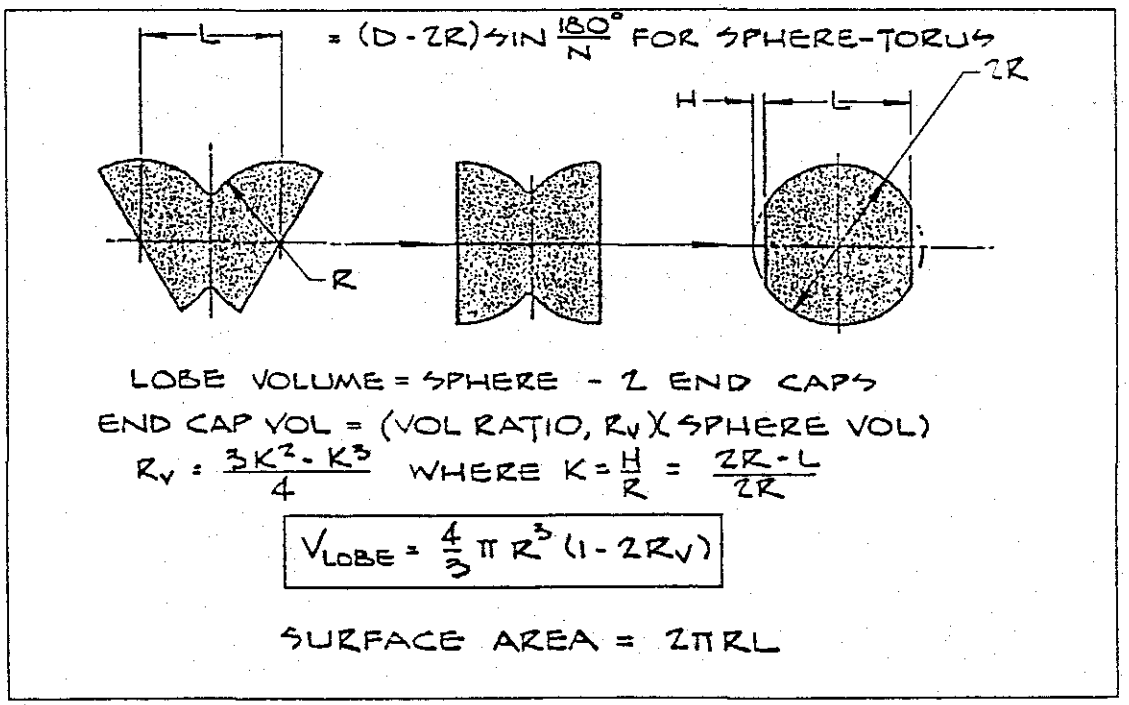


FIGURE VII-18 - Volume of a single lobe of a lobed-sphere torus pressure vessel.

Figure VII-18, a special case of the spherical cap volume formula, defines the volume of a torus lobe. Figure VII-19 aids rapid estimation of the proportions for a lobed torus of given volume, by varying outside diameter, lobe diameter, and number of lobes.

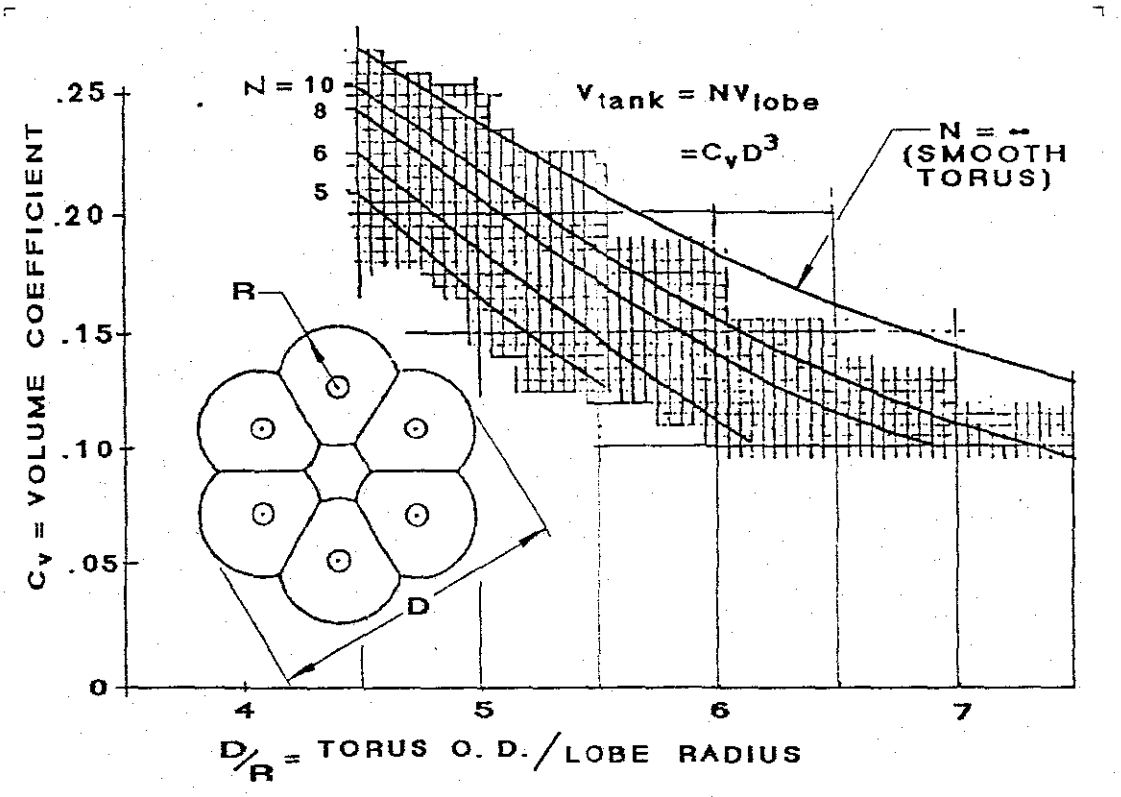


FIGURE VII-19 - Volume variations of a lobed-sphere torus as determined by outer diameter, lobe radius, and number of lobes.

Androgynous Connectors

It hardly ever happens, but it would make a lot of sense to make disconnects whose opposing sides are identical. It is beginning to be seen that this makes sense for docking mechanisms, but the principle should have much wider application than that.

Fluid couplings, garden hoses being a particularly familiar and typical example, are of the male-female variety, a probe on one end and a receptacle on the other. The system works well until a male-to-male or a female-to-female connection is indicated. For such cases, adapters must be provided, demonstrating once again that there has been insufficient forethought in the design. When the hardware store is not too far away, the problem can be remedied fairly painlessly, but what would happen in space if a scheduled delivery of parts did not come off as planned? There would be an embarrassing oversupply of the wrong units, causing a shortage correctable only when the next supply ship arrives - perhaps ninety days later. For circumstances like this, and, for that matter, as a standard design practice, it would be well to consider androgyny, the condition of **identical mating parts,** a standard practice. So far, the idea has been consistently overlooked.

When this practice is accepted as a first principle of joint design, the problem reduces to visualization of a shape which, when rotated 180

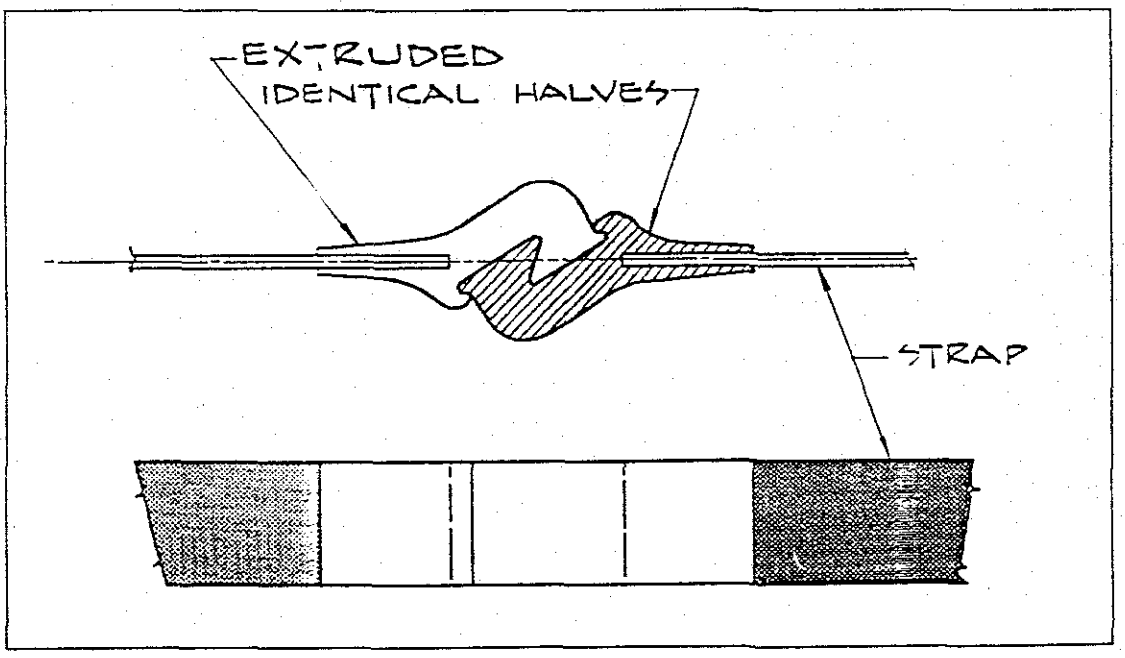


FIGURE VII-20 - A simple androgynous tension joint. The shape is one which, when rotated 180 degrees about the center point, fits itself.

degrees, will fit itself. Figure VII-20 depicts a simple application of the idea for a fitting at the end of a tension strap which can be joined to another identical unit. Some kind of tie-down kit of straps with such ends could be offered to a potential customer without fear that he would be unable to use them. They might prove useful in a space station or space depot environment. Closer to home, something like this could be applied effectively by owners of pickup trucks.

Another device of the common "garden" variety is the garden hose. the first example cited in this discussion. There has been a plethora of patented quick-disconnect couplings, all of which involve two non-identical ends. Let's see what could be done for this case, as an example of what might be possible in other instances. One way, as illustrated in Figure VII-21, is to incorporate both male and female parts of the joint in each end. There's nothing very wrong with a design like this except that the open passage covers a relatively low percentage of the available cross-section, making it either restrict flow or grow to unreasonable size. The

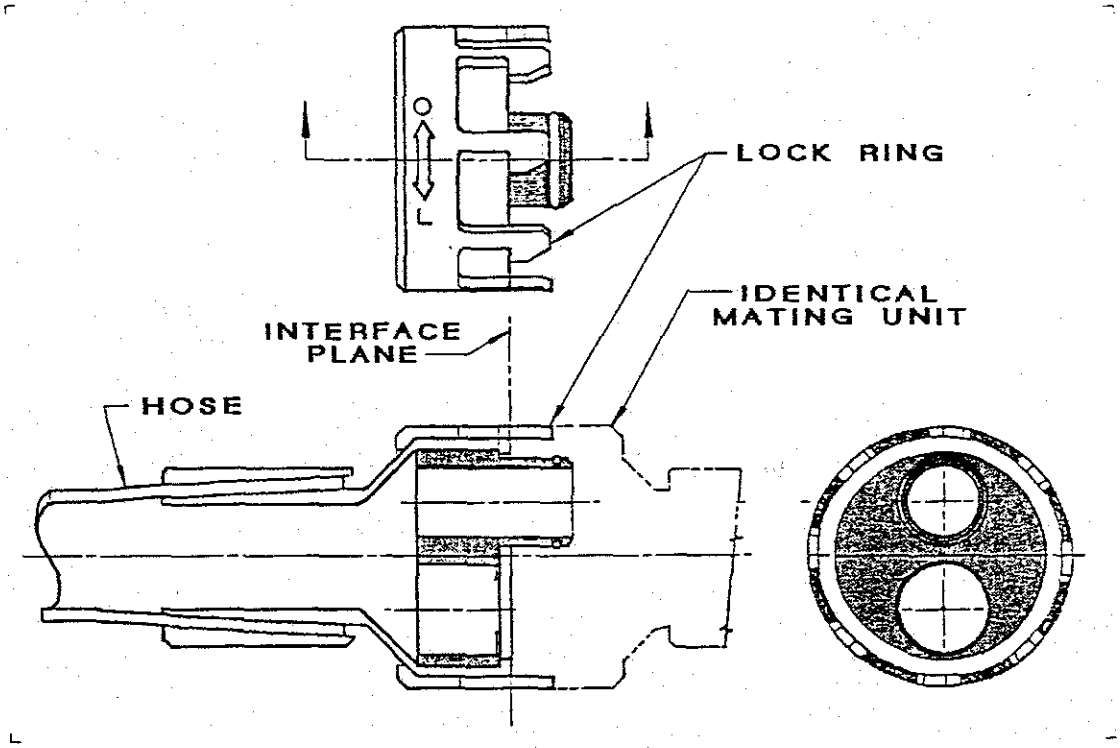


FIGURE VII-21 - A hypothetical design for an androgynous garden hose coupling. Each side incorporates male and female elements.

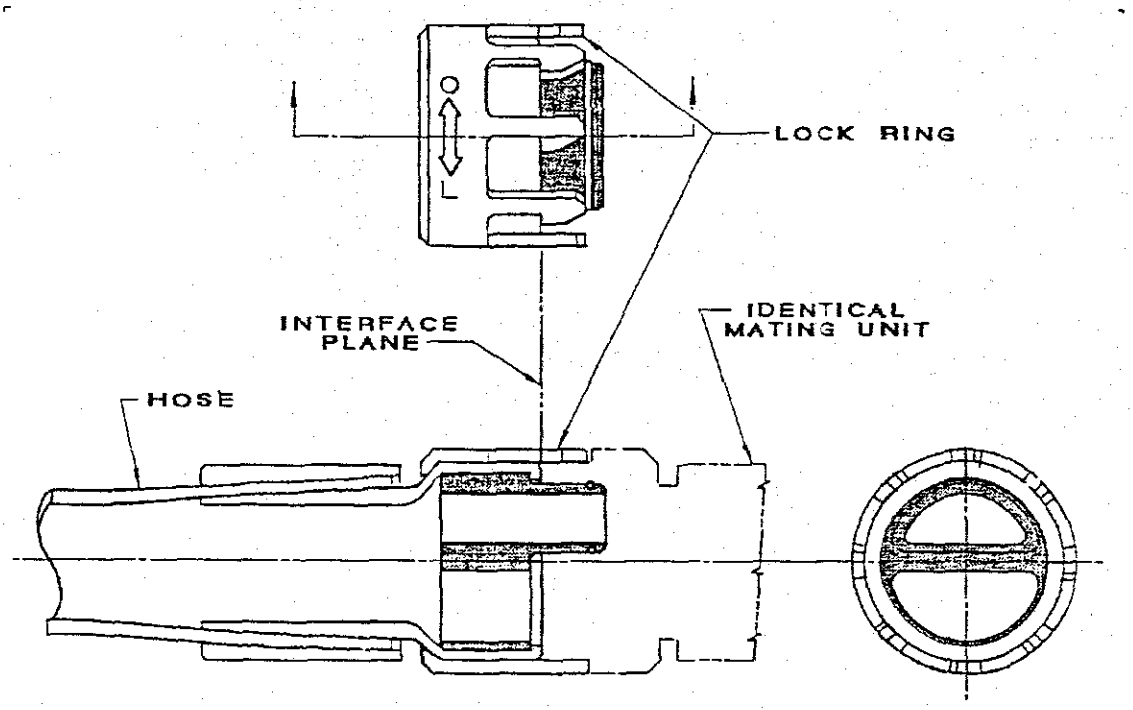


FIGURE VII-22 - A revision of the garden hose coupling to reduce its cross-sectional area by making the passages "D"-shaped.

problem can be corrected by changing the mating cross-sections to a "D" shape (Figure VII-22) and introducing the problem of questionable fit and leak tightness. Never mind; there are other ways.

One of the other ways, shown in Figure VII-23, is to alternate spring fingers and detent notches around the perimeter while preventing inadvertent separation with a pair of lock rings. Leakage is prevented by seal-to-seal face contact. In this design, care must be taken to shape the engaging elements so that the joint won't be too hard to pull apart. The extended grasping fingers may also be vulnerable to damage. No doubt someone can come up with solutions to these problems, introducing a device that has patentable novelty, reliable performance, and a lucrative return for time invested. It should cost much less to make 200,000 identical units than 100,000 each of two different kinds.

It is probable that the lack of such devices for everyday use and for the alleviation of space logistic problems stems from the fact that the idea has never been introduced as a requirement for coupling devices, though there should be a large economic incentive, as just indicated, for doing so.

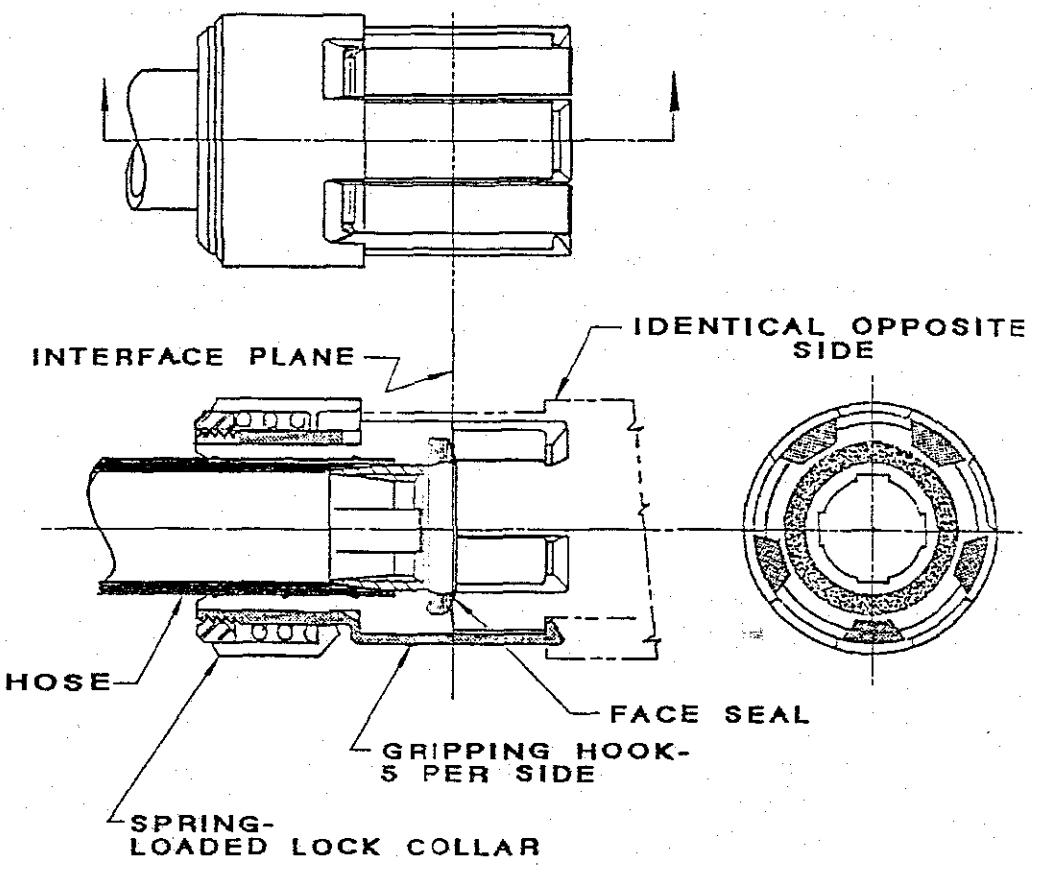


FIGURE VII-23 - A third variation on the garden hose theme, each half consisting of alternating hooks and engaging steps. A design of this general type is called for at the center joint between half-struts in the modular platform system described in Chapter IV.

Not coincidentally, the proposed scheme for the construction of space platforms, described in Chapter IV, incorporates androgynous joints where all the main elements are joined. One is that shown for the "hedgehog" and half-strut; the other is the docking/berthing interface between nodal balls and habitable modules, not to mention all experiments and accessories. In this interesting (and probably profitable) area the surface has hardly been scratched.

DIFFERENT STROKES

¤¤

A maintenance worker at one of the major aerospace firms, who had slogged through his mundane routine for fifteen years at modest pay and even more modest opportunities for advancement, found himself one night at a meeting of his local union where the latest demands for a new contract were being discussed. There he met a former fellow worker he hadn't seen for a long time.

His old friend, it turned out, wasn't there to discuss union negotiations; he no longer worked for the same old employer. He had found that there was opportunity out there and had formed a small company which offered janitorial services for large office buildings. Business had been so good that he was in need of some experienced help, someone to manage clean-up crews in one of the larger office complexes. So he offered his friend the position along with a pay increase in excess of fifty percent.

Upon his return to work, the lucky janitor told his friends of his stroke of fortune, indicating that he was about to accept and give his employer the customary two weeks notice. However, he was still pushing the same mop about six weeks later, causing his friends to wonder why.

"Well," he said,"it was really a good chance to make more money, and I gave it really serious consideration, but I just couldn't bear to miss the excitement of aerospace!"

VIII - THREE-DIMENSIONAL MODELING

Nowadays, the term "model" usually implies a graphical or mathematical model generated for work with computers. Considerable realism, including rotation, enlargement, and shrinkage, can be obtained. However, this is not the same as a physical object that can be handled and felt. For design work, such physical modeling is of real value; however, if a designer appears to be enjoying himself, he is usually suspected of indulging in frivolous play.

In structural design, comparable models can rapidly show the advantage of one arrangement over another. The designs for a speed brake, mentioned in Chapter III make a good example. Figure VIII-1 is a photograph of the models that were tested, now somewhat tattered but still capable of illustrating the point they were meant to demonstrate, that the triangular arrangement without an inner skin is twice as stiff in torsion as a rectilinear arrangement with a skin. They are only about 5 inches long, costing a minute fraction of the computer model and accompanying analysis needed to prove the same point. In fact, the computer model tells nothing about torsional stiffness unless that kind of loading is imposed on it and measurements of deflections are specified. The physical model conveys the idea directly by feel. It helps one to recognize what characteristics the analysis should be exploring.

Similarly, models of stiffening arrangements(Figure VIII - 2), thin cardboard to which thin plywood strips have been glued, show the difference between square and triangular patterns. To the surprise of a number of engineers who have practiced structural design for many years, the triangular arrangement is shown to be perhaps nine or ten times as torsionally rigid. It demonstrates that a torque box, often incorporated in a design to handle inescapable eccentricities, does not have to be closed and inaccessible. It implies, but does not show, that this form of stiffening can resist the formation of buckling waves because of its torsional stiffness. That must be demonstrated by comparative tests.

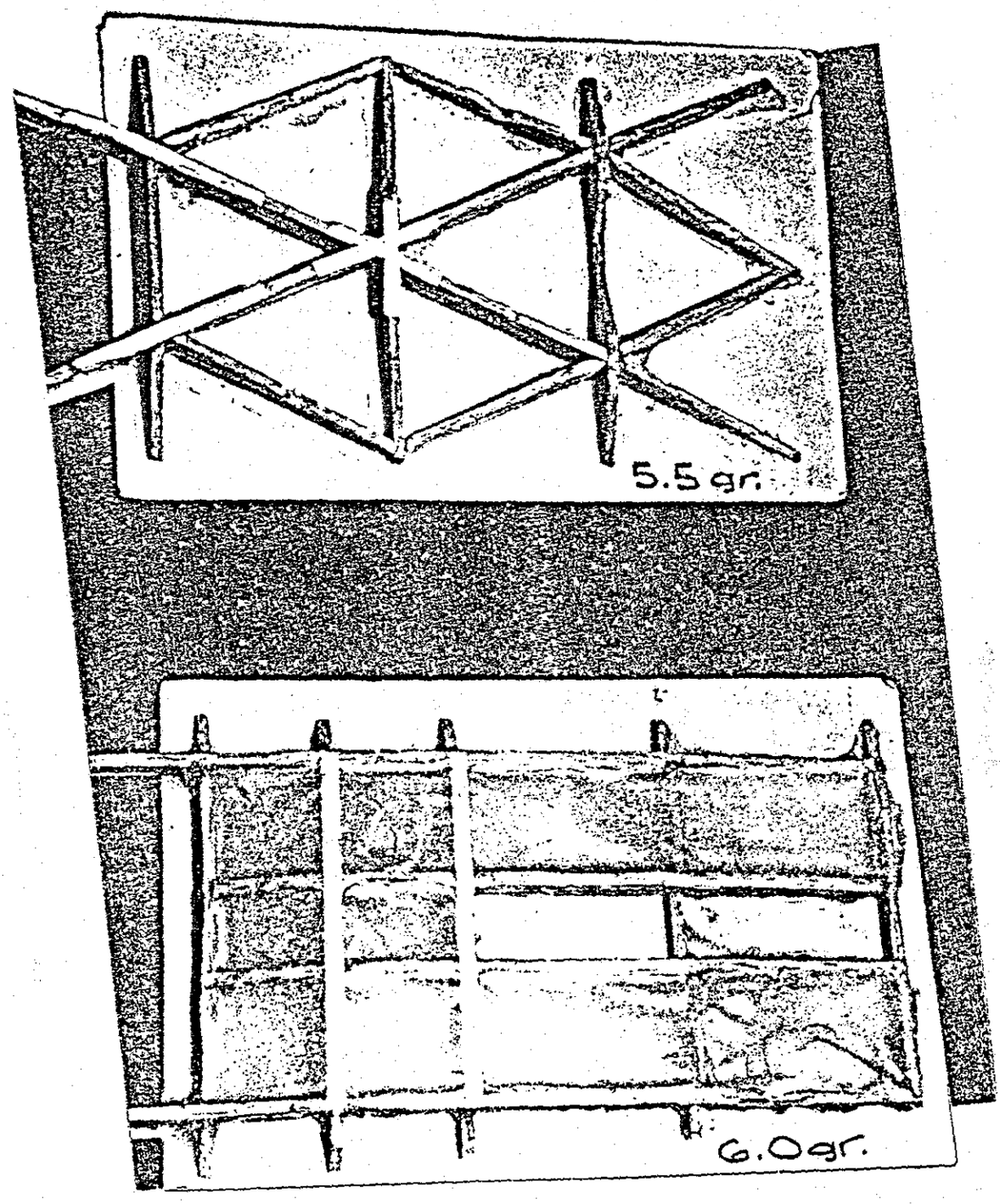


FIGURE VIII-1 - The crude but effective models made from thin cardboard, balsa wood, and tissue to demonstrate the torsional rigidity attained by triangular arrangement of structural elements.

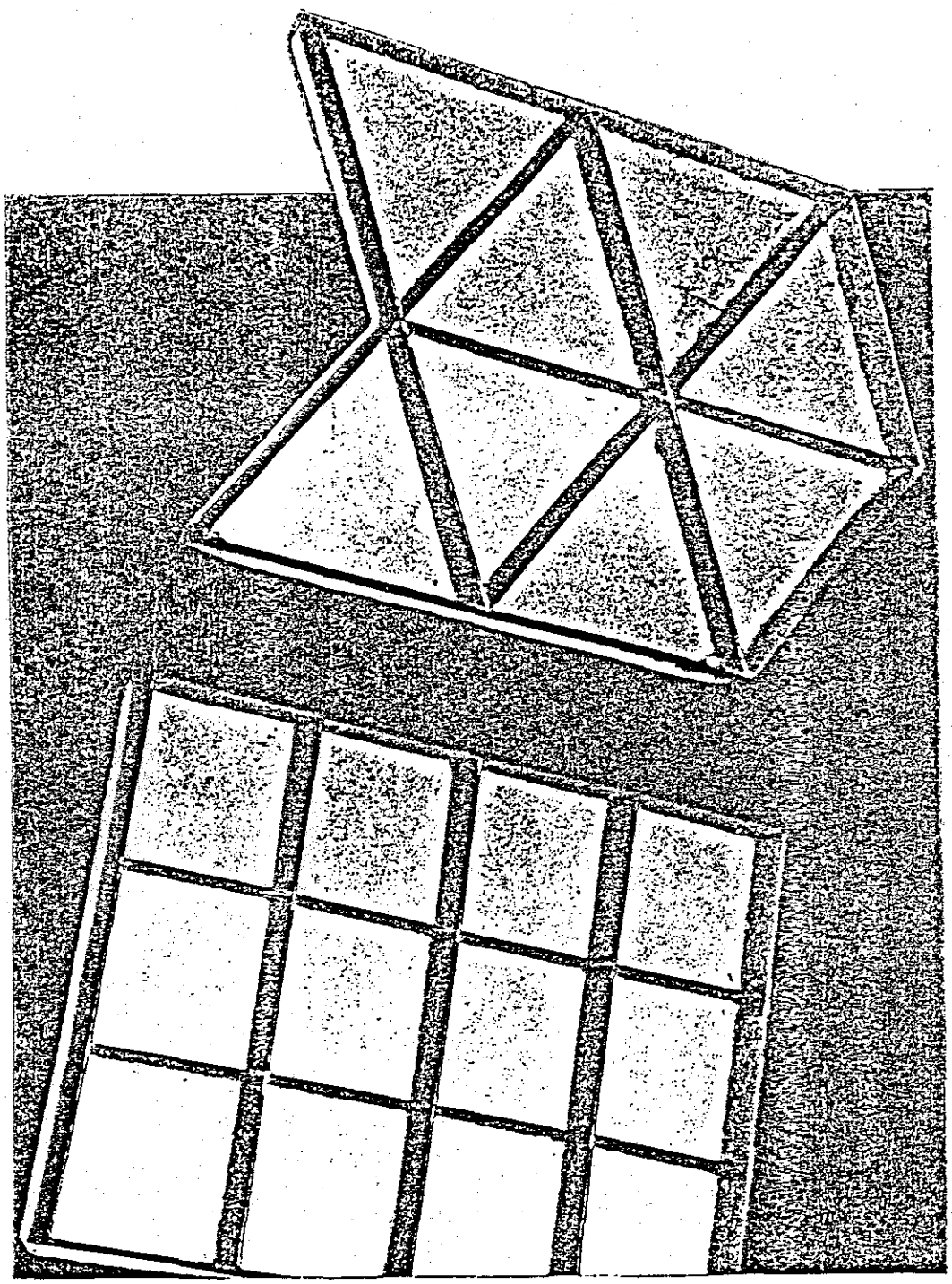


FIGURE VIII-2 - Another pair of models made from cardboard and thin plywood stiffener strips. The triangular arrangement, being torsionally stiff, is better able to handle eccentricities and resist the formation of buckling waves when compressively loaded.

The design for a cylindrical Shuttle cradle for a satellite discussed in Chapter III was first demonstrated with the cardboard model illustrated in Figure VIII-3. It proved that substantial forces in all directions could be resisted at a pair of points when they fed their load tangentially into the cylinder. The same thing was demonstrated in another case with the cardboard model shown in Figure VIII - 4. In this instance, the grid bars were printed on paper glued to the shell. Copies of drawings, printed black on white paper and glued to a stiffening sheet, help to add realism.

The reasons for taking the time to build models, from simple demonstrations to more elaborate show pieces, can be summed up about like this:

☐ The designer needs to satisfy himself - and any skeptics he must deal with - that the arrangement of elements he is proposing will indeed do the job. It can also be shown that accessibility to the interior of the structure is satisfactory - or not, as the case may be. The model, in fact, gives him the opportunity to see the effect of small changes, the addition of a strut in a critical place, or the stiffness lost when part of it is cut away. It may also allow him to discover, early in the game, that a complete rearrangement is in order.

☐ The analyst may see, from handling the model, what questions must be answered for adequate proof of the concept.

☐ Quite often, the designer's peers and his management can't visualize from a 2-dimensional drawing how the finished product will look. They need a more complete description than words and drawings will provide. Too often, in fact, the manager empowered to decide is inexperienced in design, not really competent to make sound judgments; he must be "sold" on concepts. For him, the spiffier the model, the better.

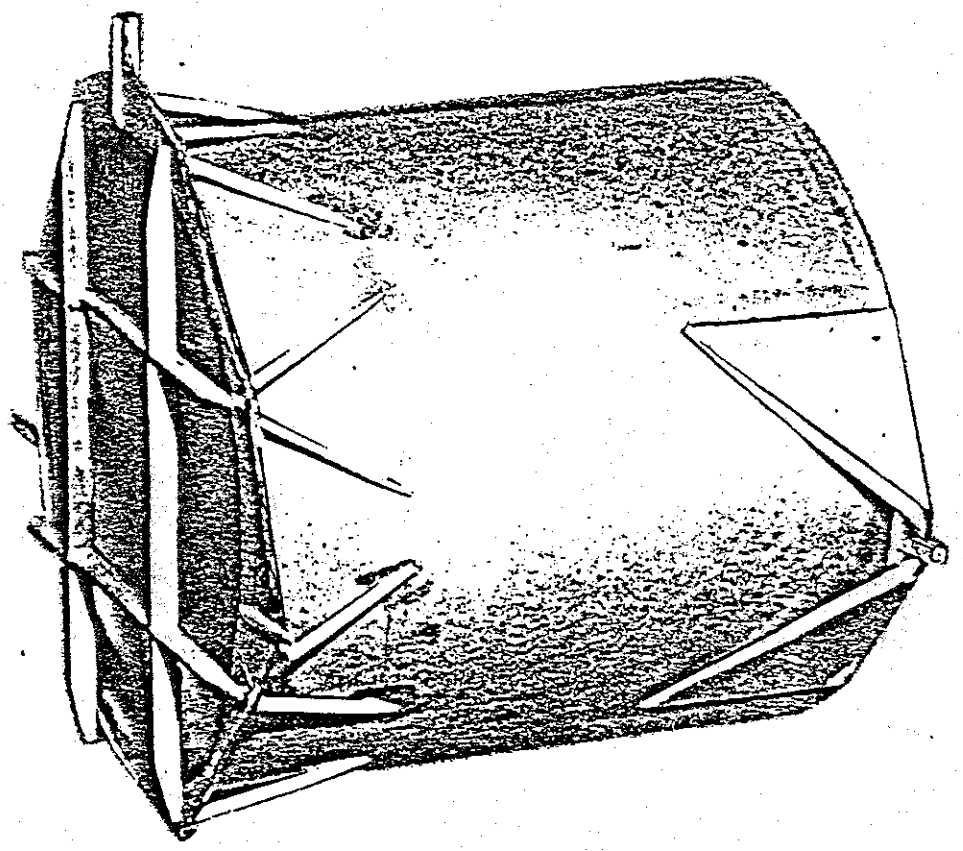


FIGURE VIII-3 - A cardboard and wood strip model made to demonstrate that a Shuttle-borne cylindrical frameless cradle can handle thrust loads when they are introduced into the shell tangentially.

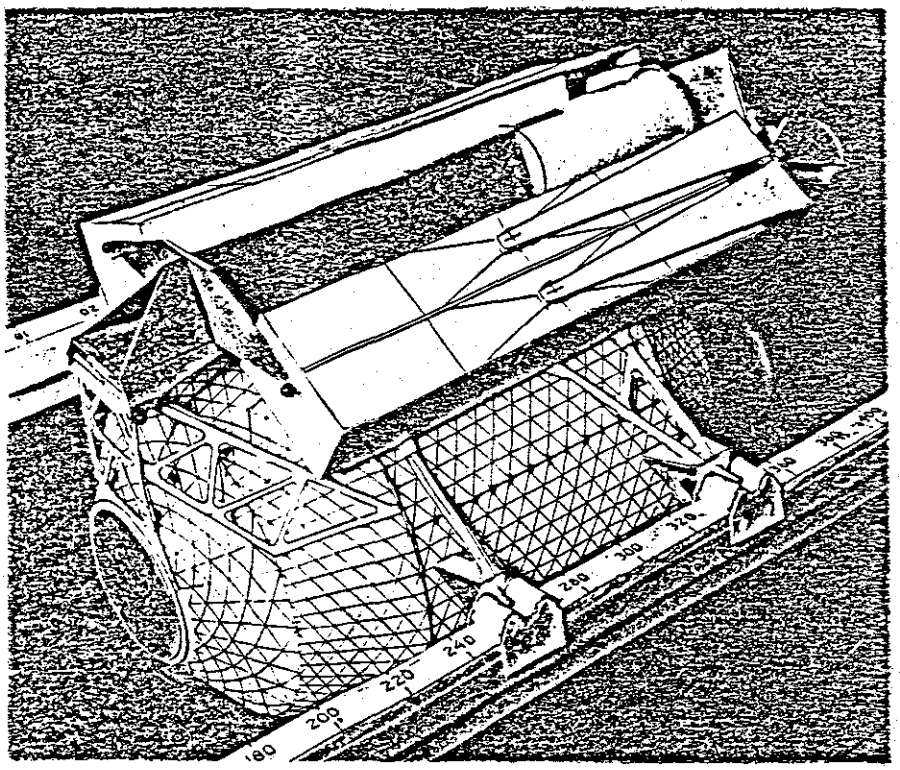


FIGURE VIII-4 - Another model an arrangement for an extended duration Shuttle crew model, where the core structure is an isogrid stiffened frameless shell into which loads are applied tangentially.

Models are particularly useful for exploring unconventional solutions to new problems - or familiar ones, for that matter. The model depicted in Figure VIII-5 was built to verify the suspicion that a structure subject to bending loads could function adequately when the shear material is not continously attached to the beam caps. In this instance, it was necessary to handle large loads in an intertank region of a large recoverable booster after large slots had been cut in it to accommodate a nose-gear well on the bottom and two large retractable panels carrying cruise-back jet engines safely out of the airstream during launch and the early stages of re-entry. The uninterrupted shear path follows an inner surface defined by the propellant tank domes and a network of criss-crossing straight struts tangentially attached to the domes and forming an open basket hyperboloid of revolution between them. The idea, which was never carried any further than this, is sketched in Figure VIII-6. This is a method, among many others, for making the best use of the awkward (and usually inaccessible) space between propellant tanks on a lot of space vehicles.

Without a "feelable" model like this, an idea as unconventional is likely to be rejected out of hand as unachievable. By handling the 3-dimensional object, one is easily able to appreciate that there is nothing unfeasible about it. It very handily resists all types of loads applied to it by hand, and doesn't rack from either side shear or torsion.

Making Models

The design tool model can be made from very simple materials and equipment. It has been said that a wing folding scheme, for many years a proprietary trademark of the Grumman company, was first demonstrated with a pair of rubber erasers and a paper clip bent to the proper shape. This system involved a rotation of the wing as it folded back so that it ended up with the chord plane vertical, leading edge down, and the wing tucked against the side of the fuselage. It was done with a single canted axis of rotation.

That was a mechanical device whose principle really needed some 3-dimensional demonstration not possible with 2-dimensional

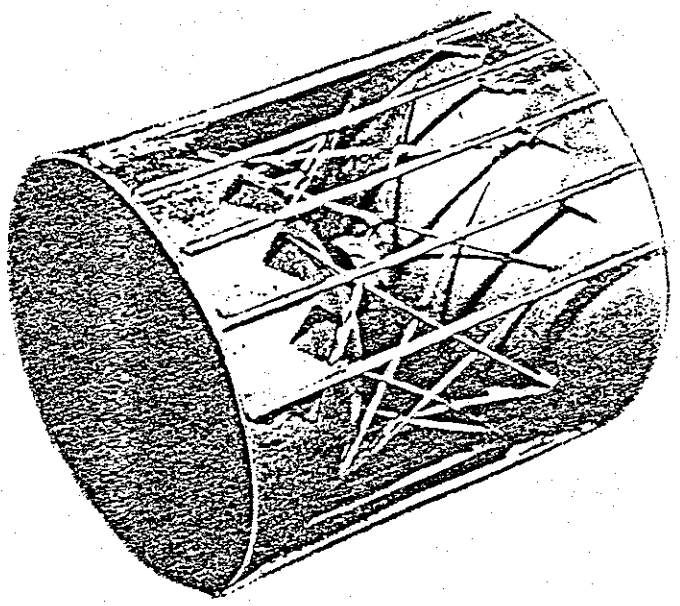


FIGURE VIII-5 - A small scale model of an unusual arrangement of structure in the area between two propellant tanks. Shear is carried across the gap by a tangentially attached network of diagonal members forming a hyperboloid of revolution. They are not connected to the main bending members.

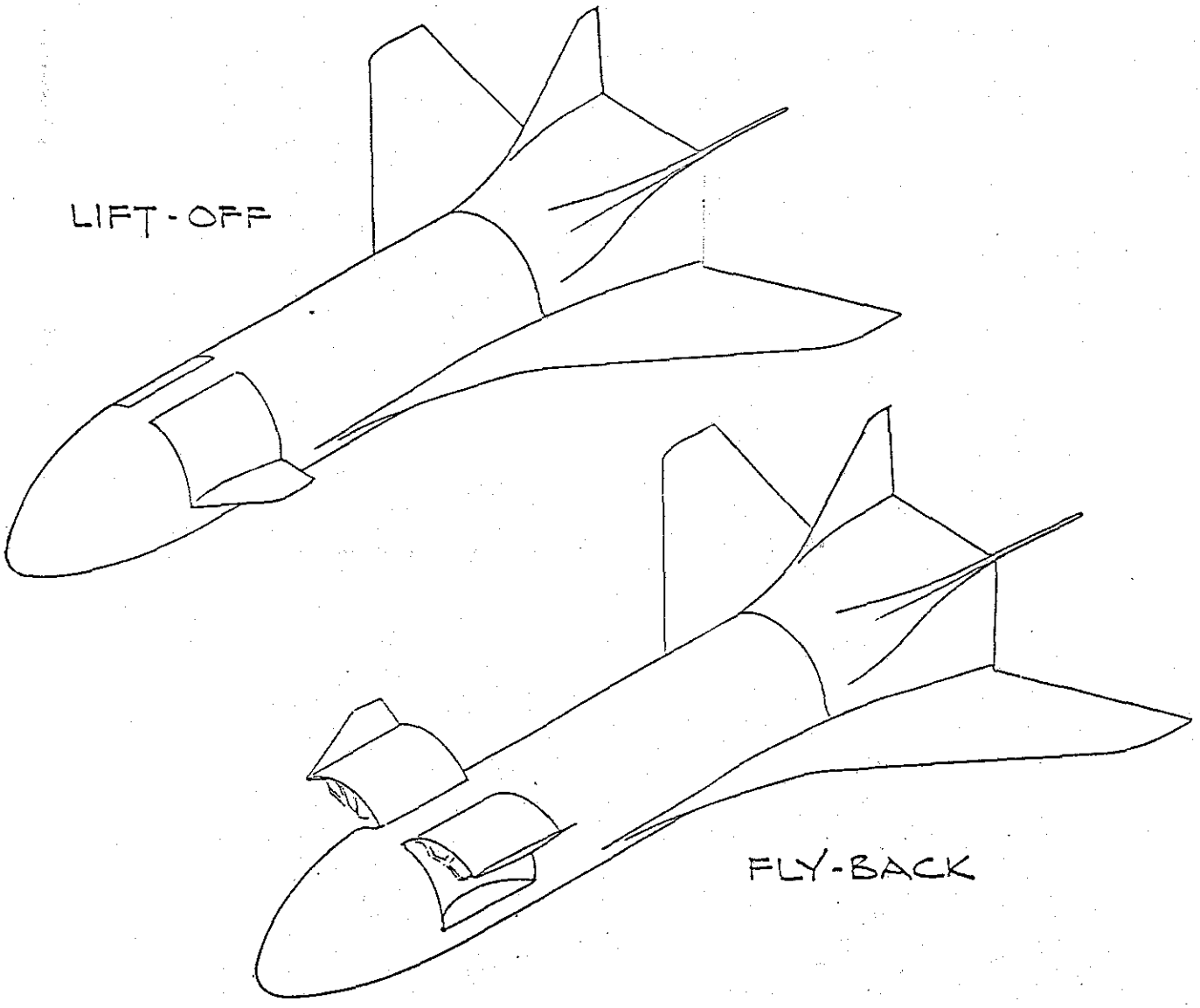


FIGURE VIII-6 - A sketch of a design for a re-usable booster with flyback air-breathing engines. They are mounted inside panels covering structural gaps in the arrangement examined by the subscale model in the previous figure.

pencil layouts, but most structural models stay fixed after being built. Shapes can be approximated, often quite accurately, with folded paper, the thin, strong cardboard scrounged from file folders, or the heavier material in pad backs. There is almost always in every engineering office a "pack rat" who has kept a stack of all the pad backs he's used for the last several years. For struts or the occasionally needed local reinforcement, there are paper clips, thin wooden dowels or bamboo skewers, and toothpicks saved from the company cafeteria or the lunch time martini. All these ingredients can be stuck together with model-builder's or household quick drying cement.

Where spherical elements are involved, about the handiest readily available unit is a ping-pong ball. Light and strong, it unfortunately comes in only one size. If it is too far out of scale, there are rubber balls from toy stores, Christmas tree ornaments (preferably plastic ones) and dangerously fragile items like light bulbs. Plastic containers and lids come in handy at times, but must be used with some caution because they often establish such a weird scale for the model that nothing else fits with it. For more irregular forms with compound curvature, a form can be made with templates (cardboard or thin plastic) which support and shape a plaster-of-paris or modeling clay mandrel. Wet facial tissue, sized with water soluble paste, can be draped on this and then dried and trimmed around the edges. Of course, in a drafting office, some of these measures are a bit untidy, so they're better done at home, where a designer can mess up his own kitchen (having first obtained permission from his wife).

Ultimately, where real fidelity is in order, patterns can be made by carving, sanding, or machining. From them silicone rubber molds can be produced for casting more parts in low-shrinkage plastic resin, a two-part epoxy or similar system. The node for a modular space platform system, shown in Figure IV-16, was made that way from twelve identical molded parts.

Large open truss structures, reduced to miniature scale for easier overall evaluation, can be made with simple bars like toothpicks which are remarkably consistent in size, regardless of source. The round, double pointed ones are 2.6 inches or 66

millimeters long. In Figure VIII-7 the framework representing a "power tower" configuration for Space Station built with the construction system described in Chapter IV is shown. Since its bars are intended to be 55 feet long, it is about 1/250 scale. A model like this demonstrates quite clearly that such a structure can be stiff and stable.

More solid objects are simply made with cut, folded, and glued paper or thin cardboard. The same pressurized node for a modular space station as shown in Chapter IV was originally made this way. It is shown in Figure VIII-8. While it seems to be round, it is actually made from flat, cylindrical, and conical elements. The "spherical" surface consists of twelve 120-degree cones with the small percentage of area between them of somewhat undefined shape but without compound curvature. The flat patterns of the pieces are shown in Figure VIII-9. There should be enough definition to allow the reader to construct one for himself - or, better yet, twelve of them to make a complete ball. It's best to leave one of the basic units unattached for access to the interior.

Flat parts and cylinders are easy to imagine and draw, but cones are more of a challenge. Therefore, the definition of cone flat patterns and the method of defining a tapered grid pattern like those on the model in Figure VIII-4 are offered for the prospective do-it-yourselfer in Figures VIII-10 through VIII-13.

Miniature Experimental Testing

For more serious testing of concepts, an accurate miniature of the intended design can be made from plastic materials, probably the most suitable being thermo-setting polycarbonate. One of its more familiar forms is marketed under the General Elecric trade name of "Lexan". Strong and impact-resistant, this material is commonly used in casings for double-insulated power tools such as hand drills, saber saws, sanders, and the like. It is also used, in its clear, unfilled form, for such applications as shatter-resistant window panes.

It is in this clear form that it is most useful for structural experimentation. It has the useful property of a straight-line

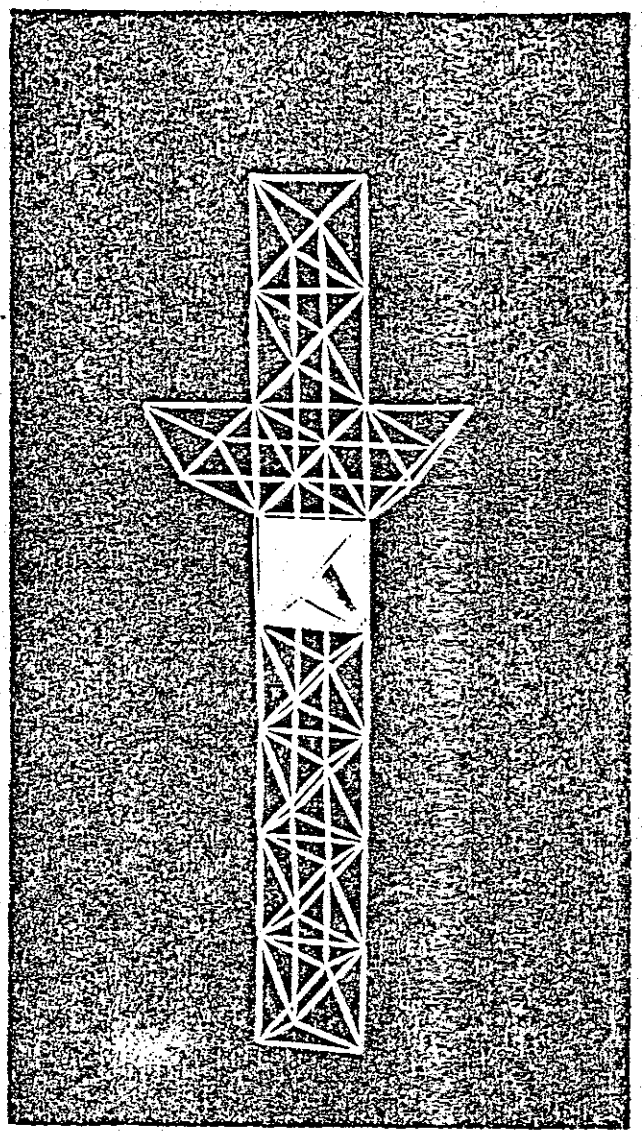


FIGURE VIII-7 A stick model representing an arrangement of standard modular elements to build a gravity-gradient space station. It is constructed of toothpicks, with tissue paper defining a hangar bay.

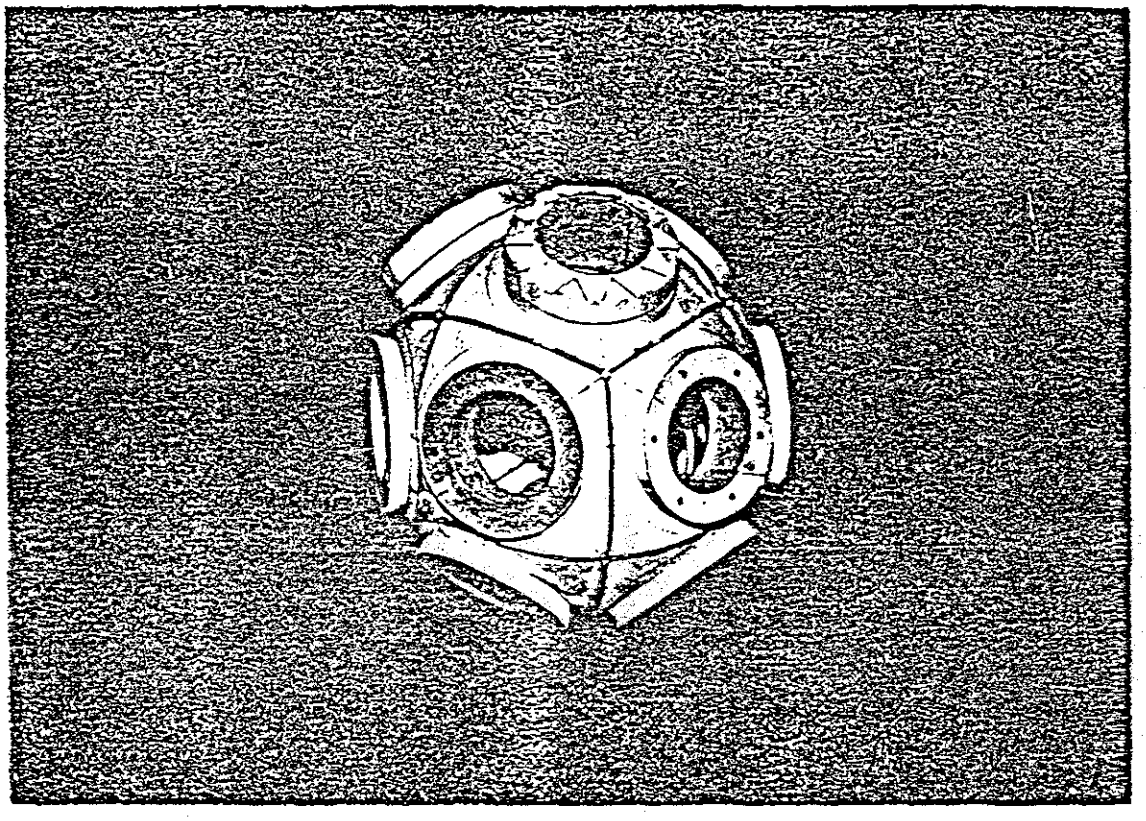


FIGURE VIII-8 A spherical node for habitable module interconnections in a modular space station assembly. Its twelve identical subassemblies are constructed of thin cardboard.

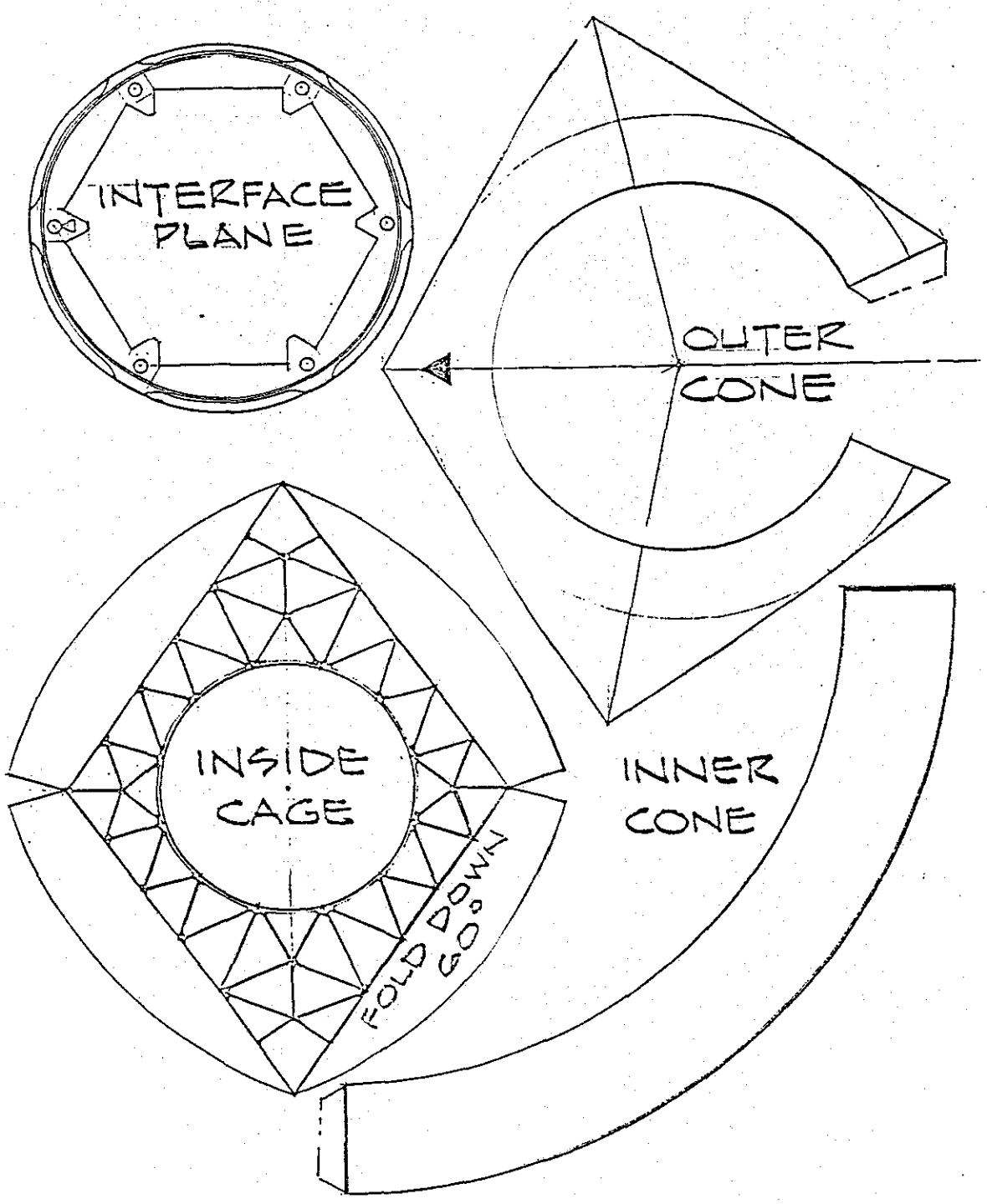


FIGURE VIII-9 - Flat patterns of the elements for a nodal subassembly, twelve of which make a complete ball.

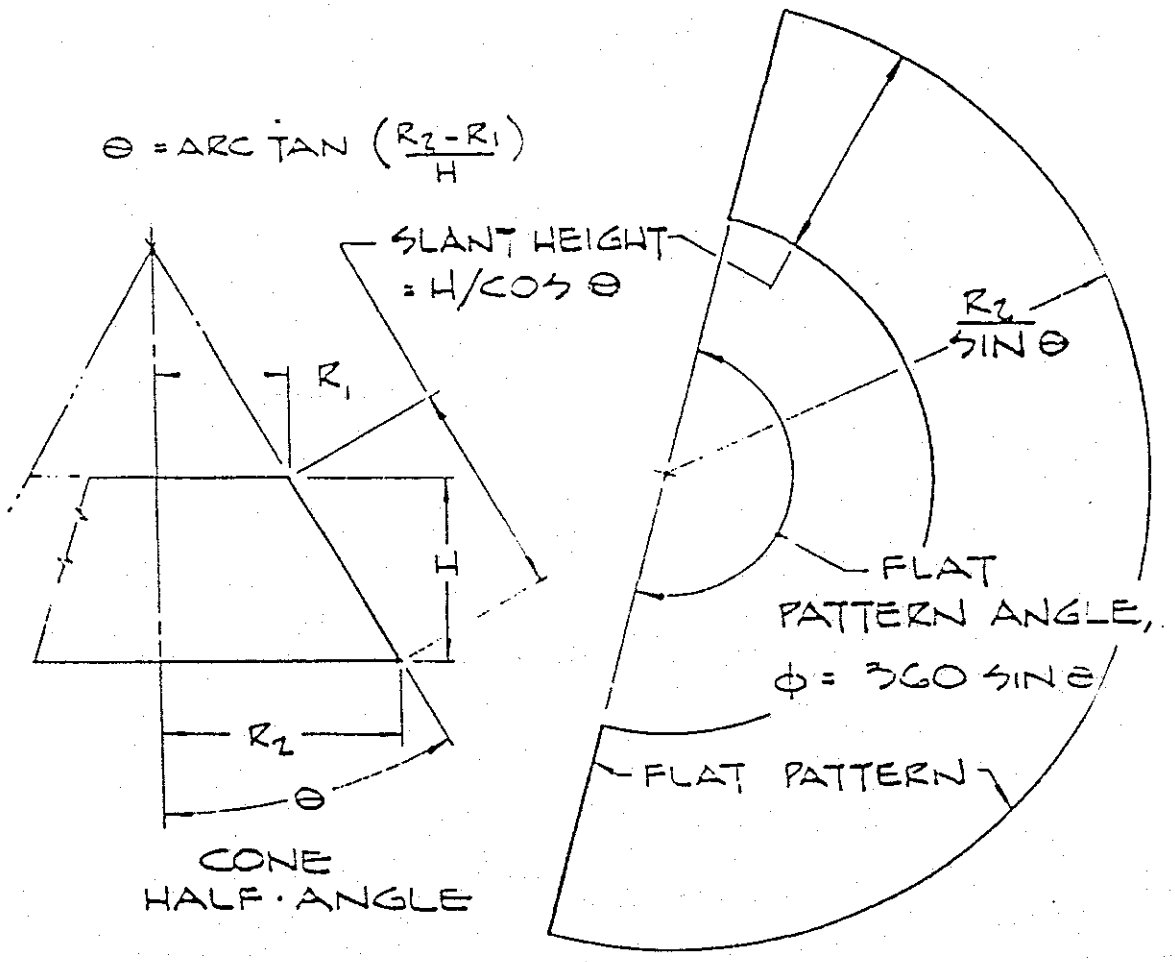
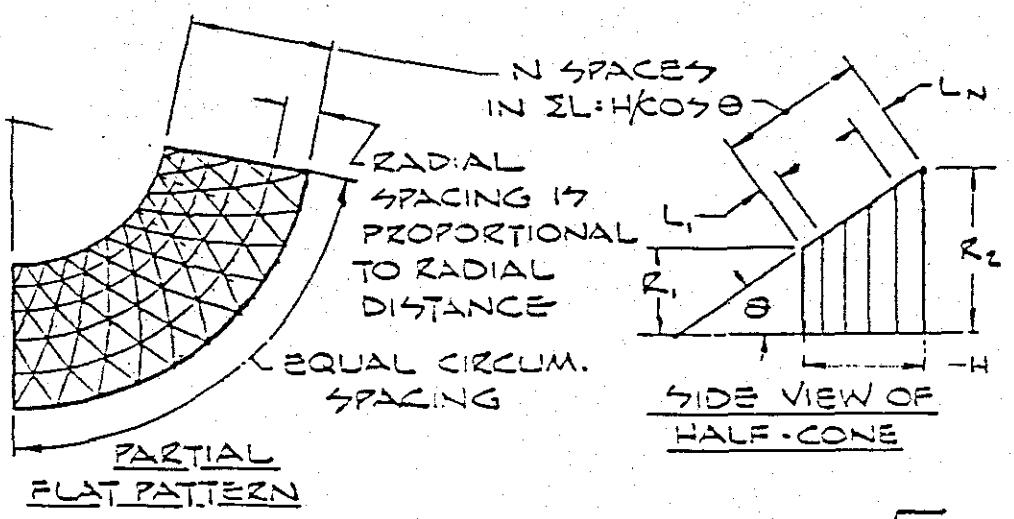


FIGURE VIII-10 - The relationship between a conical frustum and its flat pattern.



SPACING EXPANSION RATIO, $K = \frac{L_2}{L_1} = \frac{L_N}{L_{N-1}} = \sqrt[N]{\frac{R_2}{R_1}}$

$$\frac{L_1}{\Sigma L} = \frac{\text{MINIMUM SPACING}}{\text{CONE SLANT HEIGHT}} = \lambda (K-1)$$

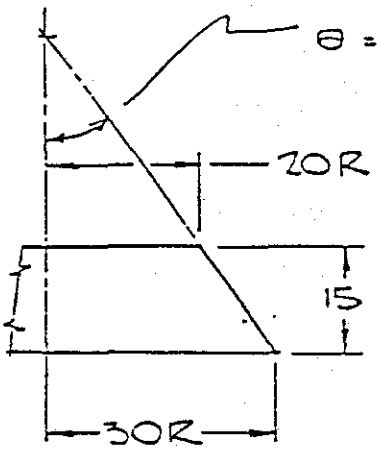
WHERE $\lambda = \frac{R_1}{R_2 - R_1}$

TO FIND N FOR ESTIMATED VALUE OF MINIMUM SPACING, L_1 :

$$N = \frac{\ln (R_2/R_1)}{\ln (L_1/\lambda \Sigma L + 1)}$$

ROUND OFF TO NEAREST INTEGER AND RECALCULATE VALUE OF L_1

FIGURE VIII-11 - A method for developing a tapered grid pattern on a conical frustum flat pattern.



$\theta = \text{ARC TAN}\left(\frac{30-20}{15}\right) = 33.69°$

SLANT HEIGHT, $2L = 15/\cos\theta$
$= 18.028$

$\phi = 360 \sin\theta = 199.69°$

- USE 36 EQUAL CIRC. SPACES * TRIANGLE BASE FOR "ISOGRID" PATTERN

- ESTIMATE $L_1 = \frac{40\pi}{36} \cos 30°$
≈ 3.0

$K = \sqrt[5]{1.5} = 1.084$

$\lambda = \frac{20}{30-20} = 2.0$

$L_1/2L = \lambda(K-1) = .169$

$L_1 = (169 \times 18.028) = 3.046$

$N = \frac{\ln 1.5}{\ln(3/2 \times 18.03)+1)}$

$= 5.073$

USE 5

L_1	3.046
L_2	3.303
L_3	3.582
L_4	3.885
L_5	4.213
Σ	18.029

CLOSE ENOUGH

- PATTERN IS NOT TRUE ISOGRID WHICH REQUIRES EQUILATERAL TRIANGLES. THESE TRIANGLES CANNOT BE LAID OUT ON A CONE. THEY MUST CONVERGE 200°/36 OR ABOUT ± 5.6°, CLOSE ENOUGH TO APPROXIMATE ISOTROPIC BEHAVIOR.

FIGURE VIII-12 - A worked example showing development of a pattern for a specific conical form.

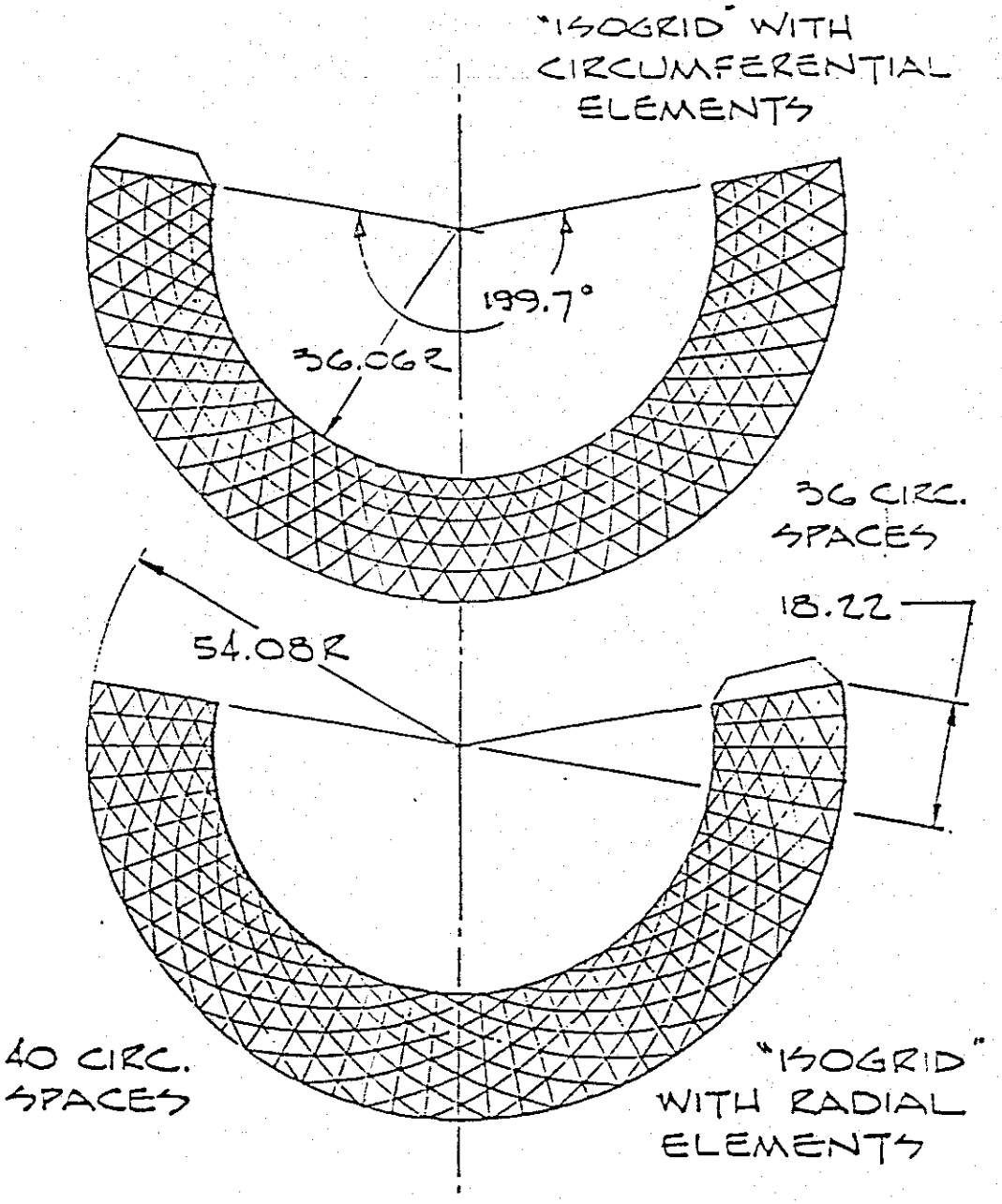


FIGURE VIII-13 - Layout of the worked example isogrid pattern in two orientations.

stress/strain curve, extending to elastic deformation well beyond that in metals at ultimate strength. Therefore, it is handy as a demostrator of compressive stability, where that characteristic is difficult to calculate because of unusual shape or arrangement. Models of this kind have shown that spherical segment ends for cylindrical pressure vessels, the shape of the domes on the Delta launch vehicle mentioned in Chapter VII, remain stable at their edges as hoop compression rings when the elastic strain is well beyond that in aluminum alloy above the compression yield stress. It has also been demonstrated that buckling will occur in such models at strains equivalent to those at which metal structures will buckle.

Unlike a metal test specimen, which is generally destroyed when it buckles in a compressive test, the polycarbonate article bounces back as good as new, ready for retesting. As a result, it can be repeatedly tested under a variety of loading conditions, providing much more information at a far lower cost. A series of tests on rib-stiffened spherical segments proved, in 1964, that the isogrid triangular stiffening arrangement (or the closest equivalent which could be mapped on a spherical surface) was superior to radial or square patterns of stiffening ribs for resisting reverse pressure. The models and the test set-up are shown in Figures VIII-14 through -18. Figure VIII-19 shows the metal article whose configuration was determined by the miniature tests in plastic.

Similar tests have been conducted with isogrid-stiffened cylinders like that shown in Figure VIII-20. More elaborate variations have also tested the effect of various shapes and sizes of cutouts with different arrangements of reinforcement around them.

Finally, there is the show-and-tell elaborate model without which no final presentation of a proposal would be complete. The miniature milling machine shown in Figure VIII-21 was such a model, intended to prove how tank panels would be produced economically, but in a losing cause. By the time a model like this appears, of course, it is too late to prove anything more useful than the fact that it can be made to look pretty with the proper application of cosmetic paint.

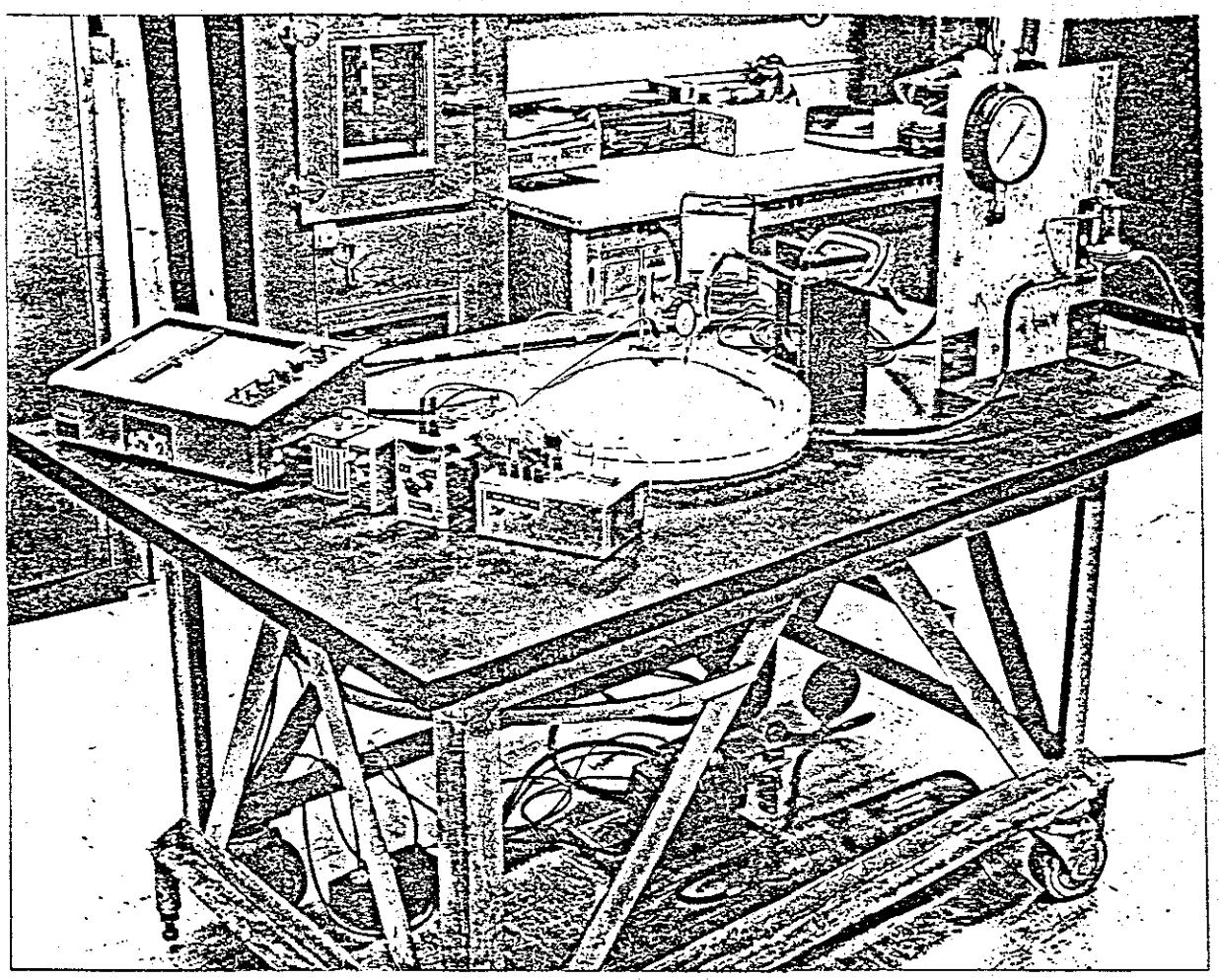


FIGURE VIII-14 – A miniature laboratory test set-up for investigating the effectiveness of stiffening patterns on a spherical segment pressure bulkhead. Reverse pressure was applied by evacuating the space below the specimen.

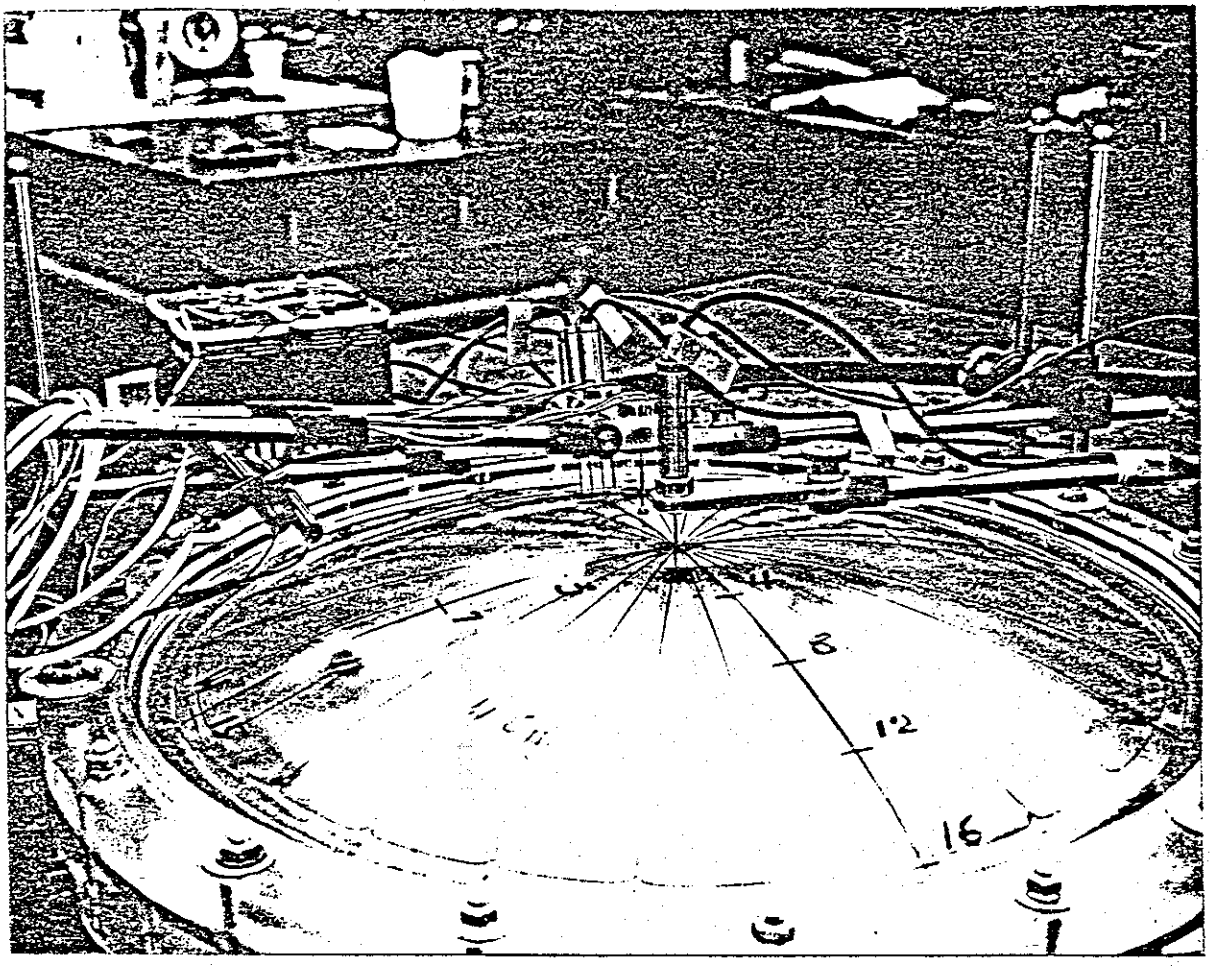


FIGURE VIII-15 – A radially stiffened dome in the test fixture.

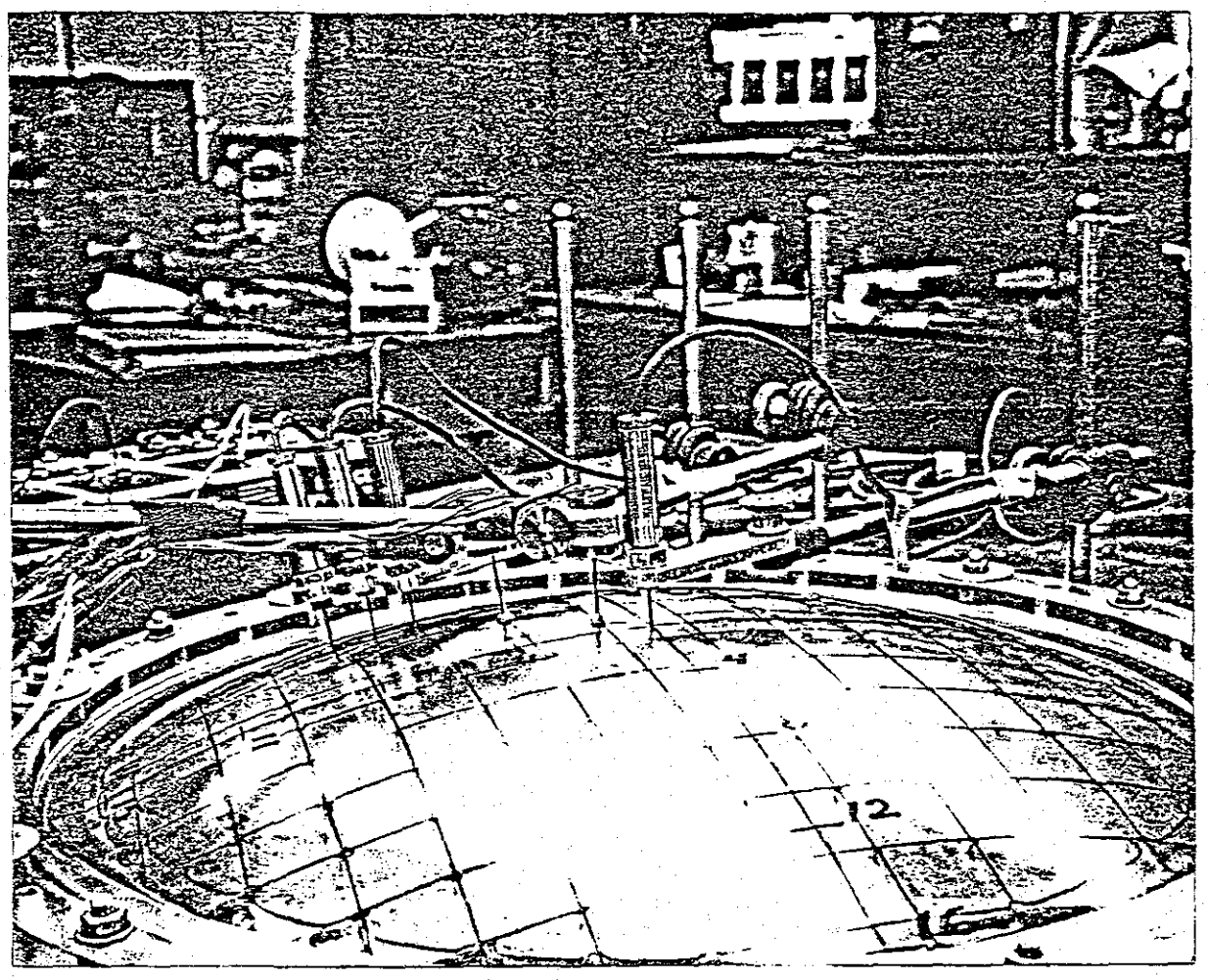


FIGURE VIII-16 - A dome section stabilized by a square pattern of stiffening ribs under test with reverse pressure applied to it.

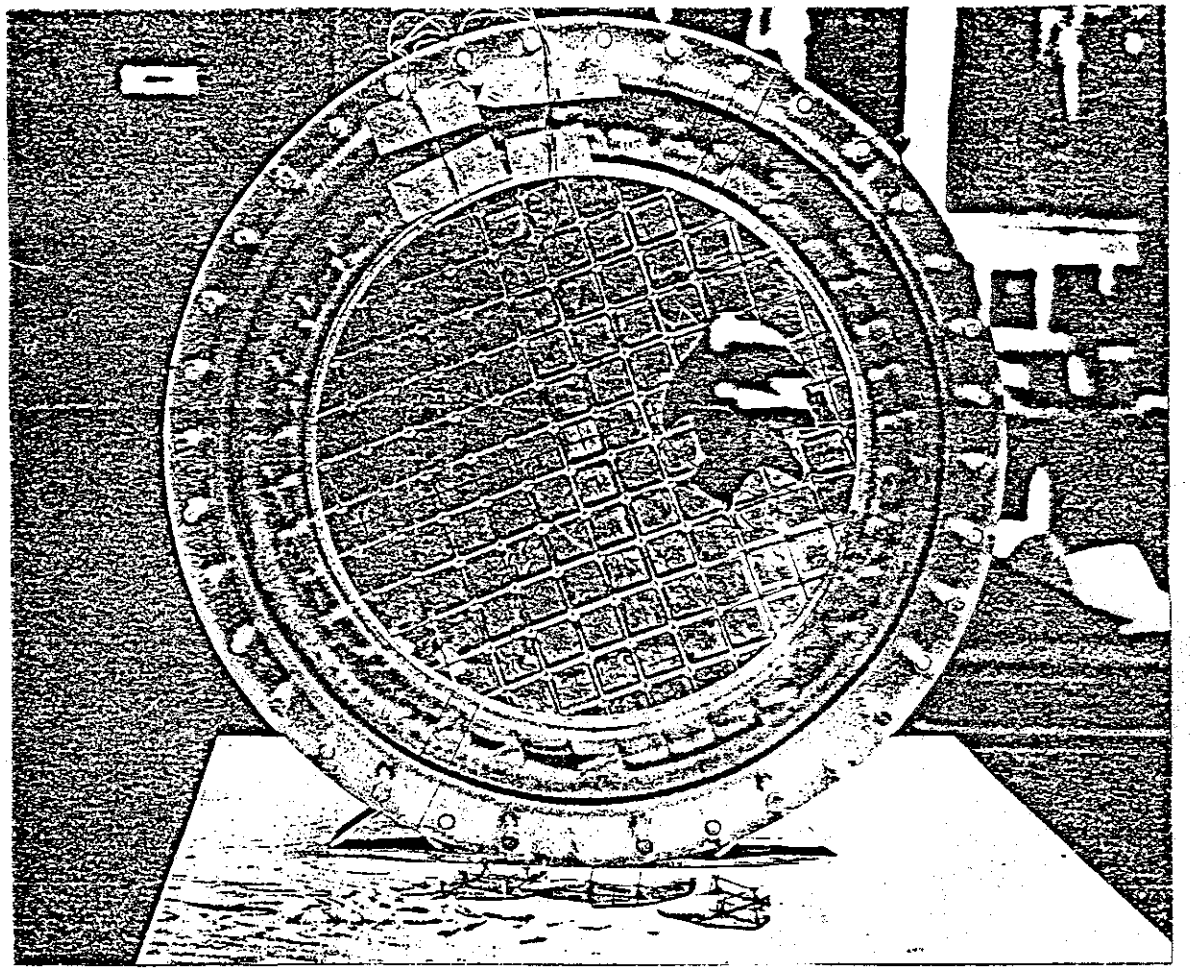


FIGURE VIII-17 - The square stiffened test dome after failure.

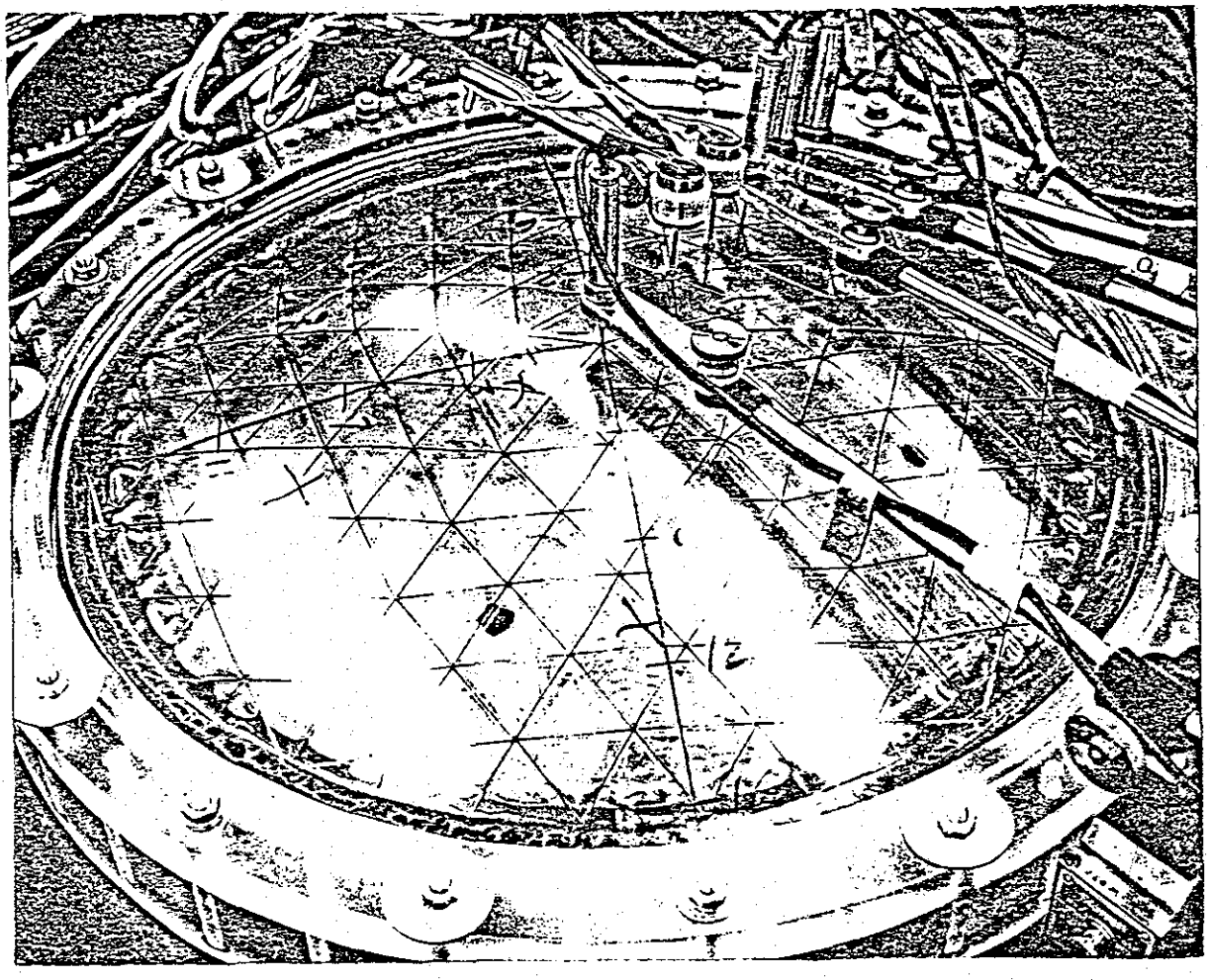


FIGURE VIII-18 - A test article with a triangular pattern of stiffening ribs in the test fixture. It proved to be the most efficient stiffening pattern investigated. It was the forerunner of the "isogrid" stiffening system which has universal application.

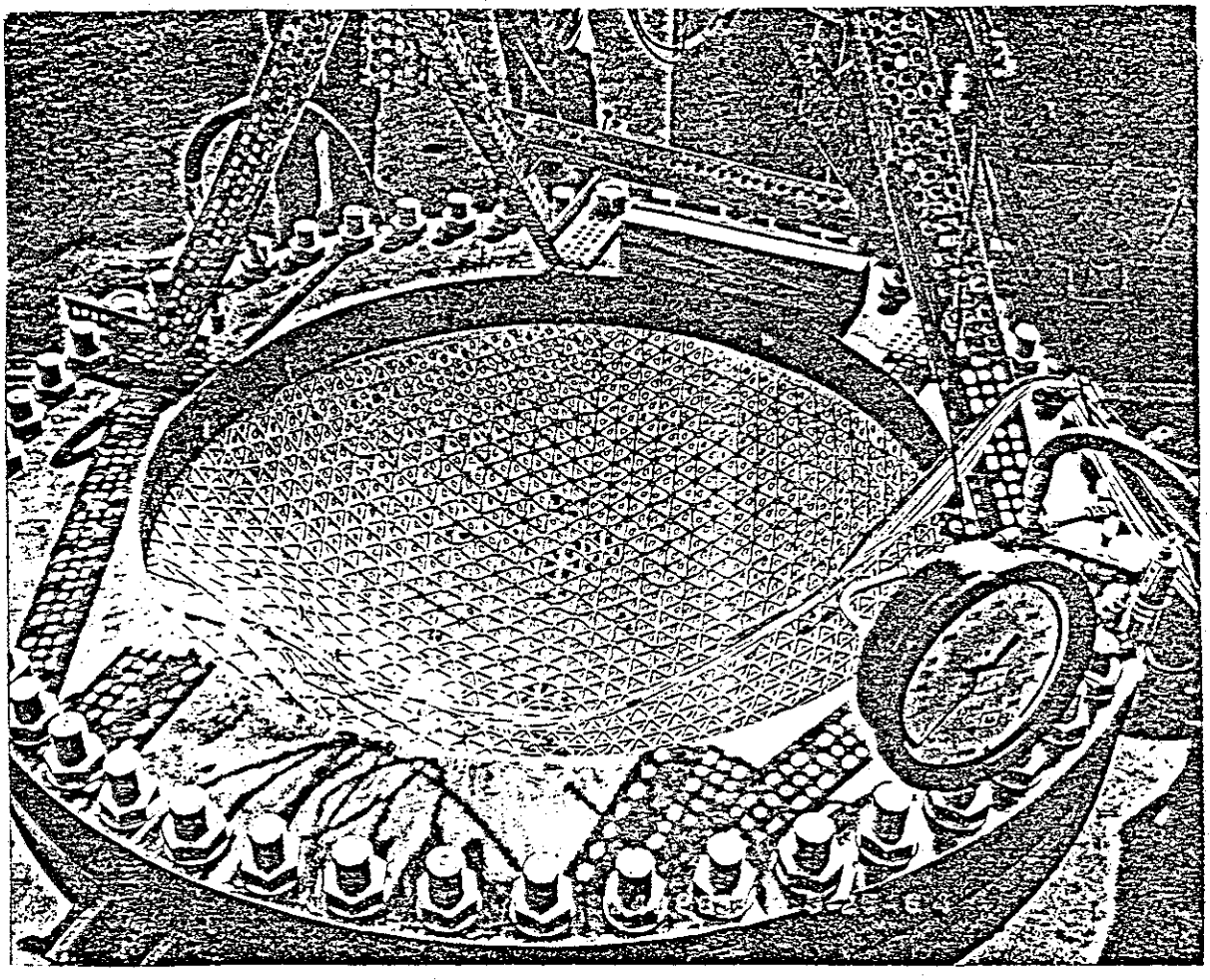


FIGURE VIII-19 - A larger scale aluminum alloy isogrid test specimen, the outcome of the previous low cost survey of stiffening systems.

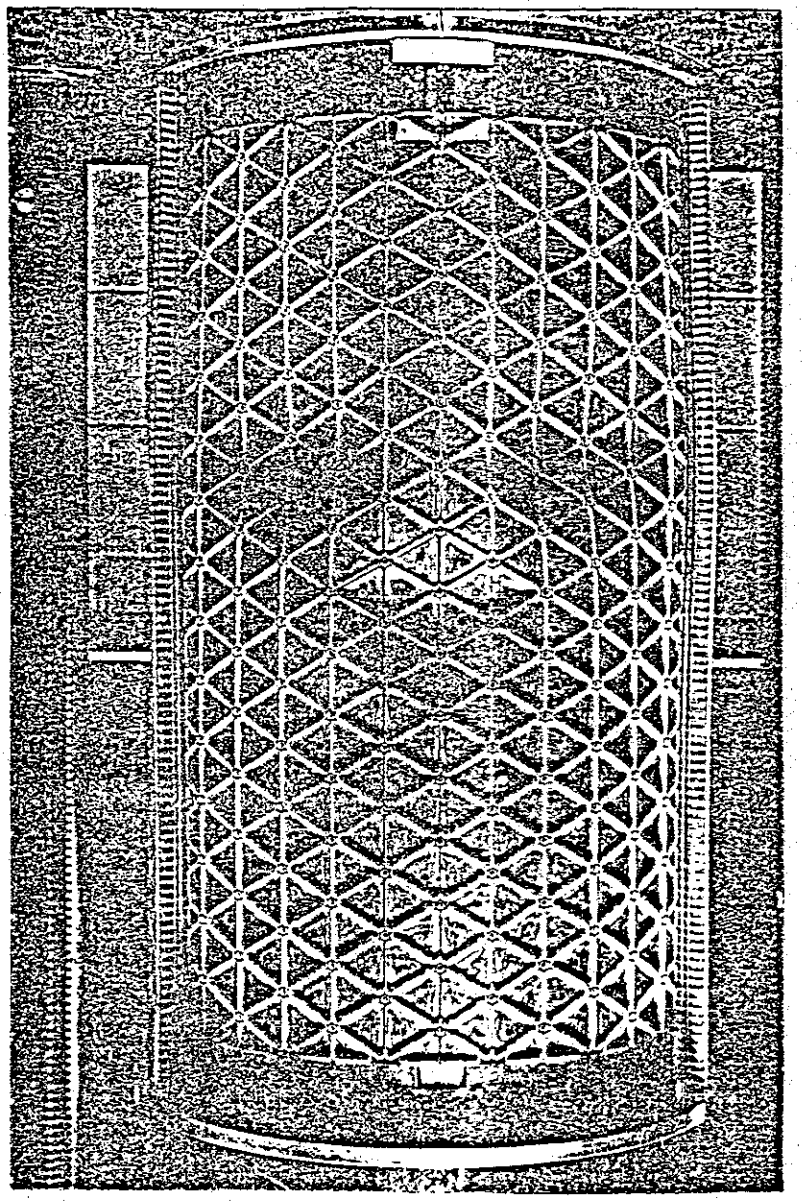


FIGURE VIII-20 – A small scale isogrid test cylinder under load. After buckling, it returns to its original condition, allowing further testing under varying load conditions.

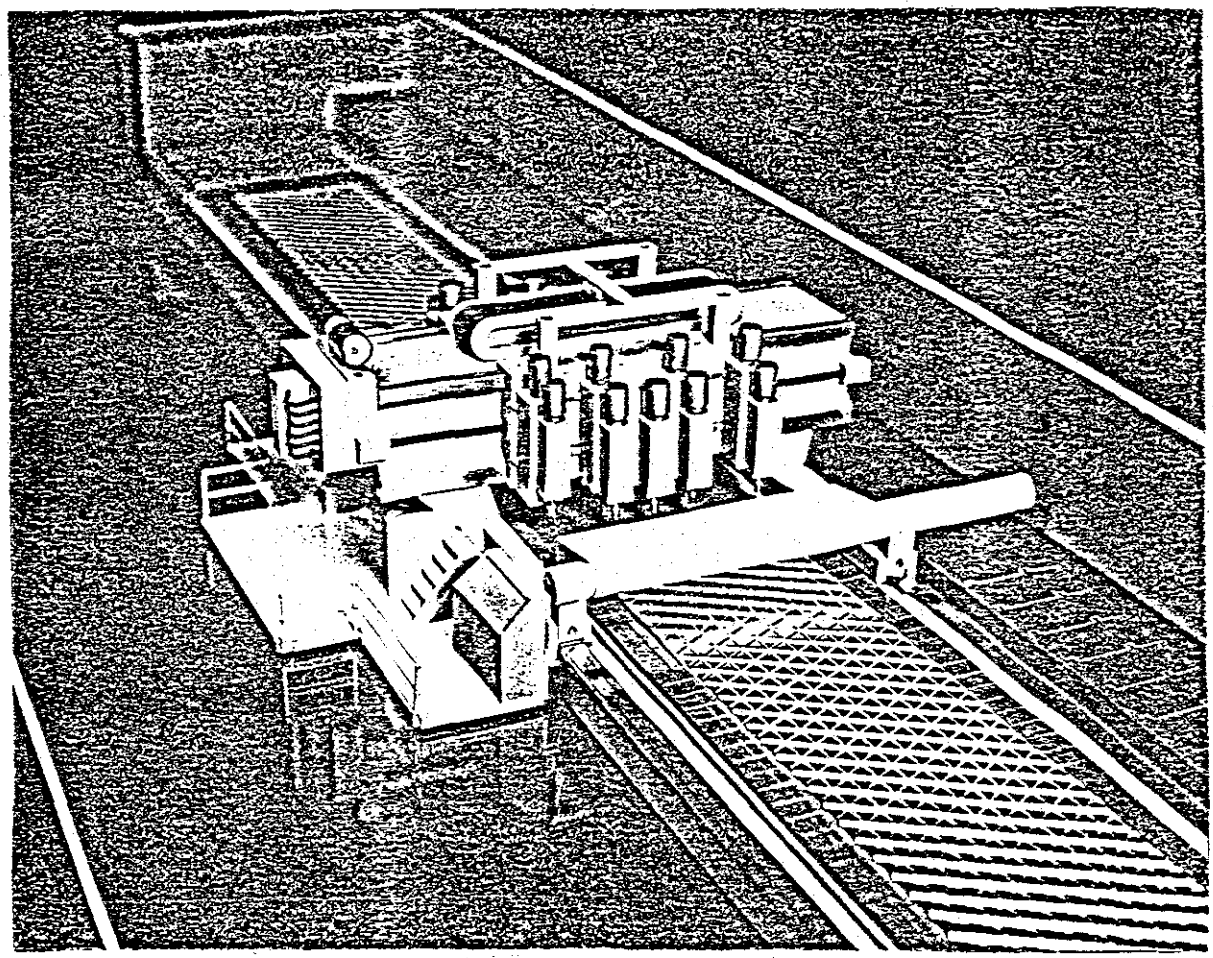


FIGURE VIII-21 - A display model of a special milling machine to produce large isogrid panels for a propellant tank. It was never built because the contract was awarded to someone else.

Too often, this is the only model built for a program other than the desk top miniatures later produced for customers and executives after the contract is awarded and practically finished. Too few management organizations recognize this model building as a useful tool for effective design, viewing a model shop as an expensive and unnecessary overhead cost. Playing around with computers is much more fashionable.

CASH FLOW

During World War II - and ever since - the identification of employees at the entrance gate has been given careful consideration by the aerospace industry. Of course, at first, it was just the aircraft industry - there was no space division anywhere.

At the Douglas Company each employee was required to show not only his badge, a plastic decoration with only a number or name on it, but a pictorial identification card as well. These photos were about the quality found on passports at the time, making it fairly easy for the forgetful at times to pass through the gates as George Washington after waving a wallet with a one-dollar bill in the window.

With all its limitations, the badge was regarded as a valuable document and carried on its reverse side an offer of two dollars for its safe return. The employee who lost one was harshly reprimanded and fined one dollar. After this company policy became generally known, there was a perceptible increase in the incidence of badge loss, not at all what was intended.

These badges seldom were lost for long ; generally they showed up in a day or two, the finder coincidentally being a friend of the loser. Each became slightly richer - fifty cents worth, to be exact.

The company took quite a while to adjust the fine and reward balance and was disrespectfully considered a little bit stupid as a result. However, there's the possibility that this was just a scheme to identify candidates for promotion to management, those who were enterprising and willing to expend inordinate amounts of effort for fifty cents. It could have been something like the corporate practice of appointing an "ombudsman" to identify troublemakers.

IX - CONCLUSIONS

Aerospace vehicles in general could be vastly improved if structural designers stopped resenting the intrusion of other subsystems, and worked at anticipating their needs. It would benefit both the structure and the subsystems living with it, minimizing argument time and making the vehicle lighter and more economical.

Provincialism within design "disciplines" was demonstrated at a recent kick-off meeting for a new program at a NASA center (summer of 1988). A manager of structural design rose to proclaim, "We will not compromise our structure an inch to accommodate avionics!" The industry teems with such defenders of lost causes. In each case, the structure loses!

Such instances are not uncommon and indicate that more feedback from previous experience is sorely needed. It is not likely to be found unless requested - and with some urgency. Until then, the information herein should be useful to show both the need for and the promise to be expected from a redirection of customary design practice.

For a start, the guidelines stated in Chapter II are restated for thoughtful consideration :

A. ***Keep the number of parts to a minimum.***

B. ***Anticipate change with standard features and patterns***

C. ***Minimize tooling with accurate, self-indexing parts***

D. ***Anticipate access needs with open internal structure***

E. ***Avoid materials which cannot produce fittings***

F. ***Modularize***

G. ***Triangulate***

* * * *

To keep parts to a minimum, it must first be clearly understood what is meant by "a part". Economy has been claimed for composite structures because they allegedly contain fewer parts. While there may actually be a sheet metal assembly so clumsily designed that it contains

more parts than its composite counterpart, this possibility is quite remote. In the early 1970's exactly such claims were made in a presentation by a composite enthusiast from Wright-Patterson Air Force Base before a dutifully respectful group at the McDonnell-Douglas Astronautics Company in California. After he was through, the Engineering Vice-President rose to ask why these cost-cutting results had not been detected in his company's research. Nobody present had the courage to say that the reason was quite simple - the statements were not true.

A part is anything that must be identified, described, stocked, handled, or inspected. A single leaf in a multi-ply layup of a composite assembly is a **part**. When a dozen to a hundred of such plies are fused together in a plastic matrix, the product is an **assembly** - though often mistakenly identified as a part. The same is true of a number of individually simple units which are welded together. They are also an assembly - not at all comparable to a single unit (that is, **part**) of the same shape which has been carved from a single block or plate.

Few parts, obviously, means **large** parts. Their size is limited by three main factors: the size of stock available in the material of choice, the size of machines available for working the material, or the imagination of the designer. Unfortunately, the last reason is too often the determinant of part size.

There are other reasons for separate parts:

- ◊ One part must move with respect to another - mechanical motion.
- ◊ Special properties are required in a local area - resistance to wear, electrical or thermal insulation, adustability for proper fit, excessively high local load intensity, etc.
- ◊ Manufacturability - part must be hollow, extreme change of shape, etc. A spherical container, for instance, must be made in no less than two halves.
- ◊ Something must be removable for access.

There are probably some other reasons in unusual cases, but these are the most likely. If there are joints for none of these reasons, there is bound to be room for considerable cost and weight reduction in the product.

There is a firmly implanted idea in aircraft as well as space vehicles that integral construction is only to be applied where it is structurally important. Implicit in such an attitude is the assumption that extra cost

is incurred. That is, the main structural boxes in aircraft wings, often functioning also as integral fuel tanks, are considered important enough. The leading and trailing edges, "feathers", so to speak, considered relatively unimportant, are assemblies of sheet metal, giving secondary structure the benefit of secondary consideration. As one engineering vice president for a major aerospace corporation put it, "We worry about the 'bones' of the construction, but the 'feathers' usually cost and weigh more." In cases like this, attitude rather than reason prevents more widespread use of integral construction. Besides, it is not generally known (because nobody asks) that it is actually more economical.

In many cases, lack of understanding that integral construction should be **preferred** practice, has led to inadequate funding for the machines that make it possible. Some aerospace companies are simply not equipped to make large parts. When they re-equip their shops with updated numerical control machinery, they order machines with small beds, incapable of making anything much larger than two or three feet wide, and often less than ten feet long. Even at that, their designs are not likely to challenge their machines' capacity. There is plenty of room for improvement.

* * * *

Providing useful attachment fittings as an inherent feature of the construction is even rarer than applying integral structure. In the S-IVB case, the one which has been most thoroughly scrutinized, a lead designer remarked that every attempt had been made to minimize weight at the tank stiffener intersections, even to the extent of drilling holes centered on these blobs of material. It was eventually decided that the labor involved was not worth the minimal weight saving, though nobody apparently considered these strong points an asset to be exploited. Where attachments were made to the tank wall, the standard pattern was interrupted, the stiffening ribs were cut down and tapered to blend with special large thick pads to which attachment fittings were welded. Ultimately, it was realized that an S-IVB, serving as the Orbital Workshop for Skylab, already possessed inherent fittings that with the minimum modification mentioned in Chapter II were sufficient to support the crew's living quarters and experimental equipment.

A by-product of this discovery was the inherent inclusion of such attachment provisions in the floors and walls of the Workshop where the open isogrid form of structure provided unusually strong fittings at the juncture of six bars. Subsequently, this geometry has been applied as stiffening for the skin of tanks, interstages, and payload fairings in the

Delta launch vehicle, about 85 per cent of its surface being in this form. The opportunities afforded by the stiffening have been recognized as useful for locating and supporting slosh baffles in the propellant tanks and for various mountings for equipment components.

Curiously, as soon as machining is accepted as a process for making parts, great attention is paid to simplifying it. That is, milling parallel slots to leave standing parallel stiffeners is usually preferred to pocket milling, although the latter can be a complete structure whereas the former cannot. It is cheaper only because it is incomplete. When the necessary frames, cross-bars, clips (or whatever) are added, the cost comparison is no longer close. Besides, there are no longer any inherent features for equipment mounting, that task (and its accompanying damage) being left to the installers.

Other than the few cases cited, there has been virtually no recognition of the opportunity that the nodes of structural patterns offer and even less indication that any procuring agency will ever consider such capability essential. No such requirement has been seen in a proposal request (not even for Space Station where it would be invaluable) or even recognized as an asset when offered. Why must it be assumed that the negotiations involving structural alterations for "sytems integration" are inevitable?

* * * *

When large parts are machined, accuracy is an inherent feature. When this is recognized, an adapter cradle or a basic vehicle itself can be built without expensive tooling. The Orbital Workshop floor pictured in Figure I-1 used the accurately made machined panels themselves to align all the rest of the parts, allowing it to be built on nothing but sawhorses which held it off the assembly floor, as shown. This floor assembly, as it happened, was not the final version, but the original one which still contemplated the so-called "wet workshop" immersed in liquid hydrogen. For the later one, an assembly jig was made anyway. The intent of the very large structural sandwich core of a standardized upper stage, shown in Figure V-11, was to exploit the accuracy of the full-bay face plates in the same way. This one, however, was never built.

Jig borers are precision tools which can usually be seen in an air-conditioned dust-free room off to one side of a large machine shop floor. Their function is to make very accurate and precisely located holes for indexing pins in precision assembly fixtures. Most of the time they just sit there, looking shiny and unused and expensive. It would seem logical to employ these machines to produce actual parts for low satellite production. They could at least locate and drill accurate hole patterns in an integral bulkhead, rib, or similar structure, making an assembly tool

unnecessary by turning the unit itself into an assembly fixture. The accurate hole patterns can also index the core part on the machines which subsequently shape it.

It is safe to say that this accuracy only applies to parts which are flat. By the time a flat part has been formed to a half-cylinder or one-third-cylinder, there is probably enough plastic deformation to require at least a trim tool to true up the edge. Conical formed parts are even more susceptible to uneven deformation. For these cases and others where even more severe forming is required (involving compound curvature, for example), an assembly tool is sure to be needed.

* * * *

When the internal structure is open, consisting of discrete bars instead of obstructive barriers, it is self-evident that wiring and plumbing runs can pass through it. Without any need for changes which add new parts, extra reinforcement, argument and negotiation, the open structure habit can be expected to produce less costly and lighter structure than can be obtained by conventional practice. The passenger airplane floor beam example in Chapter III and the revised cross-section for a Shuttle Orbiter payload bay shown in Chapters IV and VI typify the kind of improvement that can be expected. It can be achieved most effectively if the trusses are considered machinable from single plates instead of built up from tubes in conventional fashion. It's so obvious that it should be tried more often than it is. The hang-up seems to be a mental block holding a designer back from a bold move which includes discarding over ninety per cent of the material in the starting blank.

To carry the theme further, one should re-examine the orthogonal frames, longerons, beams, and such internal framework, replacing as much of it as possible with a lightweight internal strut system. Only as heavy as it needs to be to stabilize integrally stiffened external shells, it allows these shells to contain all the elements now identified as spar caps, frame caps, and bulkhead rings. A wing spar thus becomes nothing more than a light truss lattice with no caps because those are part of the skin. The idea is essentially the same as that which created sandwich structure - only, in this case, the faces of the "sandwich" are the outer surfaces of the vehicle.

* * * *

As soon as the old sheet metal way of doing business is adopted, as in the case of composite construction now considered fashionable for weight saving, individual fittings are required wherever large concentrated loads are found - at landing gear attachment points, control surface and flap

hinges, door hinges and the reinforcement around the openings, engine mounts, etc., etc. On the other hand, with thoughtful design, these provisions can be incorporated into a large integral panel or shell. Load intensity can vary within the same part from perhaps 100 to 200 pounds per inch of width all the way up to the maximum capacity of the basic plate - about 50,000 pounds per inch for one-inch aluminum plate. The plate can be whittled to match any load intensity between these extremes, a property which permits exceptionally efficient tailoring of the material for light weight as well as for minimum cost because only one piece is involved.

It must be added that prudent blending of cuts between areas of varying load intensity to avoid stress concentrations, as has been done for many years on wing spar caps, can significantly extend the fatigue life of such structures, particularly when load is not transferred between overlapping sheets by rivets or bolts with their crack-inducing holes. Where there are attachments, as between one large plate and another, the points of attachment can, and should, be adequately reinforced with integral bosses.

These desirable properties must be forfeited when the basic material (rolled sheet or laid-up plies) can handle only a limited range of load intensity. The inability of these material forms to make fittings is a sound reason for avoiding them. Their promising physical properties cannot be effectively employed. It is why the engine bypass duct mentioned in Chapter III could be made lighter from titanium than from graphite composites although the titanium is about three times as dense.

As indicated in Chapter V, there is nothing wrong with the remarkable strength and stiffness of graphite fibers imbedded in some kind of matrix, except for the method of application. When it takes the form of an isotropic block or slab which can be molded or machined to shape, it should offer exceptional improvement in flight weight structure. Until then, it will only be superior to poorly designed metal structure - which is abundant enought to foster the illusion of laid-up composite superiority.

In general, the economy of very large parts with inherent fittings and load-tailored members justifies avoidance of materials unsuitable for fittings - even when the material properties of the integral parts appear to be inferior.

* * * *

Modularization is seldom found in flight vehicles, the single exception probably being standard cargo containers found in later model air transports. There have been studies for its application in space vehicles,

and one attempt at a real system, but these cases have rigidizeded the subsystem packages into invariable modules, drastically restricting the range of applications.

Not only must modularization **start** with the structure, but the structural parts must be recognized as those least in need of change from one mission or application to another. They are the backbone, along with some distributive runs. The subsystems are the **variables** which can adapt for different purposes while the structural frames and containers remain essentially constant. Even the structures can be more useful if geometrically standardized while allowing for variable weight and strength to widen their application.

* * * *

It should not be necessary to mention it, because every structural designer should know it, but structure can be much more effective if it is arranged in triangular arrays instead of rectangles and squares. That is, when structure is arranged in rectangular patterns it must be stabilized by obstructive shear webs, or worse, suffer weight penalties from carrying shear by bending loads in the structure surrounding an opening. But when structure is a lattice of straight, stiff, **axially loaded** bars, it is light, penetrable, and inspectable, in most cases needing no rework when other subsystems must have space and support. This open basket form can **only** be efficient when the arrangement is triangular. That is, to say it again, there is **only one stable polygon** - the **triangle.**

SNOOPY AWARD

When Daniel Haughton first took over as President of the Lockheed California Company, having acquired somewhat of a reputation as a disciplinarian at the Georgia division, he was seen every morning for a few weeks standing at the entrance to Building 63 at the Burbank Airport (then Lockheed Terminal) watching latecomers arrive. This led to considerable muttering, *sotto voce* of course, to the effect of "I wonder what's being left undone in **his** office, while he spends his time watching what **we're** doing?"

Before long the question was answered in the fashion known to workers throughout the industry, the warning memo about employee attendance:

". . . . . it has come to our attention that our working hours from 7:30 in the morning to 4:15 in the evening are not being observed by all employees. Some have been arriving late, taking too long for lunch, and departing early in the afternoon. Offenders are warned that disciplinary action may be necessary if these habits continue - and **you know who you are!**"

Ken Watson, an immigrant from the Bristol Company in England, was one of a fairly large British contingent, properly assigned because of their lengthy experience to the Preliminary Design department, but frustrated by underutilization and underestimation of their worth. He carefully read the memo, a smile lighting his face.

"A-a-ah," he said, waving the paper above his head, "**Recognition**, at last!!"