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SPACE SHUTTLE EXTERNAL TANK PERFORMANCE IMPROVEMENTS - THE CHALLENGE

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The External Tank (ET) has been actively involved in performance improvements since the inception of the program, primarily by weight savings. Weight savings were realized on the first block of flight articles [Standard Weight Tank (SWT)]. With a need for further performance improvements, the ET Program Office was requested to develop a program to reduce tank weight an additional 6000 lb and schedule delivery of the first lightweight ET (LWT) for June 1982.

The weight savings program was accomplished by (1) a unique approach to use of factors of safety, (2) design optimization, and (3) redesign of structures with large margins of safety which resulted in an actual weight savings of 7294 lb. Additional studies have identified further weight savings which will be implemented at appropriate times in production flow. Examples are an improved TPS system for the LH₂ tank aft dome and reduction of slosh baffles in the LO₂ tank based on flight data. All performance improvements were compared and selected based on non-recurring and recurring cost and technical risk.

INTRODUCTION

The primary method of ET participation in Shuttle performance improvement is weight savings. Weight savings were realized in the first block of flight articles (ET-1 through ET-6) as all had actual weights less than specification (Fig. 1). This was attributed to having to establish the specification weight using the high side of tolerance bands for metal and thermal protection system material thicknesses, whereas, the actual thicknesses were less than nominal.

Because the ET is the structural backbone of the Space Shuttle, load paths are complex, making weight reduction a difficult task (Fig. 2). With the challenge to reduce the weight of the basic design by 6000 lb to improve Shuttle performance and since the ET is the only expendable element of the Shuttle, economics of saving weight was extremely important. The weight savings were achieved for only \$75/lb/flight increase in 1978 dollars (Fig. 3).

An initial list of 30 weight-saving candidates was identified with a potential saving of 7500 lb, providing a 20% contingency to assure the required 6000 lb. A screening process was established based on recurring and non-recurring costs as discriminators using a 1978 dollar base. The recurring cost screen was selected at \$75/lb for welded aluminum fabrication and the non-recurring cost was \$15,000/lb based on removing the same weight from the Orbiter. Since it was difficult to mix the Standard Weight Tank (SWT) and the Lightweight Tank (LWT) across the same tools, a single production line concept was used to minimize total costs.

WEIGHT SAVINGS PROGRAM

The weight-savings program was focused primarily on structural components and was accomplished by using the SWT and optimizing that design for LWT loads and environments to arrive at the LWT design. Additionally, all excessive margins of safety were reduced and a unique approach to factors of safety was applied. This approach was tailored to repeatability and predictability of loads. The standard factor of safety (F.S.) of 1.40 was applied to all aerodynamic and dynamic loads; whereas, a F.S. of 1.25 was applied to all well-defined loads, i.e., thrust loads, internal pressure, inertia loads (Fig. 4). The resulting combined equation,

$$F.S. = \frac{(1.25 S/S + 1.40 DYN.)}{S/S + DYN}$$

yields a factor of safety between 1.25 and 1.40.

- S/S = Steady State Loads (well-defined)

- DYN = Aerodynamic and Dynamic Loads

As the result of applying these factors to redesign and optimization, a total weight saving from the SWT to LWT of 7294 lb resulted.

DESIGN OPTIMIZATION

Most of the significant design optimization candidates not only saved weight (2748 lb), but also resulted in lower recurring cost. The major weight saving items are the antigeysers line deletion, crossbeam depth increase, LH₂ tank stringer removal, Fire-Retardant Latex (FRL) coating deletion, and changing interface hardware fitting material to Ti-641-4V (Fig. 5).

Antigeysers line deletion (Fig. 6), replaced by helium (H_e) injection in the main feedline to prevent geysers, took four years to develop through extensive flow testing in a lox feedline simulator and system testing on the Main Propulsion Test Article at NSTL. Main feedline injection is possible because helium rising in the feedline provides transpiration cooling to keep the liquid below saturation temperature, thus precluding formation of vapor which causes geysers. The change eliminated expensive propulsion hardware and a TPS ablator strip along most of the length of the LH₂ tank with more efficient packaging of the propulsion lines (GH₂ pressurant line moved to former location of the antigeysers line). The total weight savings of this change was 666 lb.

The ET/Orbiter aft crossbeam height was deepened and chord thickness was reduced providing increased structural stiffness with a resulting weight saving of 91 lb (Fig. 7). The ET/Orbiter aft crossbeam is limited by its proximity to the Orbiter. A flow restrictor attached to the top of the aft crossbeam was eliminated to allow increased height. This structure is an attractive candidate for composite construction.

A net savings of 235 lb was achieved by deletion of some of the stringer and Z-frames (Fig. 8) in the LH₂ tank, optimization of design of the Station 2058 frame and several intermediate frames, and operational optimization for loading the LH₂ tank. Detailed finite element structural analyses in conjunction with cryogenic structural tests of the SWT LH₂ tank at MSFC showed that many of the integral stringers on the -Z axis (side away from Orbiter) and the intermediate Z-frames in five locations could be eliminated. Originally, the stringers and Z-frames were designed in to make as many of the LH₂ tank parts common to each other as possible for low cost. The 2058 frame was optimized by reducing backup fittings and reconfiguring stiffener design. Operational optimization was required to allow the LH₂ tank to be loaded without preload to assure no bulkhead buckling. Additional material was added to the aft LH₂ bulkhead to assure no buckling.

Since operational ET's will not be exposed for long periods on the pad, TPS top coat (Fire-Retardant Latex) could be eliminated over most of the acreage. The rind of the as-sprayed CPR-488 Spray-On Foam Insulation (SOFI) provides adequate protection from the elements for short periods of time (11 weeks). Areas where rind has been removed require painting with matching color top coat. Over 580 lb were saved by elimination of the top coat.

Major interface fittings were changed to more efficient and available materials. All titanium alloy fittings at the SRB/ET interfaces were changed from Ti-5Al-2.5 Sn to more widely used Ti-6Al-4V because of higher strength (Fig. 9). Most of the ET/Orbiter interface hardware (thrust struts, vertical struts and diagonal struts) had material change from 7075-T73 to 7050-T73 to take advantage of the 10 percent strength increase. The total weight savings from all these changes was 379 lb.

Other weight savings attributed to design optimization include miscellaneous hardware in the Intertank, using an integrated receiver/decoder in the range safety system, miscellaneous electrical wiring changes and deletions of development flight instrumentation and Thermal Protection System (TPS) thickness optimization on the LO₂ and LH₂ tanks. These savings totaled 797 lb.

MARGINS OF SAFETY REDUCTIONS

Structural margins-of-safety were reduced by changing design criteria (LH₂ proof test) and tailoring the structure to specific internal loads (Fig. 10). Commonality was reduced resulting in most margin reduction items increasing recurring costs. Those selected met the \$75/lb criteria. Total weight saved by margin reduction amounted to 3244 lb.

The LH₂ tank proof test was originally based on a relief pressure of 37 psig. This was changed to a maximum operating pressure basis of 34 psig for LWT. This change makes the LH₂ tank a fail-safe

structure; like the fail-safe approaches used for the rest of the Space Shuttle. This change realized a weight savings of 500 lb.

Significant weight savings were also realized in the tank major frames, especially in frame 2058 in the LH₂ tank. Excellent correlation between structural testing data and analysis allowed this to happen. Intertank areas that were tailored to specific internal loads include all skin panels, frames, and the SRB crossbeam. Primary methods of reduction include skin panels reduced in thickness, stringers reduced in thickness and chem-milled; main frame chords machined down to tailor them for specific loads and intermediate frame chords were reduced in thickness.

The LH₂ tank structural changes included added machining of skin panels, especially on the -Z side, increasing the number of different panel types from 21 to 30. Also, two massive LH₂ thrust longerons were redesigned to eliminate unnecessary stiffeners. Elimination of the stiffeners reduced weight, improved producibility and improved the difficult weld of the longeron into the tank, our most difficult weld. Total weight savings of all these items is 1918 lb.

Significant weight reduction was also realized in the hardware at the ET/Orbiter interface (struts and fittings). Margin reductions amounted to a savings of 166 lb. Additional weight reductions occurred in the Intertank skin-stringer panels and frames. Thicknesses were reduced, resulting in a savings of 660 lb.

FACTOR OF SAFETY APPROACH

Structure designed by highly transient flight events (lift-off and high "q") will have a factor of safety of 1.40. Those structures designed by steady state events (max SRB acceleration, post SRB staging, end burn) will have a factor of safety of 1.25. Structures designed by a combination of the above will have safety factors between 1.25 and 1.40. Most of the 1312 lb saved by utilizing this approach came from reducing the material thickness of the Intertank thrust panels, crossbeam, thrust fittings, reinforced skin panels and struts, where 556 lb were removed. The LH₂ tank barrel skins and frames were reduced in thickness, and thrust longerons were redesigned and lightened resulting in a savings of 618 lb. Interface hardware (struts and ball fittings) were reduced in weight by 138 lb.

STRUCTURAL VERIFICATION PROGRAM

The primary ingredient in making the LWT performance improvements work was the unique approach to structural verification for the LWT. It was established that no full-scale, flight type structure would be provided for ultimate load testing, as the structural design approach was essentially the same as for the SWT. This, of course, drove the LWT program to heavy dependence on analytical techniques to verify designs.

STANDARD WEIGHT TANK (SWT)

Early in the SWT program, it was recognized that if extensive and continuing structural testing was to be avoided, it would be necessary to:

1. Establish ultimate strength capability for flight certification
2. Do sufficient testing to validate internal load distributions
3. Do influence coefficient testing to validate math models for analysis
4. Generate a data base to handle future load increase and margin assessments.

The SWT test program was established and completed successfully in late 1979. In all the tests, major emphasis was placed on determination of internal loads through extensive use of strain instrumentation, supplemented by deflection and thermal measurements. The total number of instrumentation channels used during the test program was in excess of 7000. Test data were essentially linear to ultimate load levels and provided satisfactory correlation with analytical predictions. With only minor adjustments based on test data, the analytical tools were verified for use in design of the LWT.

LIGHTWEIGHT TANK (LWT)

Upon undertaking the LWT program, a major effort was made in using SWT data to reduce test requirements necessary for LWT certification. Retests were necessary only in areas where there was a significant configuration change. Wherever configurations were similar with only dimensional changes, the design was supported by the verified analytical methods.

For LWT the only components requiring additional validation tests were:

1. The LH₂ tank - significant configuration changes in some barrel panels and the STA 2058 frame
2. The aft Orbiter/ET interface hardware - material changes and significantly reduced margin of safety.

Major changes in the LWT LH₂ tank consisted of removal of stringers in all 4 barrel panels adjacent to the ±Y axes and reduced margins of safety in the inner chord of STA 2058 frame to levels below those demonstrated on SWT.

A series of development tests was identified where the existing SWT tank could be modified structurally to simulate the LWT configuration in the barrel 4 area. Stringers were removed to test various stringer spacing effects on unpressurized panel stability. Out-of-plane stiffness of the LWT design STA 2058 frame was simulated by material removal of the inner chord. Wherever possible, original SWT instrumentation locations were utilized for correlation. Ultimate load test data indicated all structure responded linearly and good correlation was achieved with predictions further verifying the analytical allowables.

As a final step in the certification of the LWT, the first two LWT LH₂ tanks were subjected to a series of special tests in the Proof Test Facility at MAF.

LWT-1 was instrumented with deflection gages to support influence coefficient tests to verify modeling of the reduced stiffness STA 2058 frame.

LWT-2 was instrumented with nearly 500 strain gages to support limit load testing. Tests were conducted to verify performance of barrel panels having wide stringer spacing and reduced skin thickness, to verify analysis and performance of the longeron, barrel panel 2 in compression and STA 1871 frame; and to validate the redesigned STA 2058 frame. All measurements during these tests were linear and agreed very well with predictions.

Maximum utilization has been made of test data generated during the SWT and modified SWT structural test programs, and coupled with judiciously selected limit load testing on flight hardware has provided verification of the structural modifications made to establish the LWT and realize and exceed the goal of 6000 lb of performance improvement.

IMPLEMENTATION STATUS

All engineering has been released; preliminary design reviews, critical design reviews, and design certification reviews have all been completed. The first Lightweight Tank was delivered to the Kennedy Space Center in August 1982, and was flown successfully on STS-6 in April 1983.

ET IS ALREADY ACTIVE IN SHUTTLE PERFORMANCE IMPROVEMENT:

STANDARD WEIGHT ET

	<u>ET-1</u>	<u>ET-2</u>	<u>ET-3</u>	<u>ET-4</u>	<u>ET-5</u>	<u>ET-6</u>
Specification Weight	78.278 LB	78.581 LB	77.789 LB	77.902 LB	77.462 LB	77.457 LB
Actual Weight	77.099 LB	77.249 LB	75.770 LB	75.895 LB	75.172 LB	75.453 LB
Performance Improvement	-1.179 LB	-1.322 LB	-2.019 LB	-2.007 LB	-2.290 LB	-2.004 LB

LIGHTWEIGHT ET

	<u>LWT-1</u>	<u>LWT-2</u>	<u>LWT-3</u>
Specification Weight	71.278 LB	71.173 LB	71.144 LB
Actual Weight	66.824 LB	67.009 LB	66.809 LB
Performance Improvement	-4.454 LB	-4.164 LB	-4.335 LB

Figure 1. Performance Improvements.

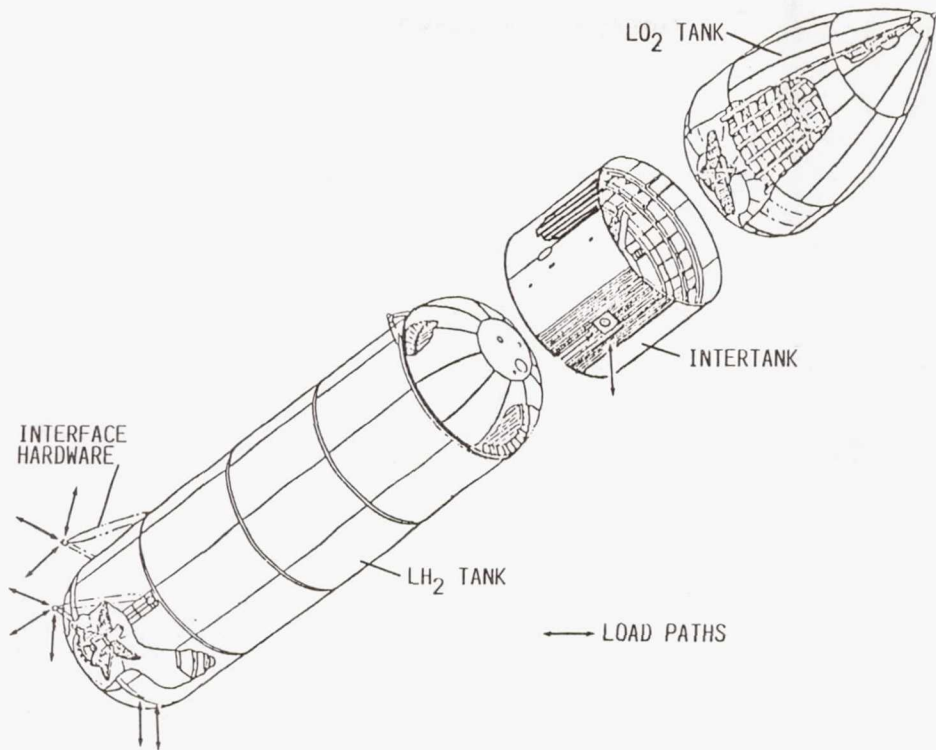


Figure 2. ET General Arrangement.

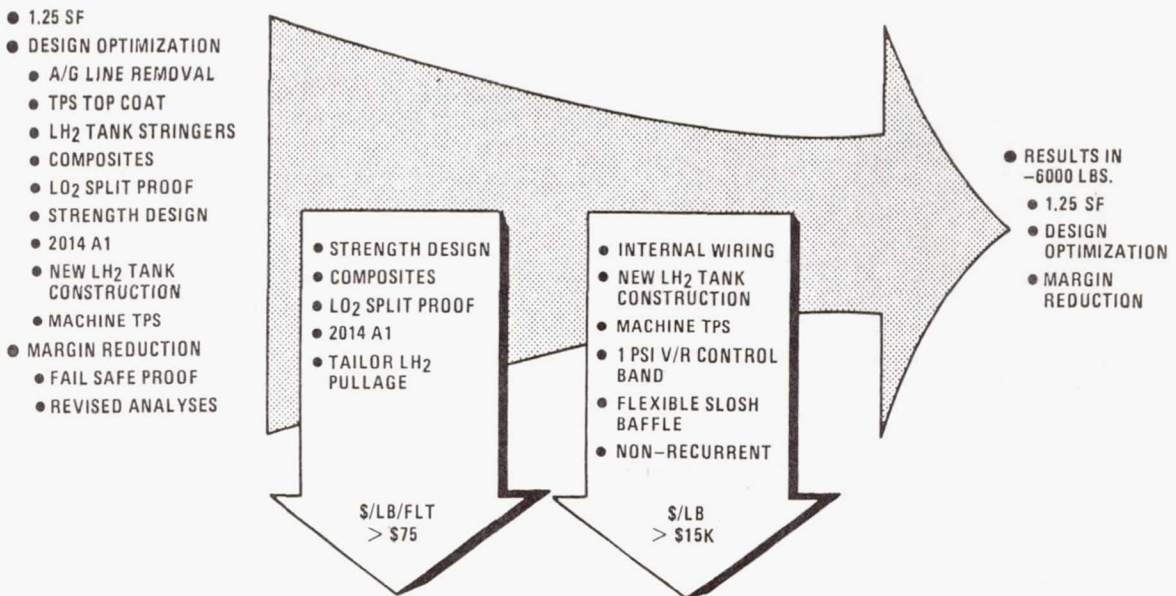


Figure 3. Weight Savings Screening.

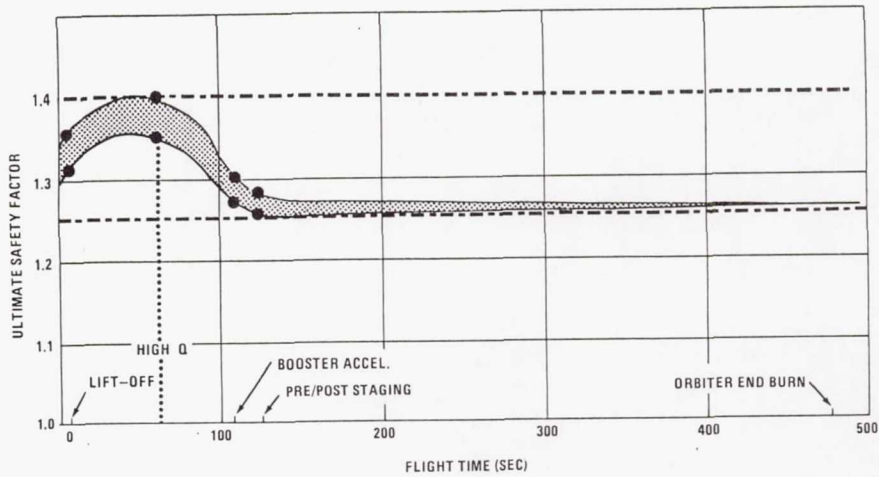


Figure 4. A Different F.S. Approach.

- MAIN FEEDLINE GHe INJECTION (ANTI-GEYSER LINE DELETION)
- EFFICIENT CROSSBEAM IN INTERTANK
- LH₂ TANK STINGER/Z-FRAME REMOVAL
- DELETE FIRE-RETARDANT LATEX PAINT ON TPS.
- NEW MATERIALS
- MISCELLANEOUS HARDWARE

Figure 5. Design Optimization Within Design-To-Cost Goals.

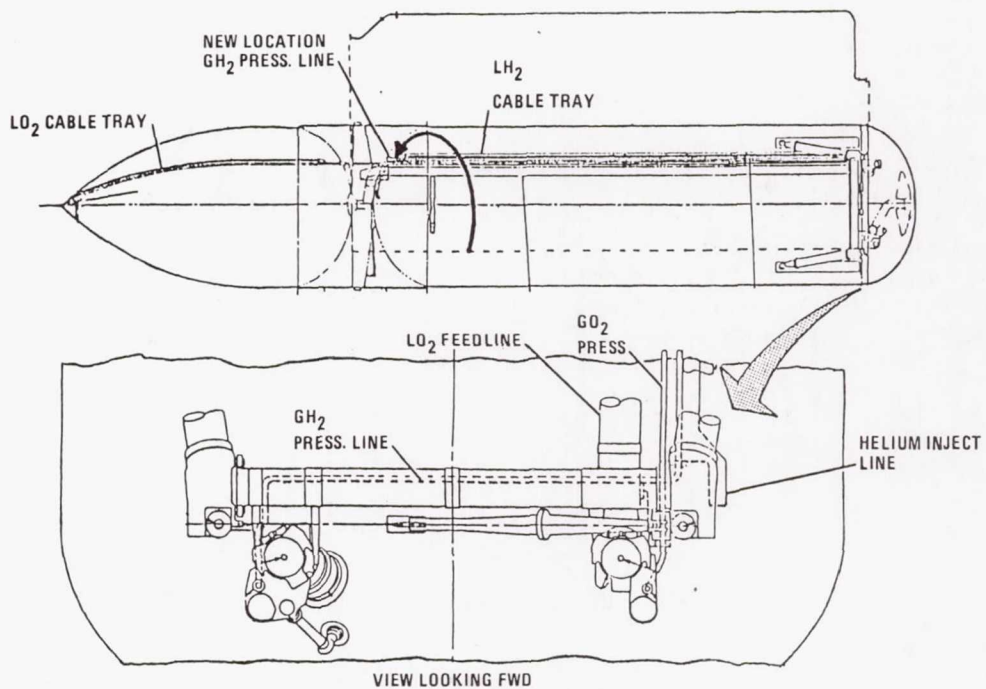


Figure 6. Main Feedline Injection Saves Weight and Dollars.

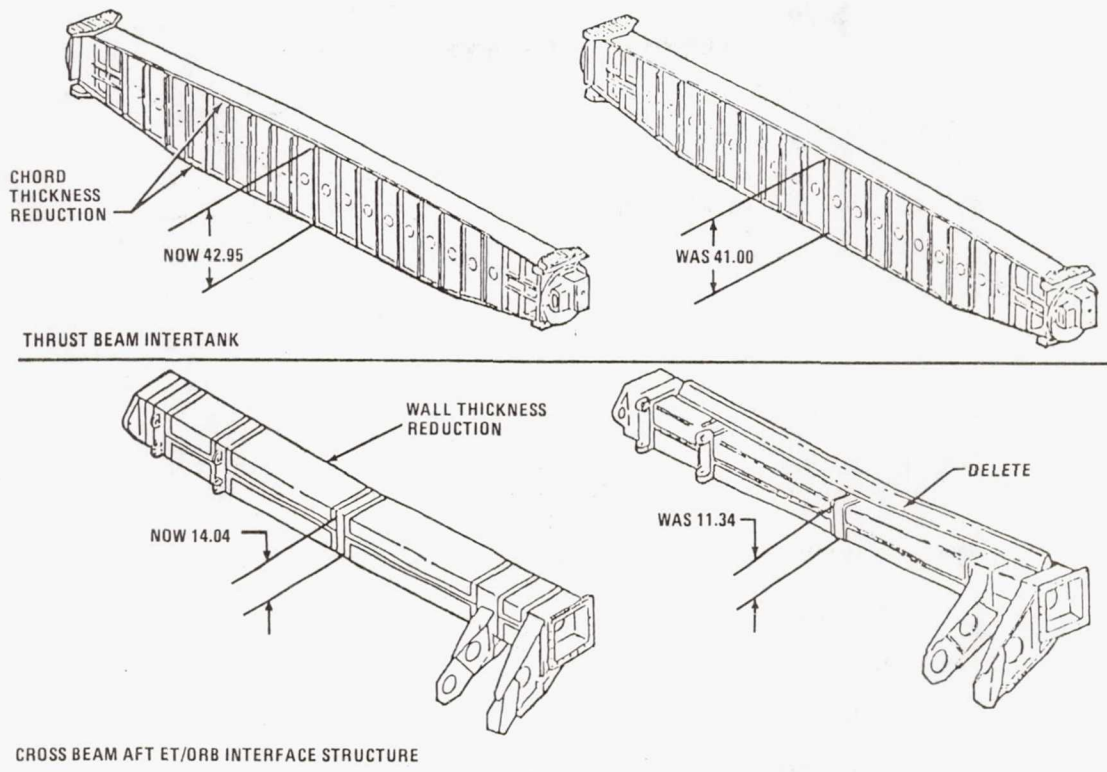


Figure 7. More Efficient Crossbeams.

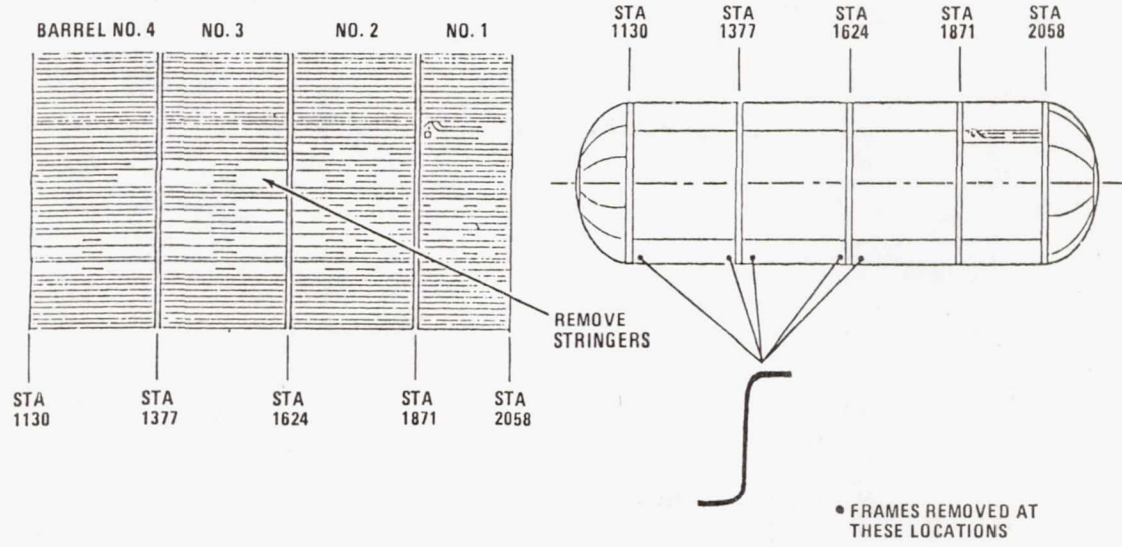
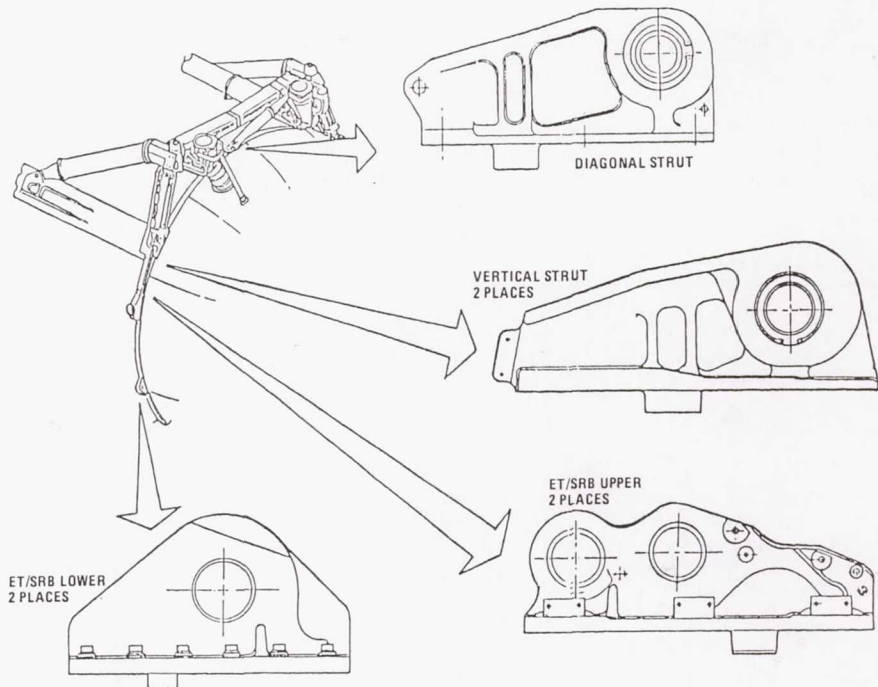


Figure 8. LH₂ Tank Selected Stringer and Z Frame Removals.



NOW: TITANIUM 6A1-4V-ELI GR. WAS: TITANIUM 5A1-2.5SN-ELI GR.

Figure 9. New Materials.

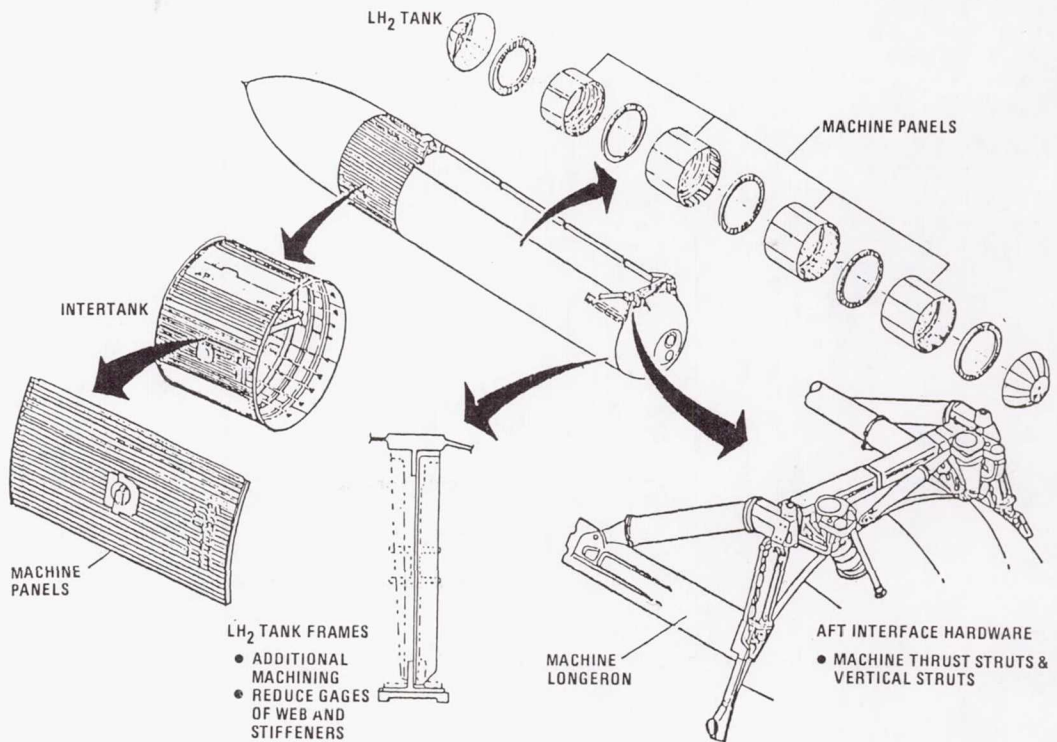


Figure 10. Margin Reduction Areas.