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SPACE SHUTTLE EXTERNAL TANK
PERFORMANCE IMPROVEMENTS*

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ABSTRACT
The passive External Tank (ET) is a very active ingredient in the overall Shuttle performance improvement program. Currently, the ET is successfully achieving a 6000 pound weight savings program with the first Lightweight Tank scheduled for delivery in June 1982. Weight savings are being accomplished by: 1) an unique approach to factor of safety, 2) design optimization and 3) reducing large margins. Future performance improvements include studies that develop: 1) an improved Thermal Protection System (TPS) for the aft dome, 2) improved propellant management, 3) potential use of composites, 4) use internal wiring to eliminate the cable trays, and 5) elimination of the slosh baffle in the L02 Tank depending upon the results from the DDT&E flight test program. All of the ET performance improvements are compared and selected on the basis of non-recurring and recurring costs and technical risk.

INTRODUCTION
The primary method of ET participation in Shuttle performance improvement is in weight saving. The ET is already active in this effort. ET-1 and ET-2 are 1179 and 1322 Ibs underweight, respectively. Since the ET is the structural backbone of the Shuttle, the load paths are complicated and thus make weight savings difficult (Figure 1). The weight savings program, which started in October 1975 at a savings of 2560 Ibs, grew to 6000 lbs in January 1979. Since the ET is the only expendable portion of the Shuttle, the economics of saving weight are extremely important. The current 6000 lb weight savings was achieved for only $75/1b/flight (1978 dollars) increase (Figure 2).

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CURRENT WEIGHT SAVINGS
A screening program was set up for recurring and non-recurring cost discrimination using a 1978 dollar base. Also, we did not want to require a new structural test program. An initial list of 30 candidates resulted in a total potential savings of 7500 lbs to provide a 20% contingency to assure the required 6000 lbs. WEIGHT WATCHER bulletins were effectively used in highlighting weight savings and in promoting competition among design groups.

Recurring cost screen of $75/1b was chosen as reasonable welded aluminum fabrication cost. The non-recurring cost of $15,000/1b was based on removing the same weight from the Orbiter.

Since it is difficult to mix Heavyweight Tank (HWT) and Lightweight Tank (LWT) across the same tools, a single production line concept was used to minimize total costs.

FACTOR OF SAFETY APPROACH FOR LWT
An unique approach is used that tailors the structural factor of safety to the repeatability and predictability of loads. A standard Factor of Safety (F.S.) of 1.4 is used for all aerodynamic and dynamic loads. A F.S. of 1.25 is used for all well defined portions of the load (thrust, internal pressure and static inertia).

The resulting combined equation,

\[ FS = \frac{(1.25 S/S + 1.4 DYN)}{S/S + DYN} \]

an F.S. between 1.25 and 1.4

- S/S = Steady State Loads
- DYN = Dynamic Loads
The result of using the above approach is that high F.S.'s resulted for highly transient flight events (Lift-off and Hi Q), and lower F.S.'s for steady state events (Max Solid Rocket Booster (SRB) acceleration, Post SRB Staging and Orbiter End Burn) (Figure 3). Most of the 1650 lbs savings for this approach came from the Intertank thrust panels, thrust fittings, reinforced skin panels and struts.

**DESIGN OPTIMIZATION**

Most of the significant design optimization candidates not only saved weight (3150 lbs) but also resulted in lower recurring cost (Anti-Geyser (A/G) Line deletion, TPS topcoat deletions, use of Ti-6Al-4V alloy).

The major weight saving items are A/G Line deletion, cross beam depth increase, stringer removal Fire Retardant Latex (FRL) coating deletion and changing fitting materials. Anti-Geyser Line replacement with He injection in the main feedline to prevent geyser took four years to develop thru extensive flow testing in a LOX feedline simulator and system testing on the Main Propulsion Test Article (MPTA) at the National Space Technology Laboratory (NSTL) (Figure 4). Main feedline injection is possible because helium rising in the main feedline provides cooling to keep the liquid below saturation temperature thus precluding formation of vapor which causes geysering. This change not only eliminates expensive propulsion hardware but also an ablator TPS strip along most of the length of the LH2 tank as well as allowing for more efficient packaging of the propulsion lines (GH2 press line moved to a spot formerly occupied by a four inch diameter A/G Line). Total weight savings is 620 lbs.

Both cross beams were deepened to improve structural stiffness while reducing weight 150 lbs (Figure 5). Intertank cross beam depth was limited by its close proximity to the LH2 forward dome. The aft intertank cross beam depth was limited by its proximity to the Orbiter. Also, the flow restrictor attached to the top of the cross beam was eliminated with the increased height of the cross beam. Both beams are attractive candidates for composites in future weight savings efforts.

A savings of 560 lbs was affected by deletion of some of the stringers and "Z" frames (Figure 6). Detailed finite element structural analysis in conjunction with the cryogenic structural tests of the Heavyweight (HWT) LH2 Tank at Marshall Space Flight Center (MSFC) showed that many of the integral stringers on the -Z side (away from Orbiter) and the intermediate Z frames in five locations could be eliminated. Originally, the stringers and Z frames were included to make as many of the LH2 tank parts common to each other for low cost.

Since operational ETs will not be exposed on the pad for long periods of time, TPS top coat FRL paint can be eliminated over most of the acreage. The rind of the as-sprayed CPR 488 Sprayed-On-Foam Insulation (SOFI) provides adequate protection from the elements for short periods of time (11 weeks). Areas where rind has been removed will need to be painted with a matching color top coat. Over 600 lbs are saved by eliminating the top coat.

Major fittings were changed to more efficient and available materials. All titanium alloy fittings were changed from Ti-5Al-2.5Sn to more widely used Ti-6Al-4V because of higher strength (Figure 7). Many 7075 and 2219 Al components were changed to 7050 Al to benefit by the approximately 10% strength increase. The total weight savings from new materials is 100 lbs.

**MARGIN REDUCTIONS**

Excessive margins were reduced by changing design criteria (LH2 proof test) and tailoring the structure to specific internal loads (Figure 8). This reduces commonality, therefore most margin reduction items resulted in increased recurring cost. Those selected met a $75/1 b criteria. The total weight saving realized in the margin reduction category is 1200 lbs.

The LH2 tank proof test was changed from a relief basis at 37 psig to a maximum operating basis at 34 psig. This change makes the LH2 tank a fail-safe structure, like the fail-safe approach currently used for the rest of the Space Shuttle. This fail-safe proof test approach saves 500 lbs.

Significant savings were achieved in major frames, especially in Frame 2058 in the LH2 tank, because of the excellent correlation between Structural Test Article (STA) testing and analysis. Intertank areas tailored to internal loads include all skin panels, frames and the SRB crossbeam. Primary methods of reduction include skin panels reduced in gage, stringers reduced in gage and chemilled; main frame chords machined to tailor them for the loads and intermediate frame chords were reduced in gage.

The LH2 tank structure included added machining of skin panels, especially on the lower side increasing the number of different panel types from 21 to 30. Two massive LH2 longerons were changed to eliminate unnecessary stiffeners. Elimination of these stiffeners reduces weight,
improves producibility of the design including easing the difficulty of welding them into the LH₂ tank, our most difficult weld.

IMPLEMENTATION STATUS

Engineering has been released on 90% of the design and initial hardware is being fabricated.

The original STA has been modified by removing selected stringers and "Z" frames for special room temperature development tests. All LH₂ tank changes will be tested in a limit load test of a flight LWT.

FUTURE PERFORMANCE IMPROVEMENTS

In addition to the current 6000 lb weight savings program, an additional 2000 to 2500 lbs are potentially available from the ET. Attractive ET candidates include improved propellant management, slosh baffle elimination, internal cabling, material changes and improved TPS.

Generally, the lowest cost weight savings have already been achieved except for the slosh baffle elimination and the reduction in propellant reserves.

IMPROVED PROPELLANT MANAGEMENT

A reduction in the 739 lb allowance for LH₂ dropout may be possible because of the reduction in margin required for Space Shuttle Main Engine (SSME) shutdown transients (Figure 9).

For every lb of unusable LH₂ converted to usable, 1.42 lb of payload can be added if extra L0₂ is loaded at a ratio of 6 to 1. This is based on a payload increase factor of 6% of the total propellant required plus the reduction of the LH₂ usable (deadweight), i.e.,

\[ PL = H₂ + (7H₂ \times 0.06) = 1.42 H₂ \]

Therefore, for a 400 lb reduction, a payload gain of 568 lbs is possible.

Currently, additional ground flow testing is being investigated to fully understand dropout and determine exactly how much margin reduction is possible.

SLOSH BAFFLE ELIMINATION

Current analysis shows that the Space Transportation System (STS) control system gain is sufficient to provide 10% damping of the slosh mode. This is 2½ times the current 4% damping provided by the ET slosh baffle. With approximately 1% of inherent damping (tank alone), complete removal of the slosh baffle would reduce the total system damping from 12% to 11%. Studies will be conducted after the STS-1 flight to verify the slosh damping analysis and ET slosh damping requirements, if any.

Elimination of slosh baffle would save over 1000 lbs (Figure 10).

INTERNAL CABLEING

Consideration was given to the use of internal tank cabling in the original weight savings reviews; however, it was eliminated because of high non-recurring costs (greater than $20,000/1b). The use of internal cabling is still attractive because it eliminates the need for external cable trays and their protuberance airload ramps (Figure 11). It does however, add complications to the Range Safety System because of the resulting unique design required to install the Linear Shaped Charge (LSC) and the corresponding Confined Detonating Fuses (CDF) on the cryogenic surfaces.

In order to achieve Line Replaceable Unit (LRU) capability, the internal cabling must have connectors at entry and exit points in the tanks. Internal wiring eliminates existing cable trays. In the L0₂ tank, wires are routed through the tank on a steel suspension cable which in turn is attached to major frame. All cables removed from the cable trays are rerouted to the inside of the ET with the exception of the 28 volt cables which are bonded to the exterior skin of the L0₂ tank.

Internal cable saves 250 lbs but adds recurring and non-recurring costs.

COMPOSITES

Potential applications of composites on the ET are the thrust beam in the Intertank, the crossbeam and the thrust struts of the interface hardware and the straight sections of the L0₂ feedline.

The built up aluminum thrust beam could be redesigned to accommodate composite upper and lower chords constructed of titanium perforated face sheets bonded under pressure and elevated temperature to graphite/epoxy laminates (Figure 12).

The straight section of the L0₂ feedline could be made of Inconel 718 thin wall (.010 in.) steel tubing and have over wrapping of three hoop layers of Kevlar 49, ⅜ end roving and ⅜ layer of wrap consisting of longitudinal stripes of Kevlar sandwiched between the hoop layers. This design would be lighter and also improve handling characteristics over the present design.

The 2219 aluminum extruded cross beam of the aft ET/ORB attachment could be step machined to a thin skeletal shell (Figure 13). End joints could be maintained for ease of assembly. The beam stiffness would be restored by building a composite wrap on the skeletal
aluminum shell of graphite/epoxy layers. The aluminum strut forging of the thrust strut would be step machined to a thin shell and then have the strength stiffness restored by a wound, overlapped, tapered, graphite/epoxy composite. Each layer of wrap would be .008 in. thick with the build up thickness varying from 4 to 40 layers depending on the taper and the constant section. The ends of the forgings would be maintained in their present configurations for ease of assembly.

Using the graphite/epoxy designs could result in net savings of 400 lbs.

The chief drawback in the use of graphite epoxy at present is the cost of material; however, this cost is largely a function of the total composite usage in the United States which has increased significantly in recent years.

IMPROVED THERMAL PROTECTION SYSTEM - TPS

Several candidates are being investigated to replace the SOFI/Ablator composite on the ET aft dome with an improved spray-on foam insulation, SOFI. This replacement would save 250 lbs.

Current CPR 488 SOFI, which is needed for propellant conditioning, tends to burn which increases the recession rate causing the need for SLA 561 ablator. Non-burning SOFI with similar q capability as CPR 488 would eliminate the need for SLA 561.

Several candidate replacement SOFI's are:

North Carolina Foam Industries (NCFI-25-13). This SOFI is a high temperature, two part, isocyanurate foam with high trimerization content. It possesses superior characteristics in radiant and convective heating environment as determined from wind tunnel testing.

Texas Urethane (TU-301-20). This material has similar characteristics as above. It has recently been withdrawn from the market by the company due to the loss of material supply. It is being reinvestigated with a substitute material and the results are pending the outcome of tests.

Cook Paint and Varnish (COOK G-325). This material possesses adequate thermal characteristics. It is a two part modified urethane foam. Thermal/acoustic test results are currently pending. This material is similar in price to the above materials and it has good processing and cryogenic characteristics.

All of the above SOFI's have 2.5 lb/cu.ft densities.

SUMMARY

The ET has already significantly contributed to the Shuttle Performance improvement program with both ET-1 and -2 being over 1000 lbs underweight. The current 6000 lb weight savings program is progressing satisfactorily with hardware being fabricated. New and challenging weight savings are still possible within the ET and are being pursued by NASA and Martin Marietta.
WEIGHT SAVINGS SCREENING

- 1.25 SF
- DESIGN OPTIMIZATION
  - A/G LINE REMOVAL
  - TPS TOP COAT
  - LH2 TANK STRINGERS
  - COMPOSITES
  - LO2 SPLIT PROOF
  - STRENGTH DESIGN
  - 2014 A1
  - NEW LH2 TANK CONSTRUCTION
  - MACHINE TPS
- MARGIN REDUCTION
  - FAIL SAFE PROOF
  - REVISED ANALYSES

RESULTS IN -6000 LBS
- 1.25 SF
- DESIGN OPTIMIZATION
- MARGIN REDUCTION

STRENGTH DESIGN
COMPOSITES
LO2 SPLIT PROOF
2014 A1
TAILOR LH2 PULLAGE

INTERNAL WIRING
NEW LH2 TANK CONSTRUCTION
MACHINE TPS
1 PSI V/R CONTROL BAND
FLEXIBLE SLOSH BAFFLE
NON-RECURRING

$/LB/FLT
$75

$/LB
$15K

MARTIN MARIETTA

FIGURE 2
A DIFFERENT F.S. APPROACH

FIGURE 3
MORE EFFICIENT CROSSBEAMS

THRU STH BEAM INTERTANK

CROSS BEAM AFT ET/ORB INTERFACE STRUCTURE

FIGURE 5
LH$_2$ TANK SELECTED STRINGER AND Z FRAME REMOVALS

- Barrel No. 4
- Barrel No. 3
- Barrel No. 2
- Barrel No. 1

STA 1130 STA 1377 STA 1624 STA 1871 STA 2058

- Frames removed at these locations

FIGURE 6
NEW MATERIALS


FIGURE 7
MARGIN REDUCTION AREAS

LH₂ TANK

MACHINE PANELS

INTER TANK

MACHINE PANELS

LH₂ TANK FRAMES
- ADDITIONAL MACHINING
- REDUCE GAGES OF WEB AND STIFFENERS

MACHINE LONGERON

AFT INTERFACE HARDWARE
- MACHINE THRUST STRUTS & VERTICAL STRUTS

FIGURE 8
IMPROVED PROPELLANT MANAGEMENT

LH₂ ALLOWANCE REDUCTION OBTAINED BY USING SSME SHUTDOWN CHARACTERISTICS

DISPERSED DROPOUT POINT

NOMINAL DROPOUT POINT

BURN TO SIPHON LIP

TIME FROM ECO SIGNAL TO SSME SHUTDOWN COMMAND ~ SECONDS

FIGURE 9
SLOSH BAFFLE ELIMINATION IMPROVES ET PRODUCIBILITY

FIGURE 10
INTERNAL WIRING ELIMINATES CABLE TRAYS

- Eliminate existing cable trays & PAL ramps
- Route wires thru tank on cable
- Relocate linear shape charge of range safety system
- New internal wire harness pre-attached to suspension cable attached to major frame

FIGURE 11.
COMPOSITE STRUCTURE

THRUST BEAM-
INTERTANK

LO$_2$ FEEDLINE

INCONEL 718 TUBING OVERWRAPPED WITH LAYERS OF KEVLAR 49

FIGURE 12
COMPOSITE STRUCTURE
AFT ET/ORBITER INTERFACE

- COMPOSITE THRUST STRUTS AND CROSS BEAM
- REPLACE EXISTING ALUMINUM THRUST STRUTS AND CROSSBEAM WITH BUILT UP GRAPHITE/EPOXY ON ALUMINUM BASE

FIGURE 13: