Doing Things Right in Space Programs

Ten Principles for Doing Things Right in Space Programs

1. **Adopt the right attitude**
2. **Invest in knowledge and understanding**
3. **Instill ownership and responsibility**
4. **Constantly seek ways to improve teamwork**
5. **Follow a sound, systems-engineering approach**
6. **Reduce total cost through good engineering**
7. **Keep everything as simple as possible**
8. **Establish an effective quality system that involves everyone**
9. **Be willing to accept risks, but only those you truly understand**
10. **Make sure you—and everyone else—have enough time, resources, and freedom to do things right**

Article #20

Keep Everything as Simple as Possible
Part 2: Observations of a Master

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When I started in the space industry in 1979, the common wisdom was that machining was expensive, mostly because so much material was wasted as chips. Instead, it was popular to buy extruded shapes, or make them by bending sheet metal, and then attach them together or to sheet metal with rivets or threaded fasteners.

No doubt this mindset was a carry-over from early days in the aircraft industry, when the cost of material was much greater than now relative to the cost of the labor needed to assemble parts. Even then, an assembly of many parts, of course, required more sheets of engineering drawings, but a common saying was, "Paper is cheap. Metal is expensive." This is no longer true. It hasn't been true for quite some time now, if it ever was in the first place.

Following are excerpts from a remarkable manuscript, yet unpublished, that was written by the late O. P. (Ollie) Harwood: "Right for Flight: The Structural and Architectural Design of Machines that Fly."[1] Before he died, Ollie gave me permission to reprint parts of this manuscript in hopes it would do some good. The following excerpts pertain to a cost study made in 1967 on the Skylab program, when unusual requirements caused the engineers to generate a novel structural concept: planks made of aluminum-alloy plate machined to have a gridwork of equilateral triangles (Fig. 20-1).

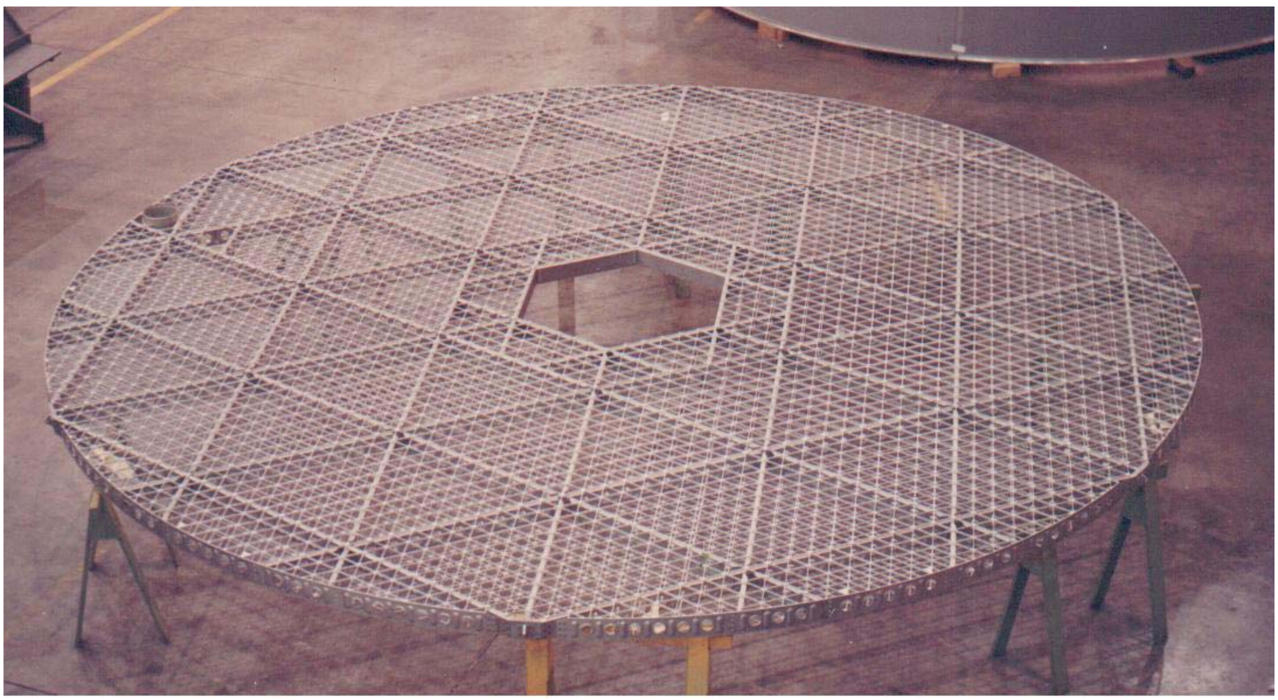


Fig. 20-1. Open Isogrid Lattice Used for Skylab. This is a photo of a floor assembly that was 21 feet in diameter. The isogrid design is analogous to a pegboard, with each node providing an attachment point.

According to Ollie, "The construction was the first hardware application of 'isogrid,' so called because of its uniform elastic response in all directions to applied structural loads." Here's Ollie:

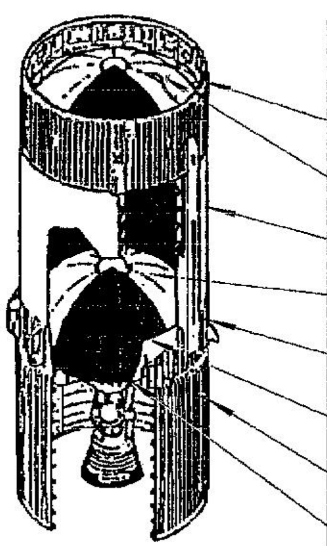
[1] Ollie Harwood was a key contributor to the design of the first space station, Skylab. He had a 44-year career, first in aircraft with the Douglas Aircraft Company, North American, and Hughes, and then in the space industry, with McDonnell Douglas, TRW, and Rockwell. He retired in 1987 after a reprimand for being too vocal in his criticism of NASA and the design for the International Space Station. Ollie—and many to whom he showed it—believed his own concept was much better because it was simple and adaptable. For a July 2003 article on Ollie, published shortly after his death at age 80, "Remembering a Rebel," by Lee Dye, go to http://abcnews.go.com/sections/scitech/DyeHard/dyehard030730.html.

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.

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 of 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 cost study Ollie was referring to was an examination of costs associated with the then-current Saturn S-IVB boost stage. Figure 20-2 summarizes the results of that study.



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

Fig. 20-2. Relative Costs for Saturn S-IVB. The "cost ratio" is a measure of manufacturing hours per pound, normalized to the least expensive subassembly, the tank cylinder.

As you can see, the subassembly with the lowest cost per pound was the tank cylinder. This cylinder was made of large, fully machined slabs welded together to assure the seams would not leak under pressure. As Ollie noted,

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 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.*

The team performing this study examined the Thor/Delta program and found similar results. This is old data, but since that time the cost of machining has gone down while the cost of labor for assembly has gone up. The cost difference should be even greater today.

Ollie continued:

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 (Fig. 20-3). 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.

Ollie was not a fan of using composite materials to reduce parts count because he considered a composite lay-up itself to be an assembly of parts. Along with the above study on design options for the forward skirt, composites were also considered:

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 cost ratio on the same baseline was 9.3—not a very good investment for no performance gain.

Ollie felt so strongly about the advantage of simplifying with metals rather than composites that he offered up the following as one of the key points at the end of his manuscript: "Avoid materials which cannot produce fittings." Fittings—the parts used to attach structures or structural parts—typically are stressed in all directions, whereas a composite laminate is strong in two directions but quite weak in the third, through the thickness.

More importantly, Ollie felt that overall thoughtfulness—or systems engineering—on the part of the structural designers can save a space program a great deal of time and money. He believed that much of the cost and weight often attributed to other subsystems actually was the outcome of a structure whose design had failed to foresee the attachment of late-arriving subsystem components. From the Introduction to Ollie's manuscript:

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.

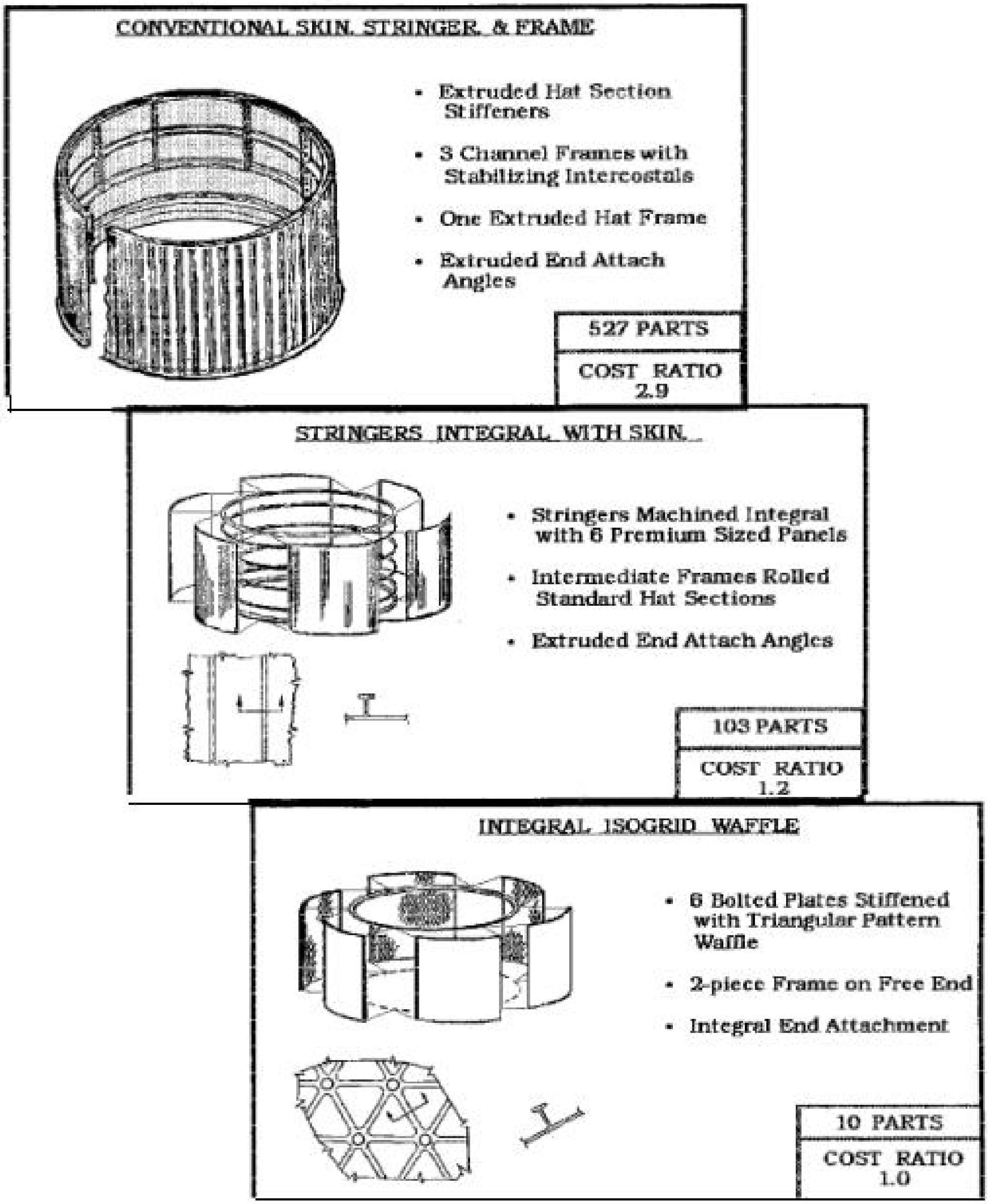


Fig. 20-3. **Results of an S-IVB Cost Study of a Simplified Forward Skirt Assembly.** The study showed how cost may have been reduced if the skirt had been designed differently, with fewer parts. Again, the "cost ratio" is dollars per pound, normalized to the lowest-cost assembly.

And, from the Conclusions section of Ollie's manuscript:

> *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 new program … (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!*
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> *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 following guidelines are given) for thoughtful consideration:*
>
> - *Keep the number of parts to a minimum*
> - *Anticipate change with standard features and patterns*
> - *Minimize tooling with accurate, self-indexing parts*
> - *Anticipate access needs with open internal structure*
> - *Avoid materials which cannot produce fittings*
> - *Modularize*
> - *Triangulate*

About the Author

Tom Sarafin has been involved in the space industry full time since 1979, at which time he graduated from The Ohio State University with a BS in civil engineering and took a job as a stress analyst at Martin Marietta Astronautics in Denver, Colorado. While at Martin, he was involved with design, analysis, verification planning, and testing on several spacecraft and launch vehicle programs. After contributing to the book *Space Mission Analysis and Design* [Larson and Wertz, editors, first edition published in 1991], he obtained management's support and funding at Martin Marietta for the development of a book on the interdisciplinary development of structures for space missions, and served as principal author and editor for 23 other authors. He left Martin Marietta in 1993 to complete this book, under the guidance of Dr. Wiley Larson at the U.S. Air Force Academy. The result of nearly four years work—*Spacecraft Structures and Mechanisms: From Concept to Launch*—was published in 1995 jointly by Microcosm, Inc., and Kluwer Academic Publishers.

In 1993, Mr. Sarafin formed his own company, Instar Engineering and Consulting, Inc. Once he finished his book, he began providing review and advice as a consultant to space programs. He also developed a short course based on his book and began teaching it throughout the industry. The course has been quite popular, and the business has grown. Now Instar offers a curriculum of courses taught by experienced engineers and continues to add to that curriculum.

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