Space Shuttle History: Super Lightweight External Tank

Myron A. Pessin

12/12/2017

Why Use Aluminum-Lithium?

- First used in 1950's (ALCOA x 2020)
  - Used by Navy on A5J attack bomber
  - Ingot casting was very difficult
  - Poor fracture toughness and stress corrosion properties
- Aluminum industry revived Aluminum-Lithium because of competition from composites
  - New formulations have improved fracture toughness and stress corrosion resistance
    - Up to 40% strength increase
    - Up to 10% density decrease
    - Up to 10% modulus increase
    - Up to 20% toughness increase
  - Aluminum-Lithium alloys currently available
    - 2195 – Martin Marietta/Reynolds
    - 2090 – ALCOA
    - 8090 - ALCAN

History of Aluminum-Lithium

- Used by North American Aviation on A3J bomber in late 1950’s
- Had problem, believed to be fatigue cracking. Alloy called Al2020
- Not used for several years
- Russians used in MIG-29 fighter (welded) but would scrap if more than 2 repairs needed. Also developed CRYO welded version but not produced for last ~10 years.
- With rise of composite materials, American aluminum companies scurries to find something to compete.
- ALCOA brought out 2090, not very weldable and limited to fairly thin plate. Used in C-17 transport.
- Martin once owned Aluminum company but sold off except for R&D. Developed a weldable Al-Li Alloy called weldalite.
- Martin explored under IRAD and formed 3 gores and chord, welded into an ET ¼ dome.

North American RA-5C Vigilante

Speed	1,320 mph
Service Ceiling	52,100 feet
Crew	Two
Range	2.050 miles
Wingspan	53.2 feet
Height	19.37 feet
Empty Weight	37,489 pounds
Maximum weight	79,588 pounds
Power plant	Two J79-GE-10 turbojet engines
Thrust	17,859 lbs trust each

- The RA-5C was a Mach 2+ aircraft, capable of electromagnetic, optical and electronic reconnaissance. It could operate at altitudes from 50,000 feet. The vigilante was employed to great effect by the 7th fleet during carrier air wing operations in the Vietnam war. The 2 man crew flew in twin cockpits, the pilot in front, and the Reconnaissance Attack Navigator, in the rear.

- The vigilante may have introduced more new and advanced designed features than any other aircraft in history.

History of Aluminum-Lithium

- Reynolds Aluminum bought production rights to this material
- Lockheed Martin proposed developing a 8000 lb lighter ET using Al-Li, JSC had no requirements for additional payload so would not authorize the study. ET had $1M unencumbered funds and requested permission to procure some Al-Li for process development. JSC wasn't willing to spend Shuttle funds for potential weight reduction that Shuttle didn't need.
- Then the decision was made to fly the Space Station in a high inclination orbit to be compatible with the Russian launch sites. This cost Shuttle 13,500 lbs of payload into this orbit. So, mad rush started for payload and L-M's proposal was resurrected. Bob White, then at JSC, chaired a "non-advocate" review which accepted a plan to reduce weight by 7500 lbs (1:1 on payload) and deliver in 4 years. Level II delayed start 4 months so 48 month program had 44 months to deliver.
  - Initial start up problems:
    - Material – When Reynolds Al (holder of license from L-M) tried to make material it didn't have same properties (fracture toughness). NASA/Martin had to teach Reynolds how to do Taguchi Design of Experiments (DOE) to bring development program down to do-able size.

History of Aluminum-Lithium Highlights

- Weld repair– When weld repairs are made in double curved surface (such as dome) weld shrinkage frequently causes flat spots – Martin, to practice straightening flatspots, made multiple repairs on same spot of IRAD quarter panel, massive cracks appeared. Meeting with whole country welding community, including Edison Welding Institute, concluded we'd never learn to repair this material, and that a change of weld wire was considered futile.
- Welding – Material didn't like excessive heat, required weld torch speeds 2.5 times that used on 2219 Al (10 inches/min vs 4 inches/min). Weld nugget formed crystalline structure called equiax zone, very brittle. Repairs caused this zone to grow until residual stress caused failure, the more repairs the worse it got.
- First attempts to form dome and ogive gores at vendor Aircraft Hydroforming (AHF) broke their stretch press. Energy release almost brought building down.
- Early Reynolds material had erratic cryo fracture toughness properties.

History of Aluminum-Lithium Highlights

So

Super Lightweight ET started

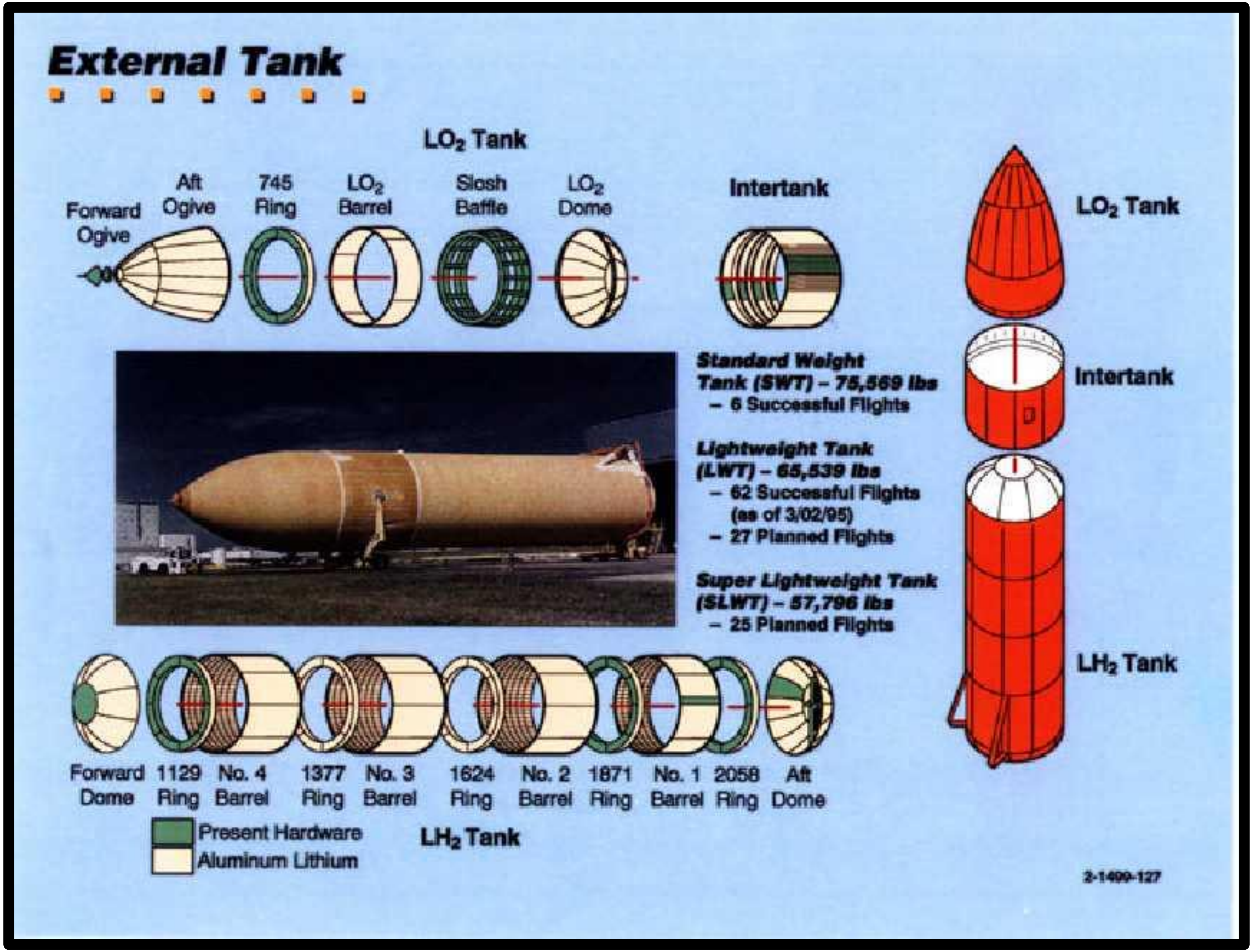
- 4 months behind schedule
- The supplier couldn’t make the material
- Martin couldn’t weld it
- Martin couldn’t repair the weld
- The supplier couldn’t form it
- Cryo fracture properties were erratic
- Al-Li cost 2.5 time the previous Al

- In order to achieve the weight savings two major changes, and many smaller changes were made.
  - Basic material changed to Al-Li from previous Al-Cu alloy.
  - Hydrogen tank barrel panels changed from “T-stiffened” to “Orthogrid.”

History of Aluminum-Lithium Highlights

Unique Test/Analysis methods were developed for SLWT

- Material simulated service testing
- Wide panel certification of weld repairs
- Langley Finite Element NASTRAN stability model of Ogive
- Top level verification program team
- Back side purge for Al-Li Welding
- Alternate side grind/weld for repairs
- VOPS and machined Foam

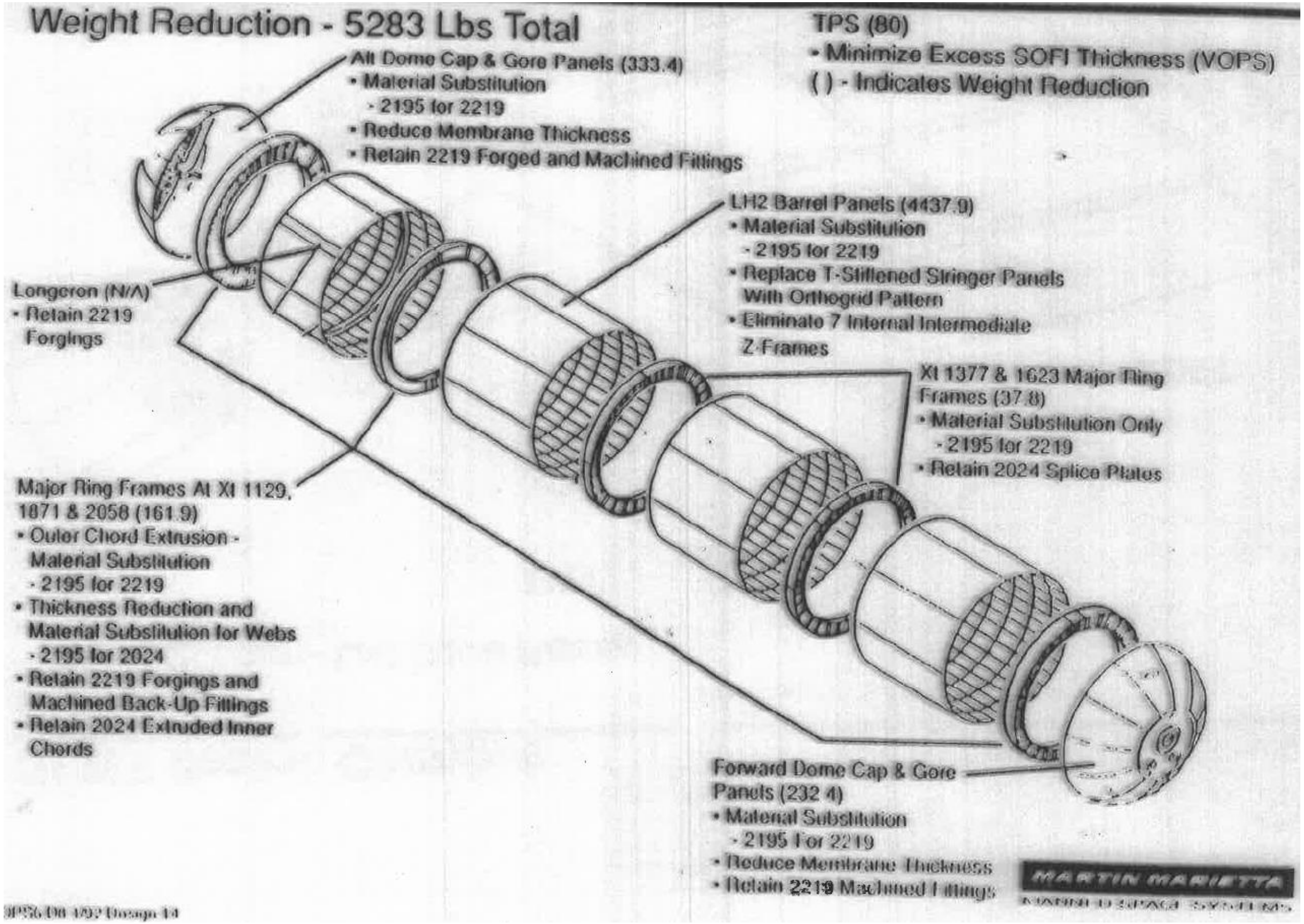

External Tank
LO2 Tank
Forward Ogive
Aft Ogive
745 Ring
LO2 Barrel
Slosh Baffle
LO2 Dome
Intertank
LO2 Tank
Intertank
LH2 Tank
Standard Weight Tank (SWT) – 75,569 lbs
– 6 Successful Flights
Lightweight Tank (LWT) – 65,539 lbs
– 62 Successful Flights (as of 3/02/95)
– 27 Planned Flights
Super Lightweight Tank (SLWT) – 57,796 lbs
– 25 Planned Flights
Forward Dome
1129 Ring
No. 4 Barrel
1377 Ring
No. 3 Barrel
1624 Ring
No. 2 Barrel
1871 Ring
No. 1 Barrel
2058 Ring
Aft Dome
Present Hardware
Aluminum Lithium
LH2 Tank
2-1499-127

Weight Reduction Summary

Weight Reduction by Assembly and design Change

Assembly	Predicted LWT (ET-71)	Weight Reduction Candidates: Al-Li Design	VOPS	Machined TPS	Design Optimization	Total	Predicted SLWT (ET-91)
LO2 Tank	12667	1700	16		75	-1791	10876
Intertank	12885	479		271	179	-929	11956
LH2 Tank	29458	2710	80		2493	-5283	24175
Other	10439	—	—	—	—	—	10439
Dry Weight	65449	4889	96	271	2747	-8003	57446

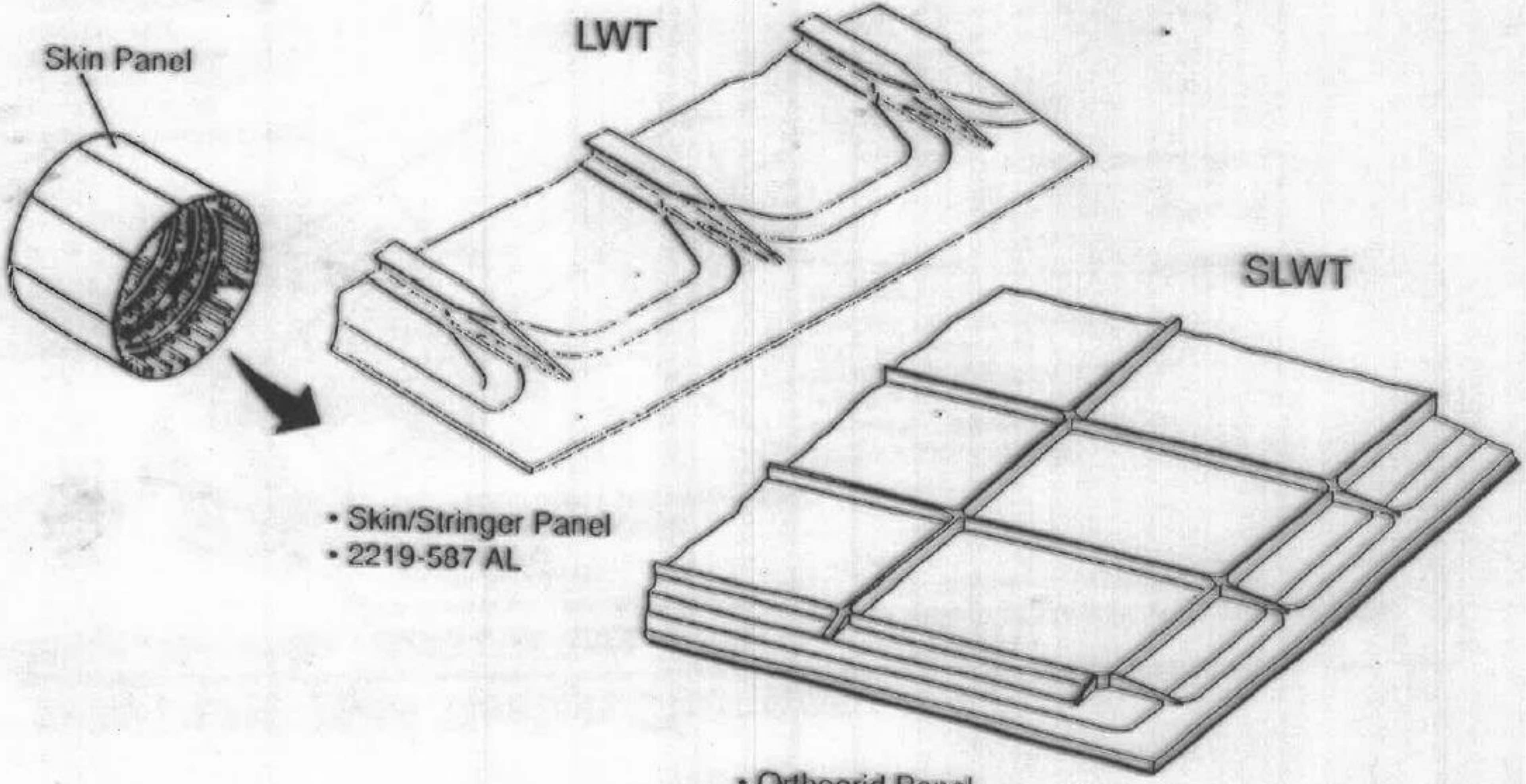
SLWT LH2 Tank Design Changes



SLWT Design Changes

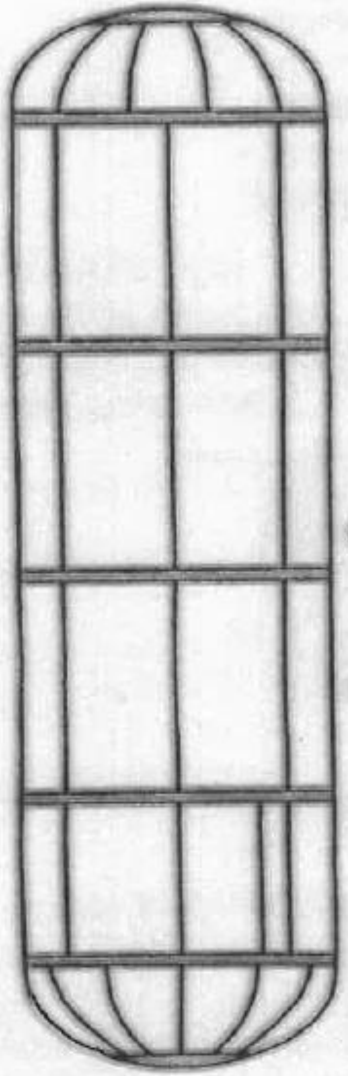
Example

- Major Redesign - LH2 Barrel Panels



MARTIN MARIETTA
MANNED SPACE SYSTEMS

LH2 Tank Process and Material Changes for SLWT

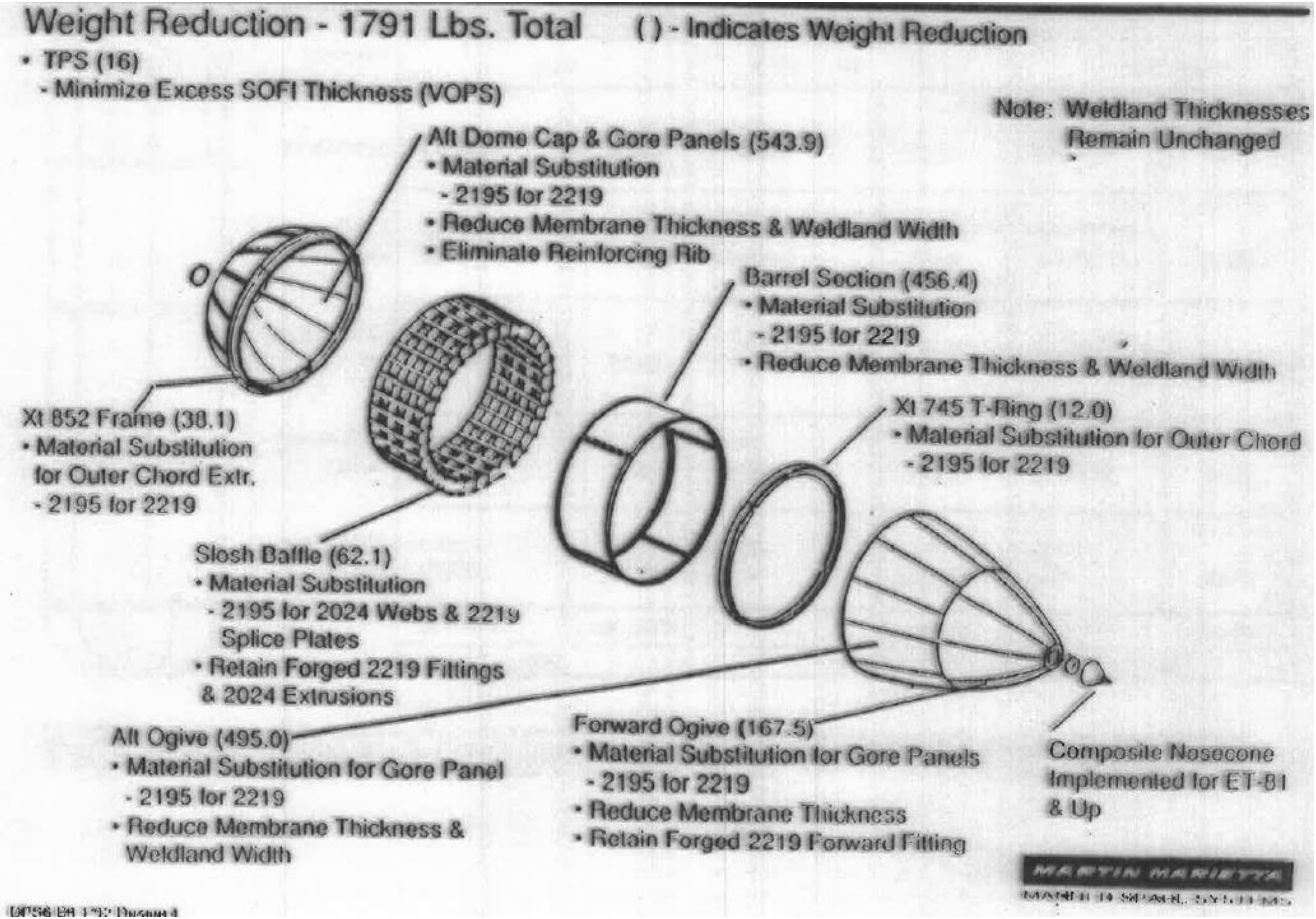


	SWT		LWT		SLWT	
	Process	Material	Process	Material	Process	Material
Dome Caps (typ)	Bulge form	2219	Spin form	2219	Spin form	**2195**
Dome Gores (typ)	Stretch form	2219	Stretch form	2219	Stretch form	**2195**
Frame Chords (typ)	Bump form + stretch	2219	Bump form + stretch	2219	**Bump form + stretch**	**2195**
Barrel Panels (typ)	Machine skin stringer	2219	Machine skin stringer	2219	**Machine orthogrid**	**2195**
Longerons	Forging	2219	Forging	2219	Forging	2219
Weld Process	GTA		GTA ➡ VPPA		70% VPPA	

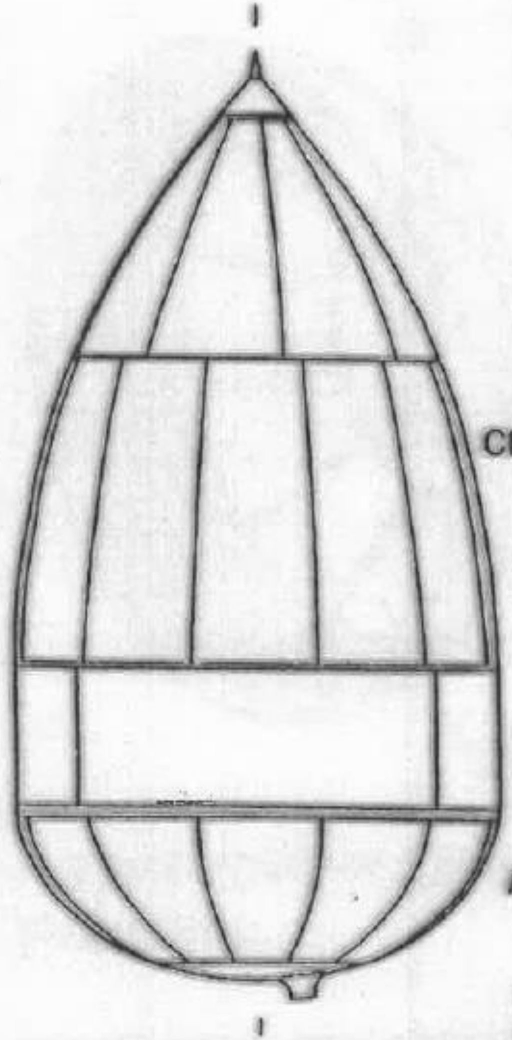
Bold type indicates SLWT change

MARTIN MARIETTA
MANNED SPACE SYSTEMS

SLWT LO2 Tank Design Changes



LO2 Tank Process and Material Changes for SLWT

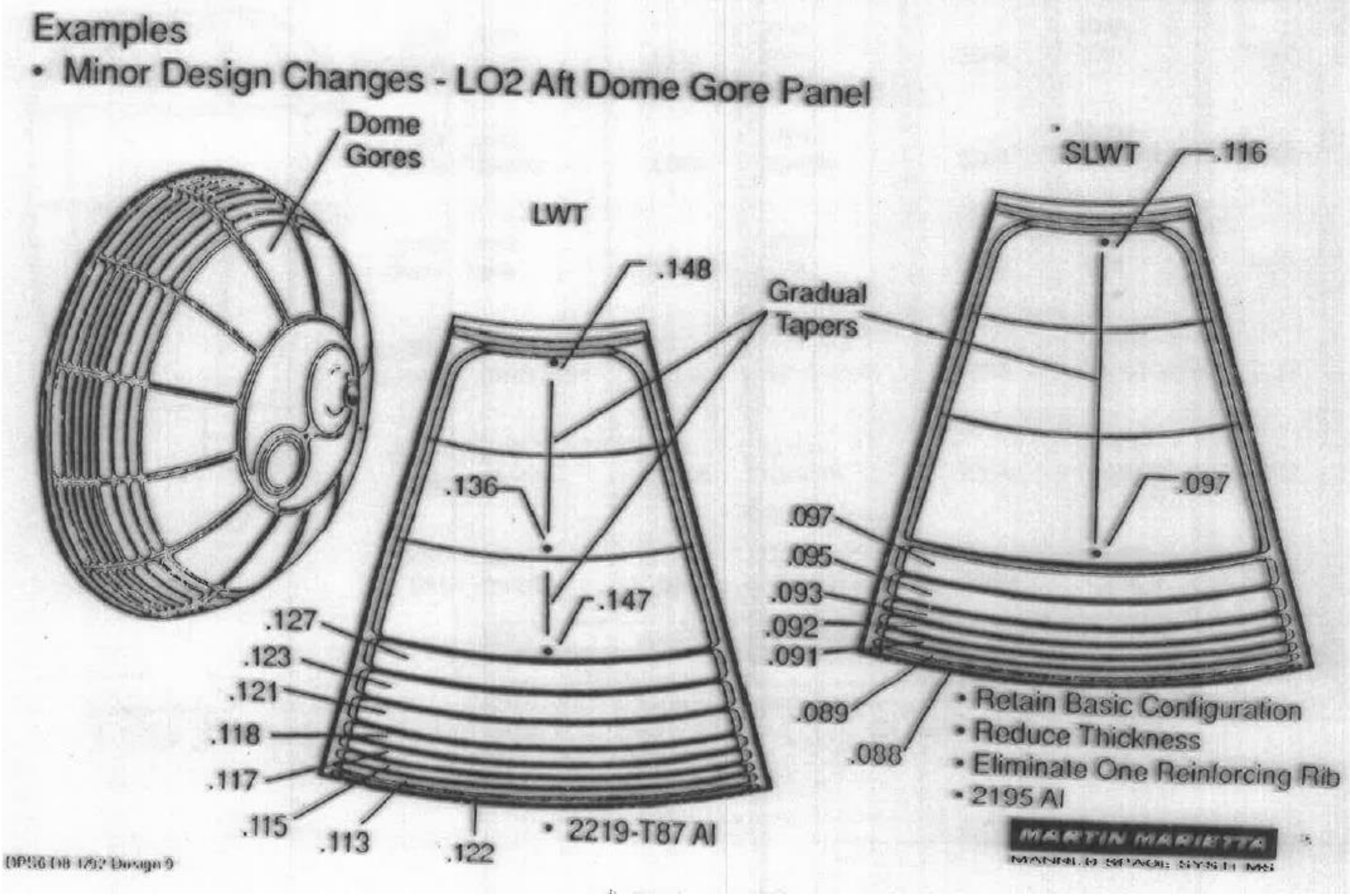


	SWT		LWT		SLWT	
	Process	Material	Process	Material	Process	
Fwd Ogive	Stretch Form	2219	Stretch form	2219	Stretch form	2195
Aft Ogive	Stretch form	2219	Stretch form	2219	Stretch form	2195
Frame Chord (typ)	Bump form + stretch	2219	Bump form + stretch	2219	Bump form + stretch	2195
Barrel Panel	Roll form	2219	Roll form	2219	Roll form	2195
Dome Gores	Stretch form	2219	Stretch form	2219	Stretch form	2195
Aft Dome Cap	Bulge form	2219	Spin form	2219	Spin form	2195
Weld Process	GTA		GTA ➡ VPPA		93% VPPA	

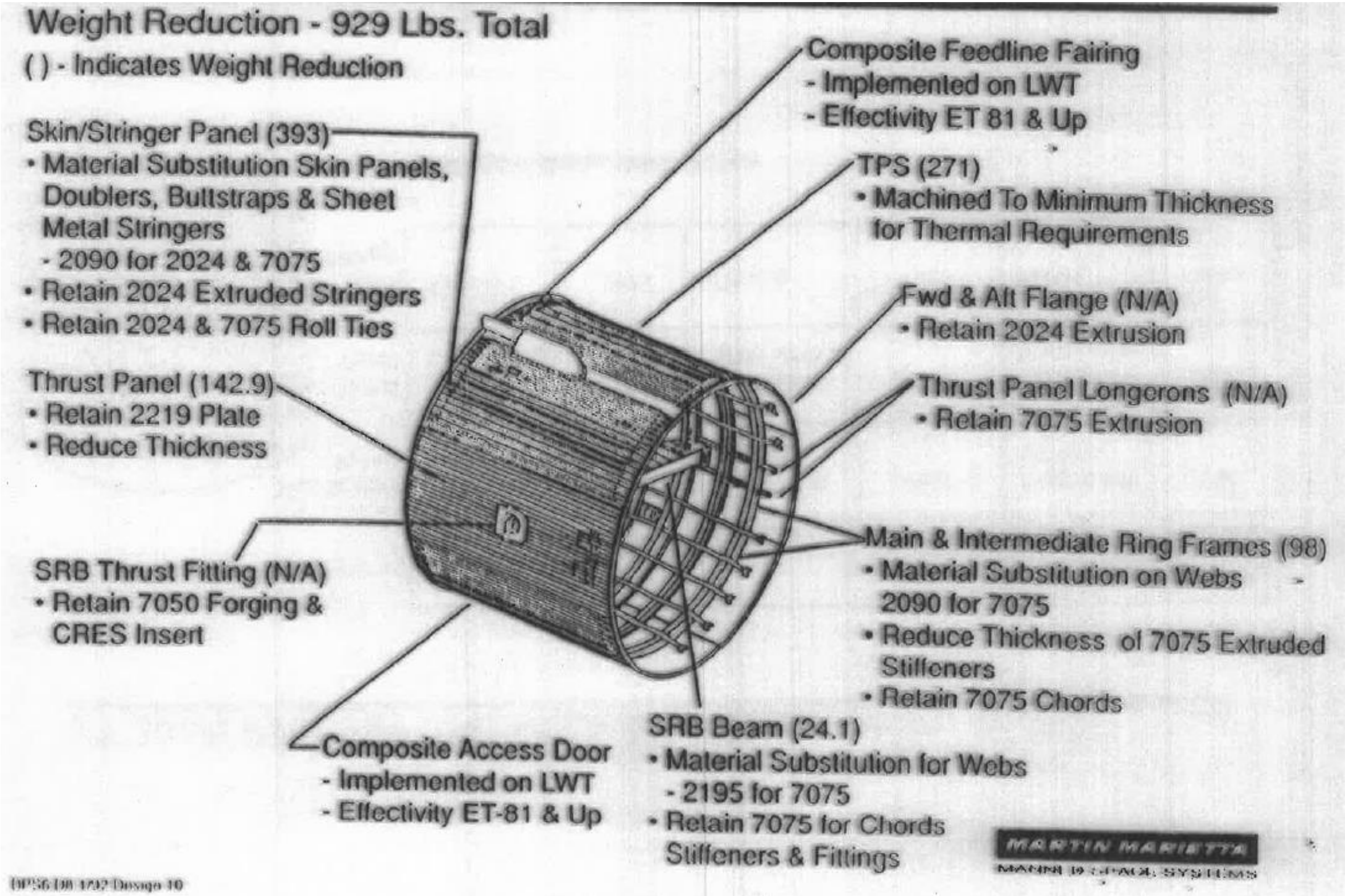
Bold type indicates SLWT change

MARTIN MARIETTA
MANNED SPACE SYSTEMS

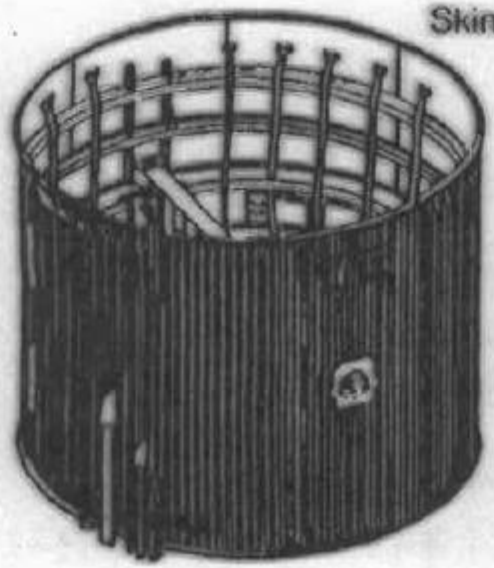
SLWT Design Changes



SLWT Intertank Design Changes



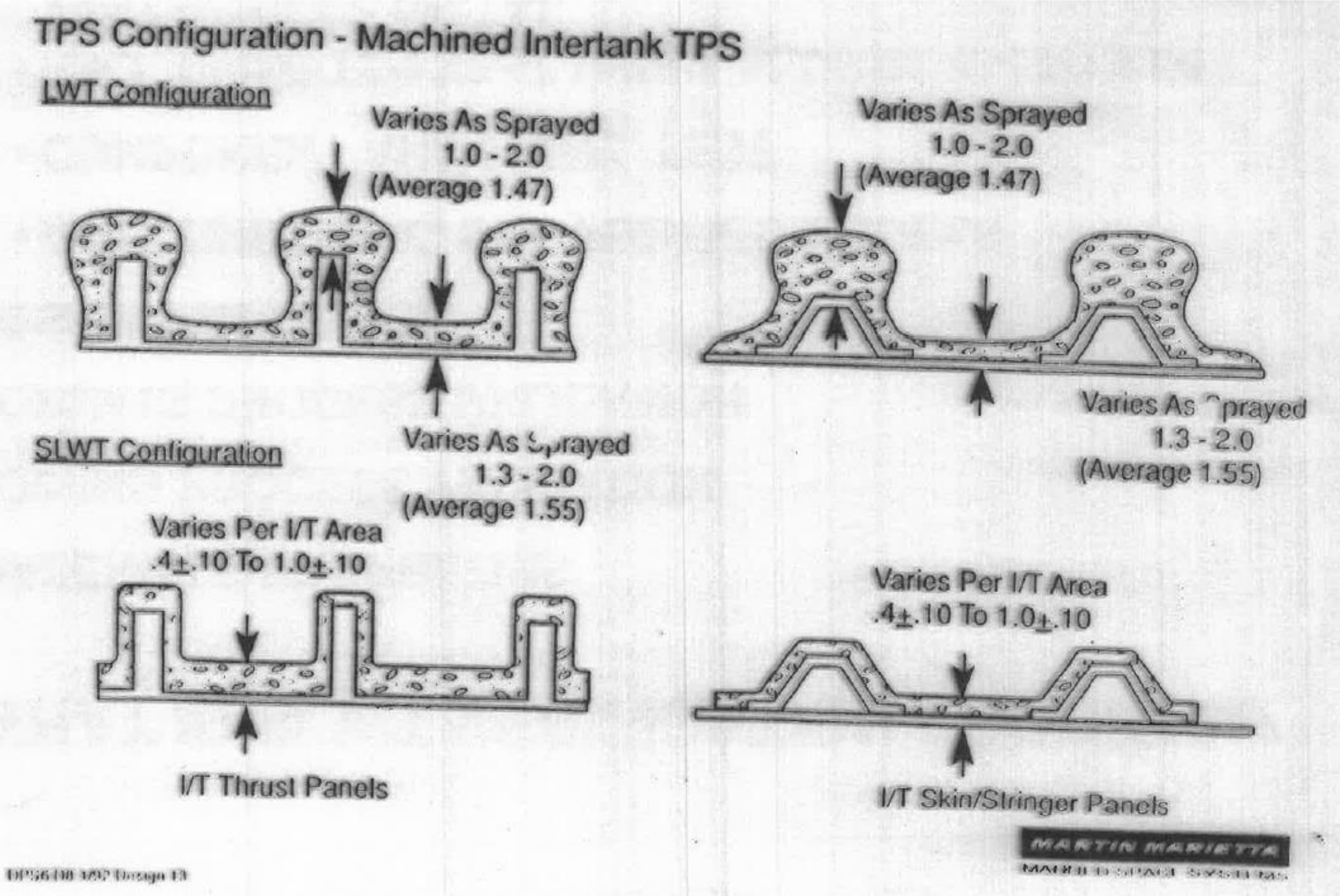
I/T Tank Process and Material Changes for SLWT



	SWT		LWT		SLWT	
	Process	Material	Process	Material	Process	Material
Skin Stringer Panels	Riveted hat sections	2024	Riveted hat sections	2024	Riveted hat sections	2090
Thrust Panel	Machined & brake formed	2219	Machined & brake formed	2219	Machined & brake formed	2219
SRB Fittings	Forging	7075	Forging	7050	Forging	7050

Bold type indicates SLWT change

SLWT Intertank Design Changes



What is SLWT verification program?

- Materials Properties
- Joining process validation
- Forming process validation
- Design validation
  - Analysis using STA verified modes
  - Component and panel test
  - Full diameter test using Al-Li test article (ALTA)
  - Test prototype Hydrogen tank

Structural Verification

ET Structural Test Evolution

SWT

- Major development tests
  - 10% scale slosh
  - Forward and aft SRB attach fittings
- Subassembly strength tests
  - ET/Orbiter Interface hardware
  - LO2 slosh baffle
- STA Program
  - Intertank static strength
  - LO2 static strength
  - LH2 static strength
  - LO2 model survey
- Ground Vibration Test Program
  - Full scale ET
- Components Qualification
  - Static strength
  - Vibration
- Secondary structure verification
  - Static strength and capability
  - Vibration
- Proof tests
  - LO2 tank
  - LH2 tank
  - Propulsion lines

LWT

- Development/Verification tests
  - LH2 skin stringer panels
  - 2058 frame stability
- Interface hardware bench tests
  - Forward and aft SRB fittings
  - Forward and aft ET/Orbiter hardware
- LWT-1 Influence coefficient test
  - 2058 frame stiffness
- LWT-2 limit load test
  - Aft LH2 barrel and frames
- New/changed components qualification
  - Static strength
  - Vibration
- Secondary structure
  - Static strength and capability
- Proof tests
  - LO2 tests
  - LH2 tank
  - Propulsion lines

SLWT

- Element component tests
  - Orthogrid panels
  - Frame webs
  - Intertank skin/stringers
  - Biaxial specimens
- ALTA verification tests
  - Flight equivalent loads
  - Flight configuration barrel
  - LH2 orthogrid panel stability
  - Proof test
- SLWT-1 LH2 limit load test
  - Similar to LWT-2 test
  - Influence coefficient test
  - Barrel panel stability
  - Aft dome pinch load stability
- New/changed components qualification
  - Static strength
  - Vibration
- Secondary structure
  - Static strength and capability
- Proof tests
  - LO2 tests
  - LH2 tank
  - Propulsion lines

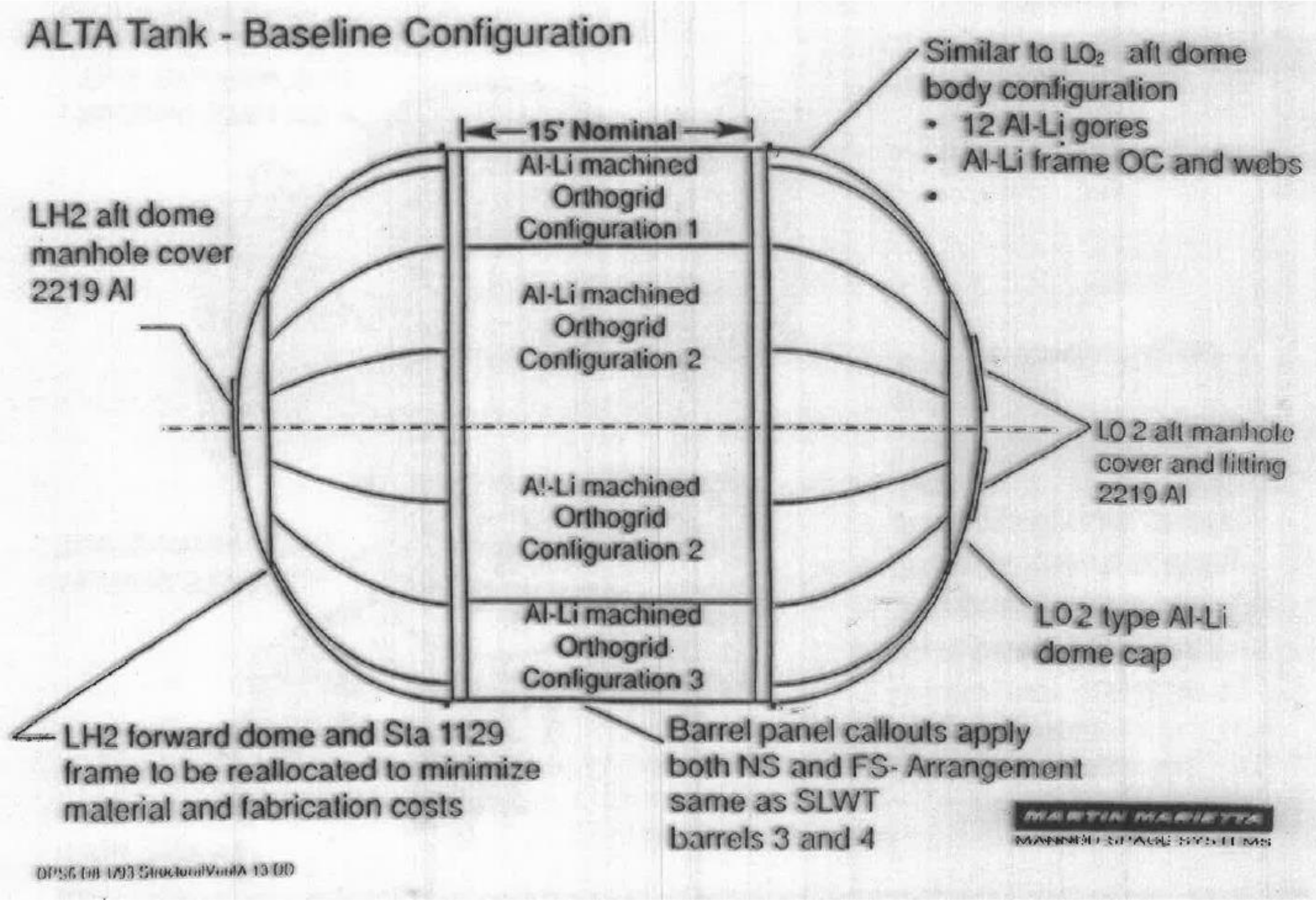
MARTIN MARIETTA
MANNED SPACE SYSTEMS

ET Structural Verification Test Evolution Matrix

Hardware	SWT				LWT					SLWT				
	Analysis	STA	Bench Test	Proof	Analysis	Post STA	Bench Test	Proto flight	Proof	Analysis	ALTA	Comp. Tests	Proto flight	Pro
LO2 Tank														
• Frame 745	X	X		X	X				X	X				X
• Ogive	X	X		X	X				X	X				X
• Barrel	X	X		X	X				X	X				X
• Aft dome	X	X		X	X				X	X	X			X
• Frame 851	X	X			X					X				
Intertank														
• Panels	X	X			X					X		X		
• Frame 985	X	X			X					X				
• Intermediate frames	X	X			X					X				
• Thrust beam	X	X			X					X				
• Thrust fitting	X	X	X		X		X			X				
• Frame stabilizers	X				X					X				
LH2 tank								I/C LWT-1					I/C SLWT-1	
• Forward dome	X	X		X	X				X	X				X
• Aft dome	X	X		X	X			LWT-2	X	X	X		X	X
• Major frames	X	X			X	X		LWT-2		X		X	X	
• Intermediate frames	X	X		X	X				X	X				X
• Barrels	X	X		X	X	X		LWT-2	X	X	X		X	X
• Longerons	X	X			X			LWT-2		X			X	
Interface														
• Forward bipod	X	X	X		X		X			X				
• Thrust strut	X	X	X		X		X			X				
• Vertical strut	X	X	X		X		X			X				
• Ball fitting	X	X	X		X		X			X				
• Diagonal strut	X	X	X		X		X			X				
• Crossbeam	X	X	X		X		X			X				
• Tank fittings	X	X	X		X		X			X				

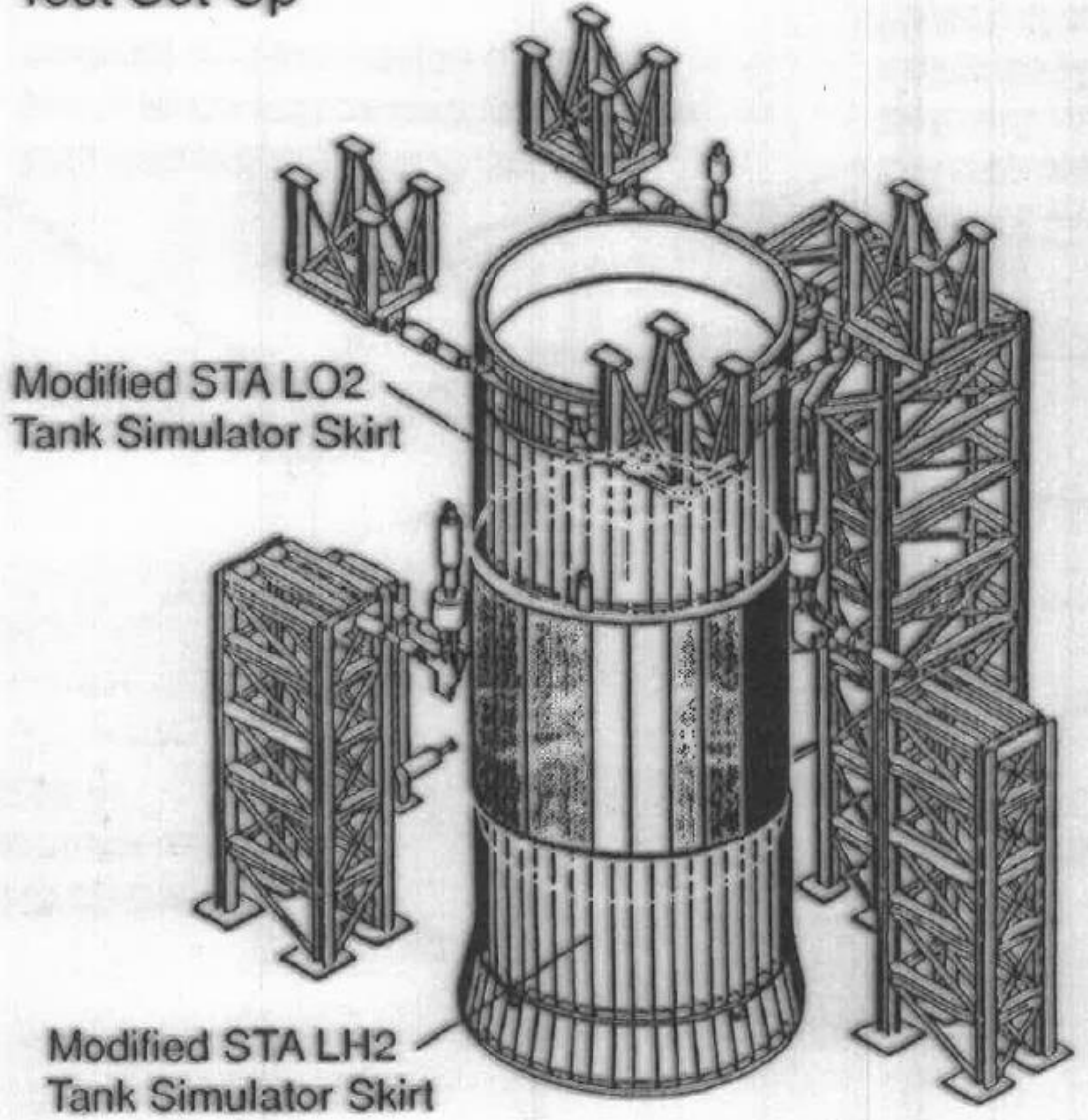
MARTIN MARIETTA
MANNED SPACE SYSTEMS

ALTA Testing



ALTA Testing

Test Set-Up

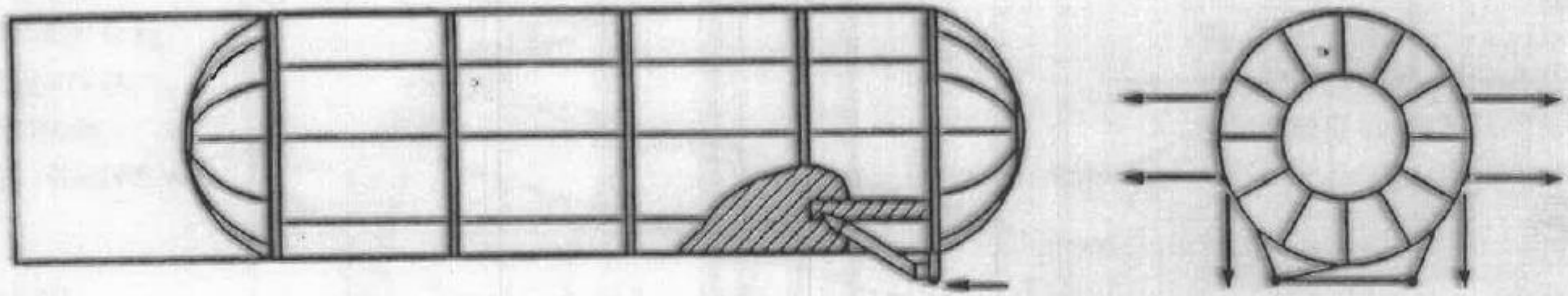


- 13 conditions @ RT
- Pressure test
- 3 influence coefficient
- Simulated flight loads
- 3 unpressurized stability
- 3 low pressure stability
- 3 high pressure stability
- Test at (MSFC)
- Limit, ultimate, zero margin MS
- AFT LO_2 Dome stability test

MARTIN MARIETTA
MANNED SPACE SYSTEMS

Protoflight Testing

SLWT Limit Load Verification Test at MAF



Purpose
- Confirm load level and distribution in longeron area and aft dome region
- Demonstrate limit load capability of barrel and aft dome

Plan
- Instrument first SLWT LH2 Tank
- Monitor and evaluate load levels
- Test all tanks at 115%

Requirements
Instrumented LH2 Tank
- Influence coefficient tests (6)
- Flight equivalent PO condition compression test (1)
- Dome pinch load test (1)
- Forward barrels pressurized compression stability (1)
- Proof acceptance tests (5)

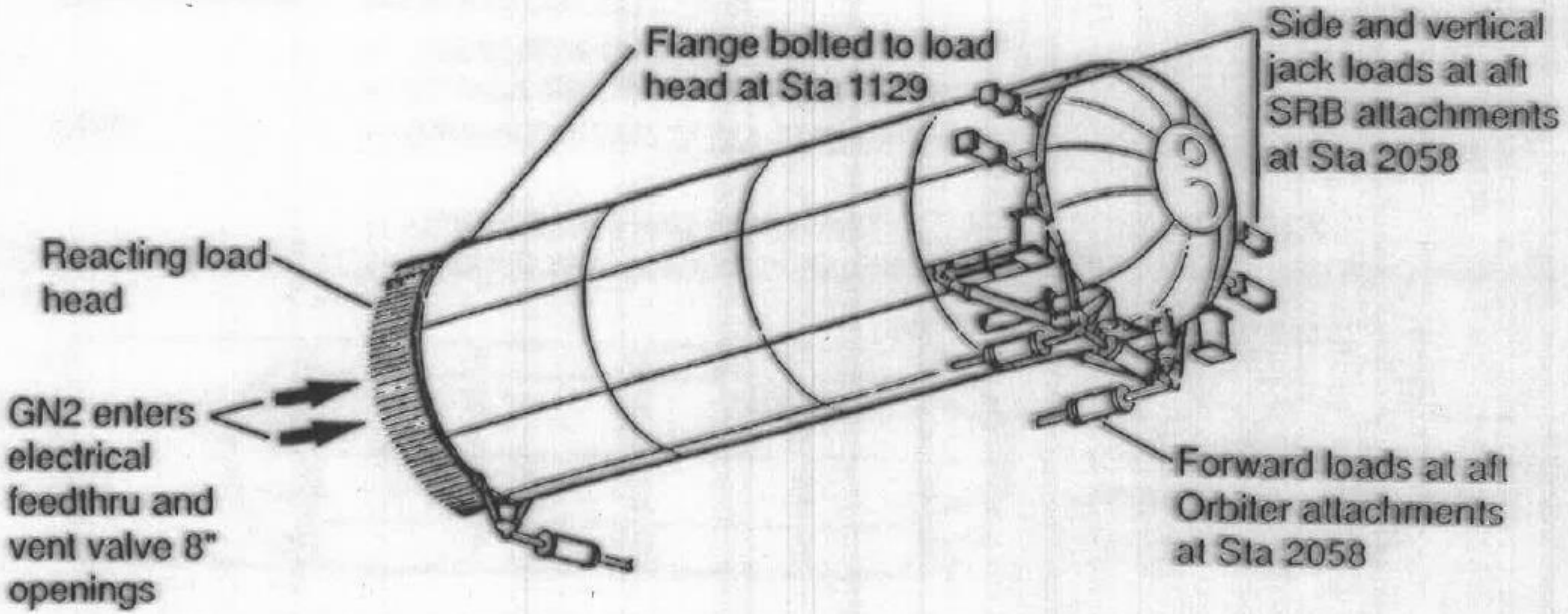
Test Bldg 451

MARTIN MARIETTA
MANNED SPACE SYSTEMS

Protoflight Testing

LH2 Tank Proof Test

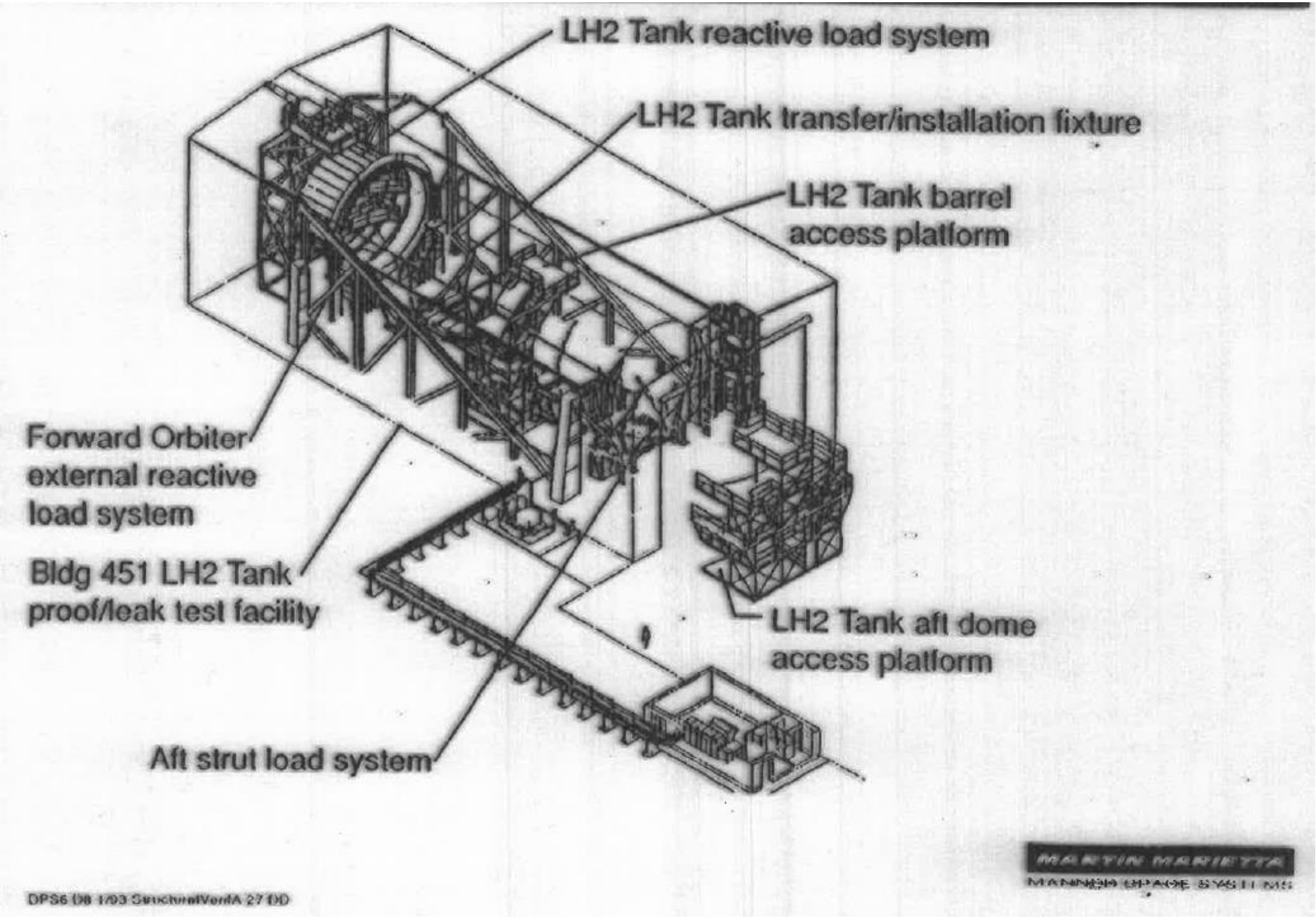
- Pressurize to between 40.7 and 41.3 psig with GN2 under controlled temperature
- Supplement pressure with jack loads to provide required tensile proof stresses
- Record pressures, loads, temperatures, and time
- Leak check and visually inspect for damage after proof test



LH2 Tank is horizontal with Orbiter side down in test facility

MARTIN MARIETTA
MANNED SPACE SYSTEMS

Protoflight Testing



Thank You