Loads and Sizing for Launch Vehicle Conceptual and Preliminary Design

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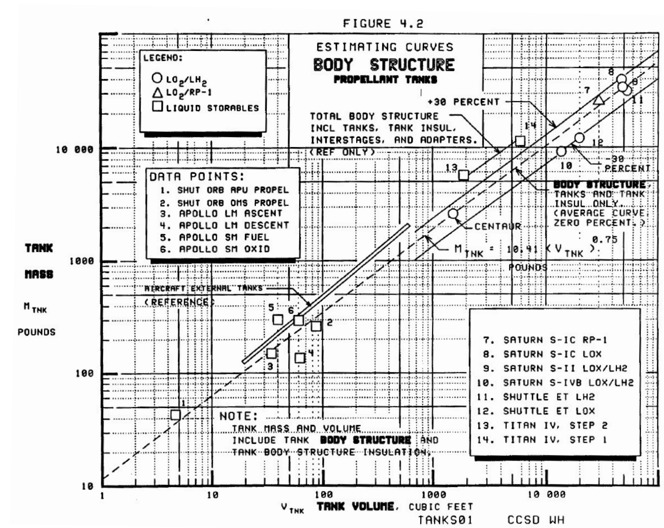
Talk Overview

- Mass estimation methods
- Apollo Program
  - LOR mission overview
  - Saturn V launch vehicle description
  - Loads and sizing for selected components
- Space Shuttle and Ares V
  - Launch vehicle overview
  - First stage load paths analysis
  - Loads and sizing for selected components
- Concluding remarks
- References

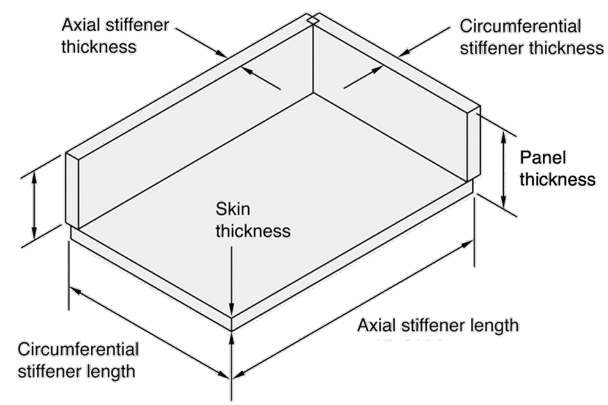
Mass Estimation Methods

Design levels (continuum across mission phases)
- Conceptual (Phases pre-A/A)
- Preliminary (Phases B/C)
- Detail (Phases C/D)

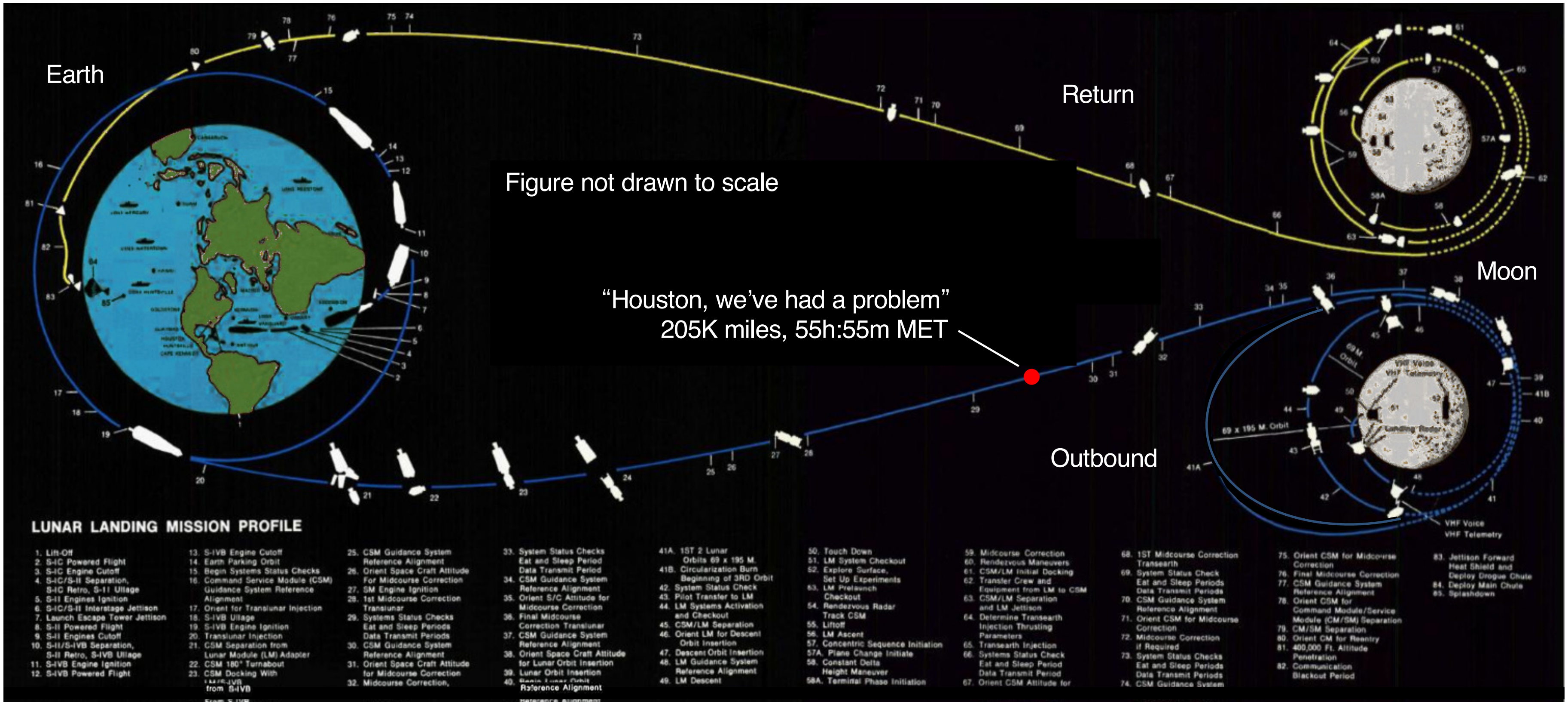


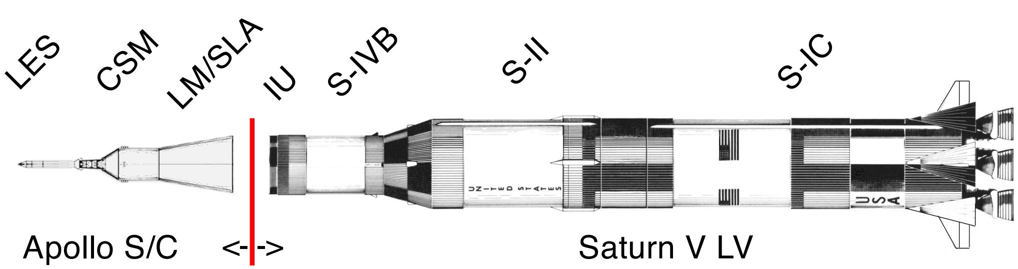
"Top-down" systems-level modeling
- Curve fits to historical data
- Quick, but low-fidelity
- Conceptual-level design

"Bottom-up" component-level modeling
- Physics-based analysis
- Takes more time, but high(er)-fidelity
- Preliminary/detail-level design



Apollo Program LOR Mission Profile

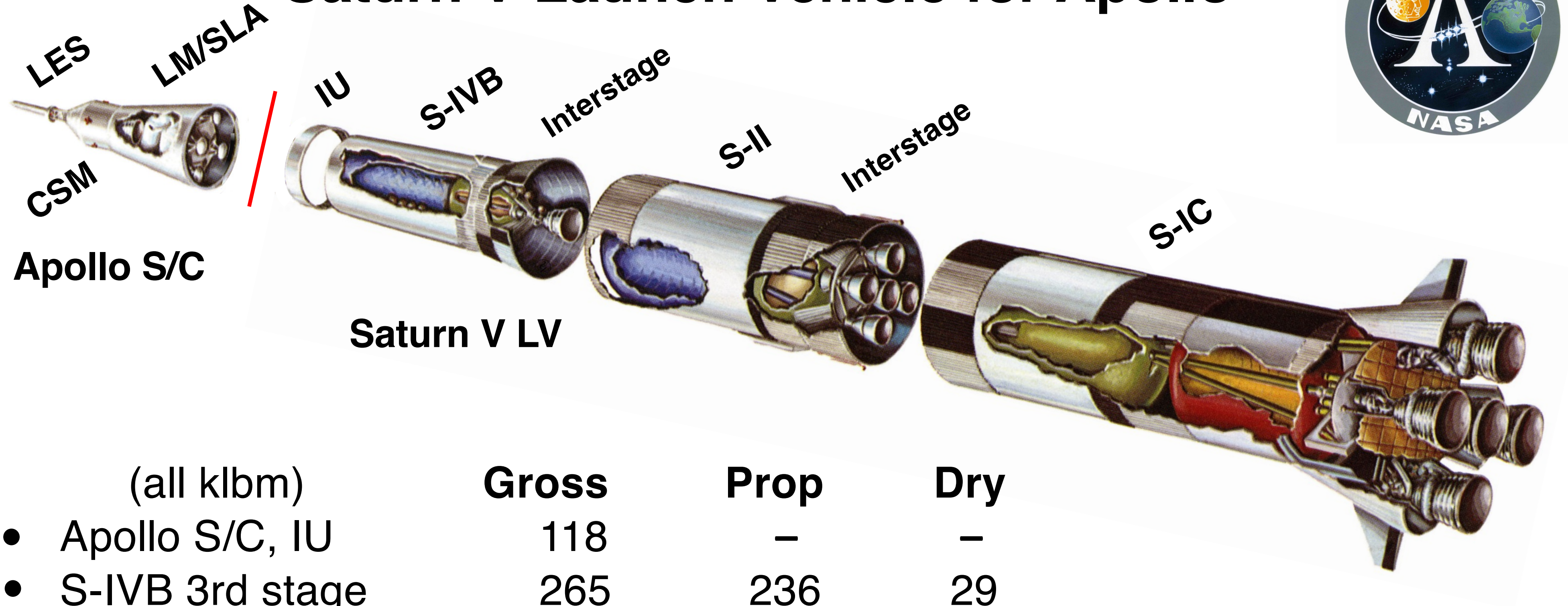




Significant schedule, cost, performance advantages over other proposed modes

Decouples S/C, LV designs

Saturn V Launch Vehicle for Apollo

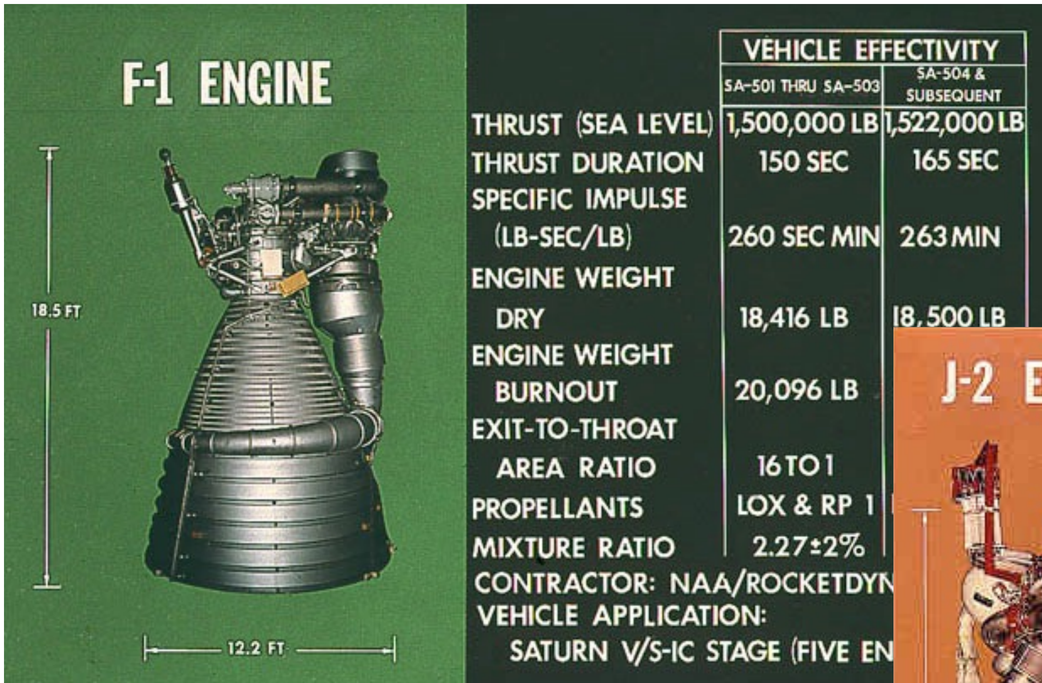


(all klbm)	Gross	Prop	Dry
• Apollo S/C, IU	118	–	–
• S-IVB 3rd stage	265	236	29
- 1 x J-2 LO2/LH2	(8 interstage)		
• S-II 2nd stage	1090	998	92
- 5 x J-2 LO2/LH2	(11 interstage)		
• S-IC 1st stage	5039	4683	355
- 5 x F-1 LO2/RP-1 oxidizer/fuel			

Gross Liftoff
6530 klbm

Avg Stage SMF, pct.
7.5 (5.9 w/o eng.)

Saturn V Engine Systems



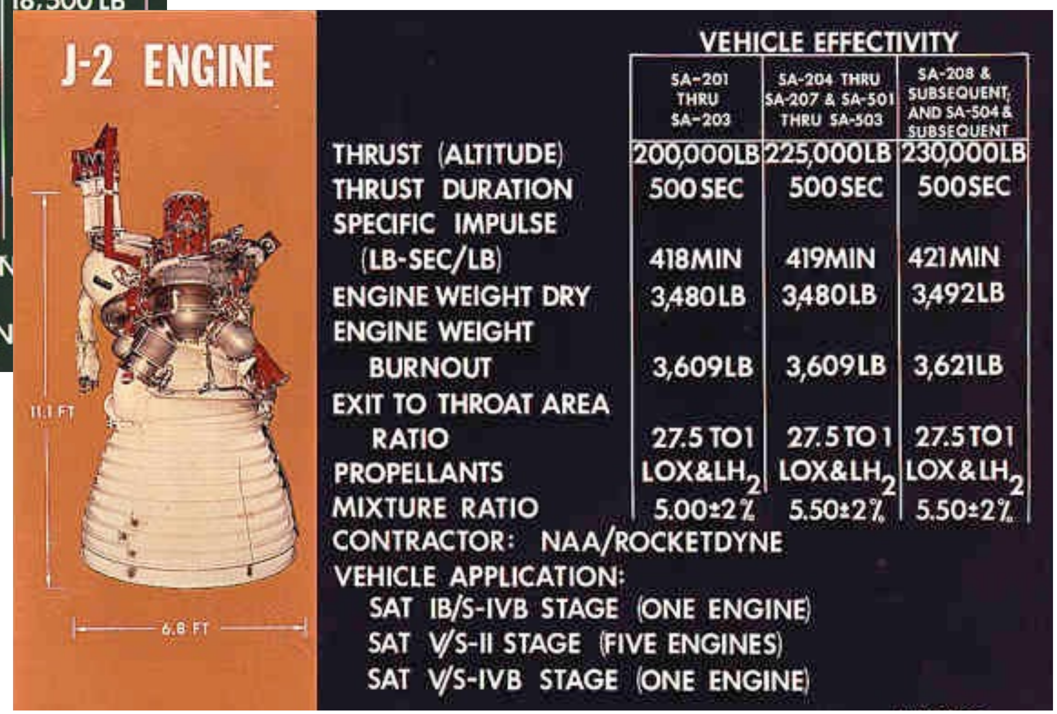
F-1 ENGINE

	VEHICLE EFFECTIVITY	
	SA-501 THRU SA-503	SA-504 & SUBSEQUENT
THRUST (SEA LEVEL)	1,500,000 LB	1,522,000 LB
THRUST DURATION	150 SEC	165 SEC
SPECIFIC IMPULSE (LB-SEC/LB)	260 SEC MIN	263 MIN
ENGINE WEIGHT DRY	18,416 LB	18,500 LB
ENGINE WEIGHT BURNOUT	20,096 LB	
EXIT-TO-THROAT AREA RATIO	16 TO 1	
PROPELLANTS	LOX & RP 1	
MIXTURE RATIO	2.27±2%	

CONTRACTOR: NAA/ROCKETDYN
VEHICLE APPLICATION:
SATURN V/S-IC STAGE (FIVE EN

1st stage F-1

- Low Isp, High thrust
- LO2/RP-1 prop



J-2 ENGINE

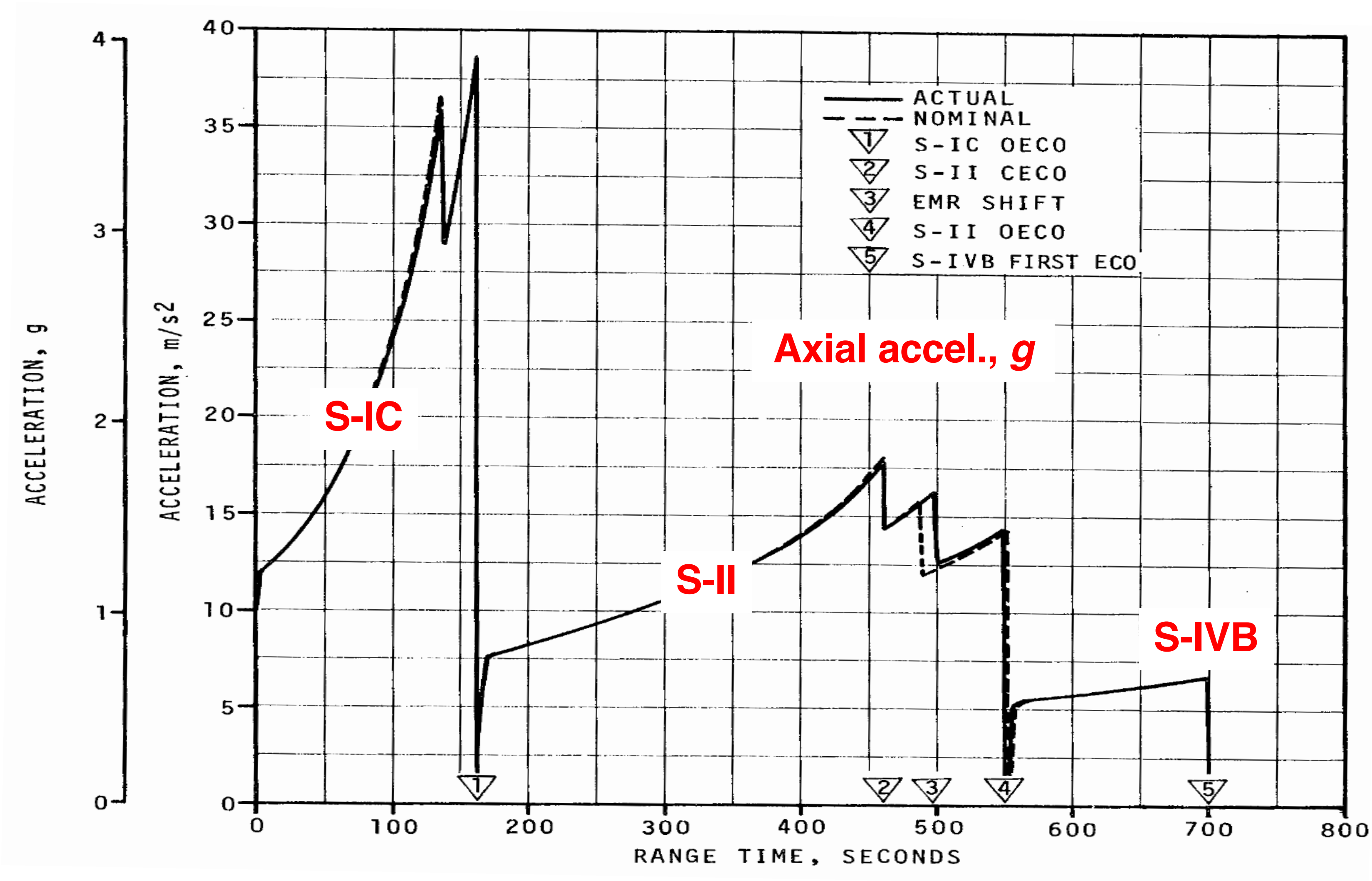
	VEHICLE EFFECTIVITY		
	SA-201 THRU SA-203	SA-204 THRU SA-207 & SA-501 THRU SA-503	SA-208 & SUBSEQUENT, AND SA-504 & SUBSEQUENT
THRUST (ALTITUDE)	200,000LB	225,000LB	230,000LB
THRUST DURATION	500 SEC	500 SEC	500 SEC
SPECIFIC IMPULSE (LB-SEC/LB)	418 MIN	419 MIN	421 MIN
ENGINE WEIGHT DRY	3,480 LB	3,480 LB	3,492 LB
ENGINE WEIGHT BURNOUT	3,609 LB	3,609 LB	3,621 LB
EXIT TO THROAT AREA RATIO	27.5 TO 1	27.5 TO 1	27.5 TO 1
PROPELLANTS	LOX & LH_2	LOX & LH_2	LOX & LH_2
MIXTURE RATIO	5.00±2%	5.50±2%	5.50±2%

CONTRACTOR: NAA/ROCKETDYNE
VEHICLE APPLICATION:
SAT IB/S-IVB STAGE (ONE ENGINE)
SAT V/S-II STAGE (FIVE ENGINES)
SAT V/S-IVB STAGE (ONE ENGINE)

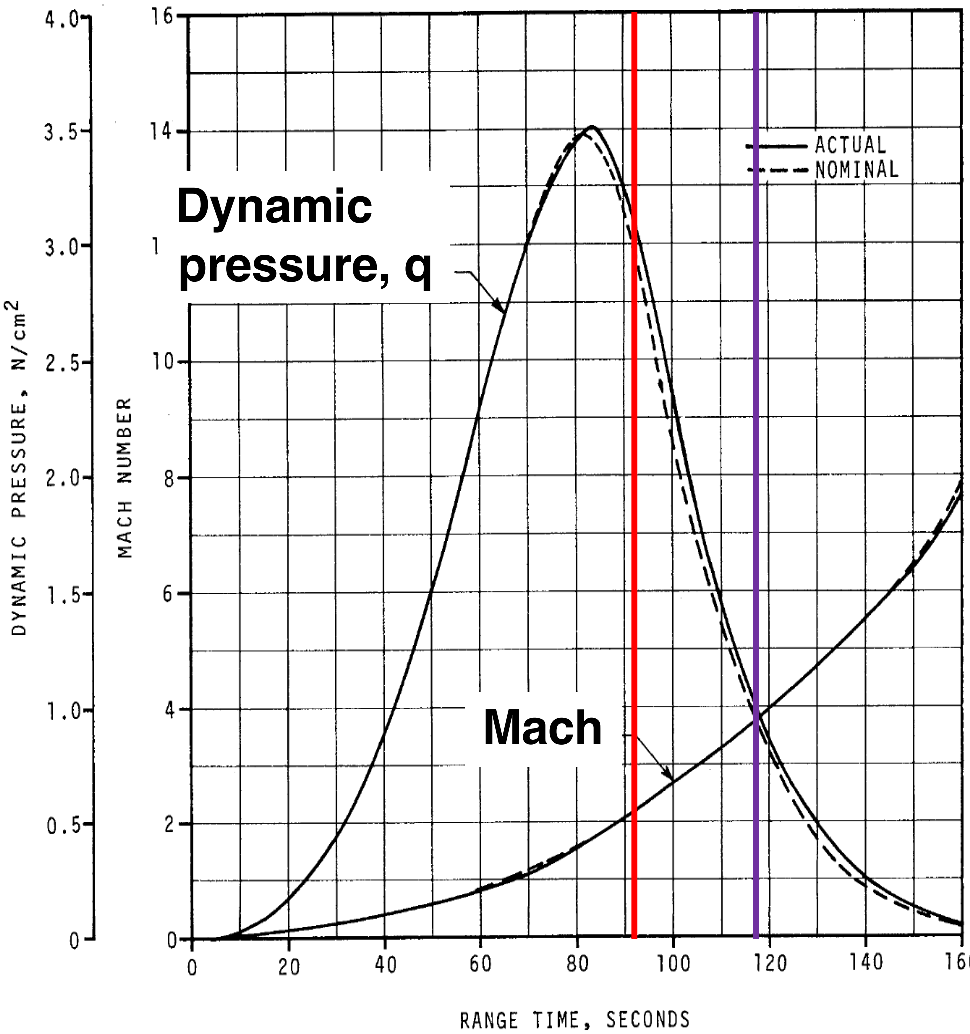
2nd & 3rd stage J-2

- High Isp, Low thrust
- LO2/LH2 prop

Saturn V Ascent Performance



Saturn V/S-IC Ascent Perf. (cont'd)



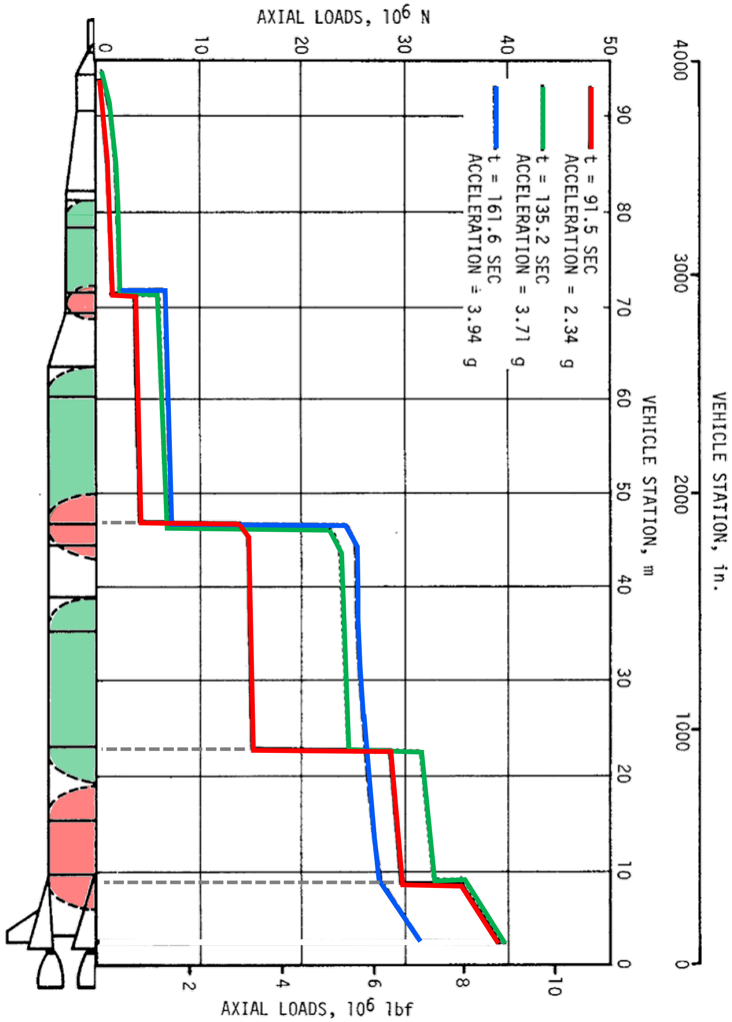
PARAMETERS	UNITS	PITCH PLANE	
		MAGNITUDE	RANGE TIME (SEC)
Attitude Error	deg	0.83	117.4
Angular Rate	deg/s	-0.97	69.1
Average Gimbal Angle	deg	0.23	90.6
Angle-of-Attack	deg	1.82	117.1
Angle-of-Attack/ Dynamic Pressure Product	deg-N/cm^2	4.93	91.4
Normal Acceleration	m/s^2	-0.331	95.5

Max. control params. in S-IC flight

Maximum dynamic pressure

- **3.5 N/cm^2 ~ 5.1 lbf/in^2**
- **Range time ~ 83 sec.**
- **~ 8 pct. > q at max. q-α**

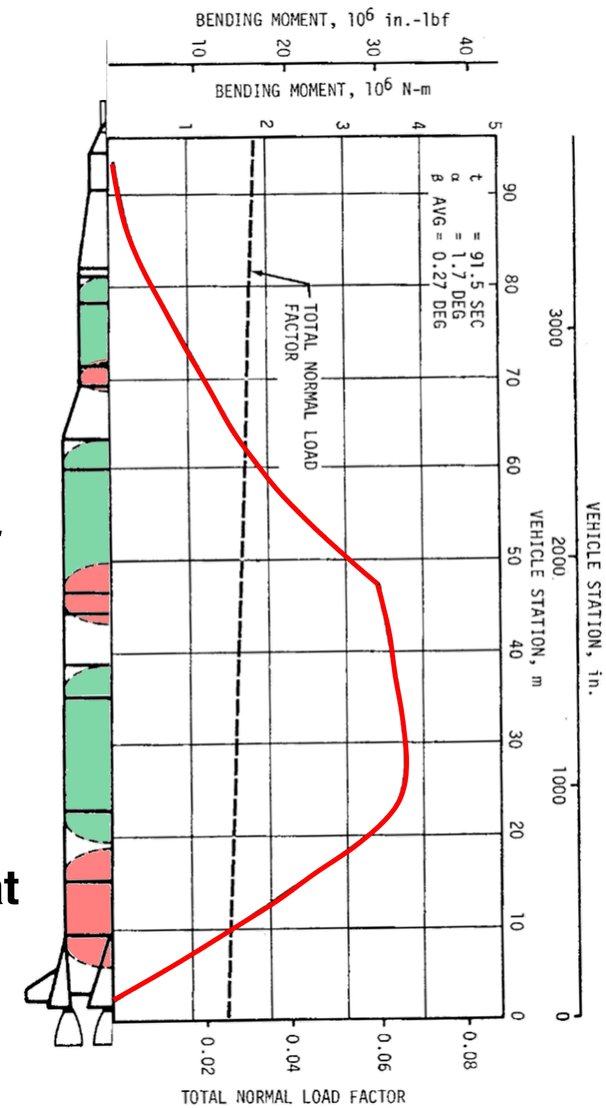
Saturn V/S-IC Flight Loads



Compression loads at max. q-α, S-IC CECO and OECO conditions

What about LV bending at liftoff and ECO?

Maximum bending moment at max. q-α condition



S-IC Intertank Mass Estimation

S-IC Intertank

- L = 22 ft, R = 33 ft/2
- Al 2024; ρ = 0.1 lbm/in^3, E = 10.1 Mlbf/in^2

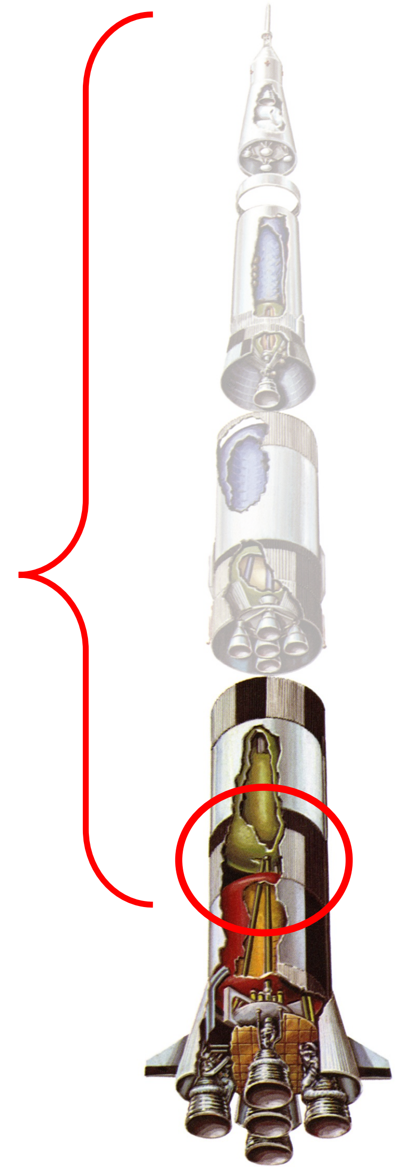
Liftoff load case

Vehicle mass above intertank aft ring
= (6530 – 1620) = 4910 klbm

Multiply by 1.2*g* at liftoff = 5892 klbf

Divide by (π*33 ft) for compression line
load Nx = 4736 lbf/in = σ_x*t

From NASA SP-8007, $\sigma_x = \gamma E t / R / \sqrt{3 - 3\mu^2}$
(cyl. shell buckling) $= 0.6 \gamma E t / R$ for $\mu = 0.3$



S-IC Intertank Mass Estimation (cont'd)

σx = (Nx = 4736 lbf/in)/t, R = 396 in./2

Apply FS = 1.4 to loads, and assume γ = 1

4736 lbf/in*1.4 FS/t = 0.6*1*10.1 Mlbf/in^2*t/198 in.

t^2 = (4736*1.4*198 in.)/(0.6*10.1e6)

t = 0.465 in. for monocoque shell wall

Estimate intertank mass = 2*π*R*t*L*ρ

Mass = π*396 in.*0.465 in.*264 in.*0.1 lbm/in^3

= 15.3 klbm

Compare to reported S-IC intertank mass of 13.2 klbm from Whitehead (+2.1 klbm; +16%)

S-IC/S-II Interstage Mass Estimation

S-IC/S-II Interstage

- L = 18.3 ft, R = 33 ft/2
- Al 2024; ρ = 0.1 lbm/in^3, E = 10.1 Mlbf/in^2

Liftoff load case

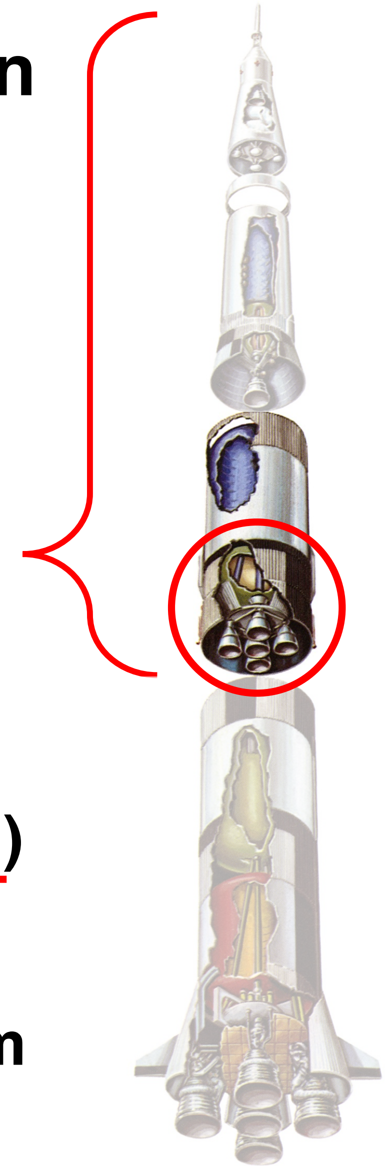
Vehicle mass above interstage aft ring
= (6530 – 5040) = 1490 klbm

Multiply by 1.2*g* at liftoff = 1788 klbf

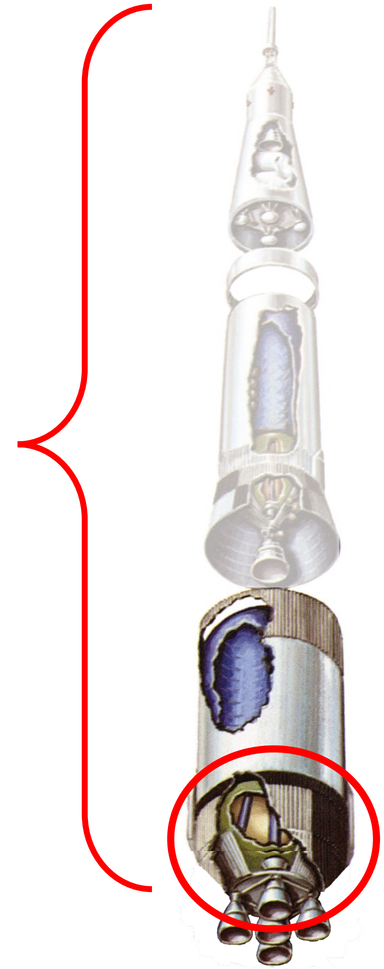
Divide by (π*33 ft) for compression line load
Nx = 1437 lbf/in (~ 1/3 of S-IC intertank load)

1437 lbf/in*1.4 FS/t = 0.6*1*10.1 Mlbf/in^2*t/198 in.

t = 0.256 in.; est. mass = 2*π*R*t*L*ρ = 7.0 klbm
(reported interstage mass = 9.7 klbm)



S-II Thrust Structure Mass Estimation



S-II Thrust Structure (conical frustum)

- L = 9.3 ft; R = 33 ft/2 fwd, 17.5 ft/2 aft
- Al 2024; ρ = 0.1 lbm/in^3, E = 10.1 Mlbf/in^2

S-II stage ignition load case

Vehicle mass = 1490 klbm; engine thrust = 5 x 230 klbf = 1150 klbf => F/mass = 0.77*g*

Compression line loads Nx = 1743 lbf/in aft, and 924 lbf/in forward

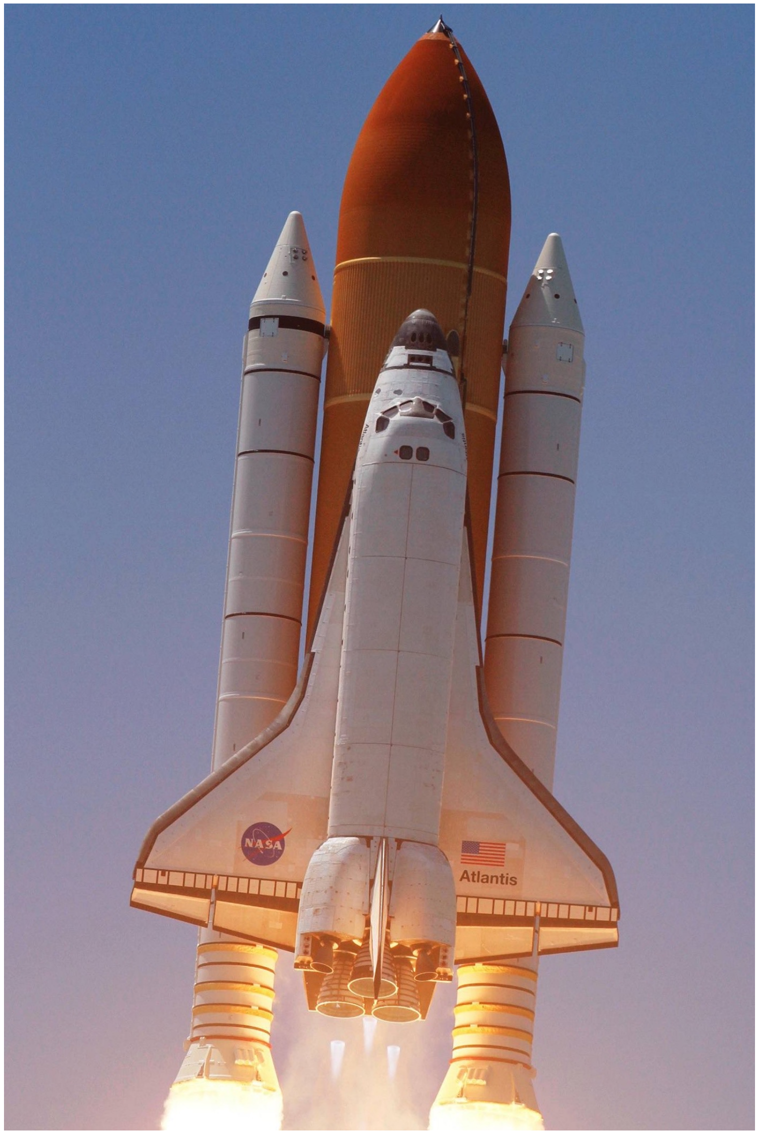
Buckling load from SP-8019, $P_{cr} = \gamma \dfrac{2\pi E t^2 \cos^2 a}{\sqrt{3(1-\mu^2)}}$

t^2 = 1.33*Pcr/E; t = 0.460 in.

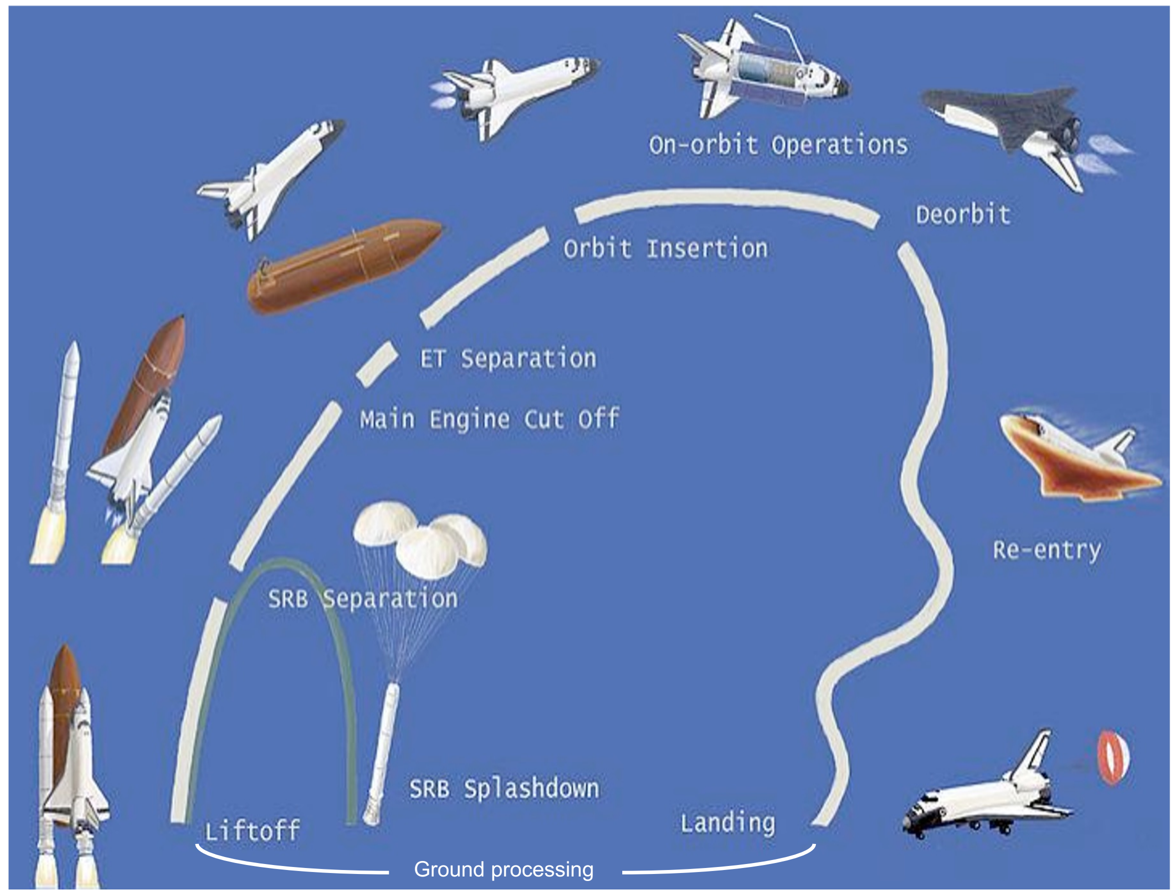
Est. mass = 2*π*Ravg*t*L*ρ/cosα = 6.4 klbm

(reported interstage mass = 7.3 klbm)

Space Transportation System

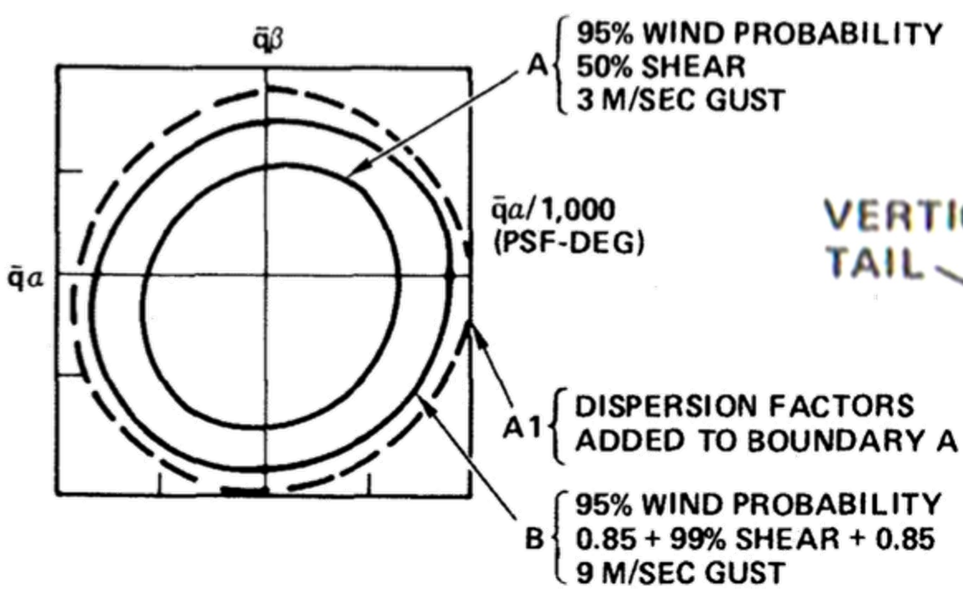


Space Shuttle composed of Orbiter with 3 LO2 / LH2 reusable engines (SSMEs), External Tank (ET), and 2 Solid Rocket Boosters (SRBs).

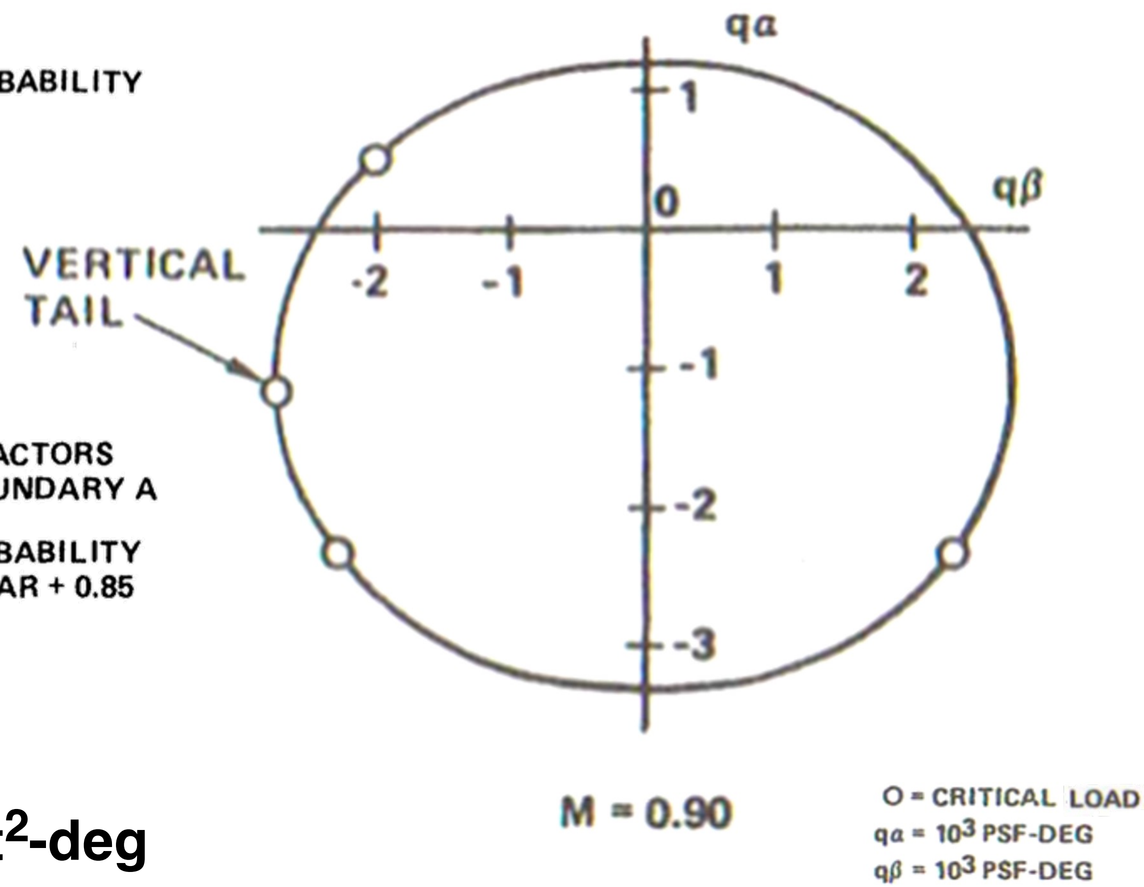


Shuttle Flight Loads

For *asymmetric* vehicles, q-α (normal force) and q-β (transverse force) are critical, vs. max.-q for *symmetric* LVs



Generic "squatcheloid"



Saturn V max. q-α =
4.9 deg-N/cm^2 ~ 1025 lbf/ft^2-deg

Space Shuttle Main Propulsion

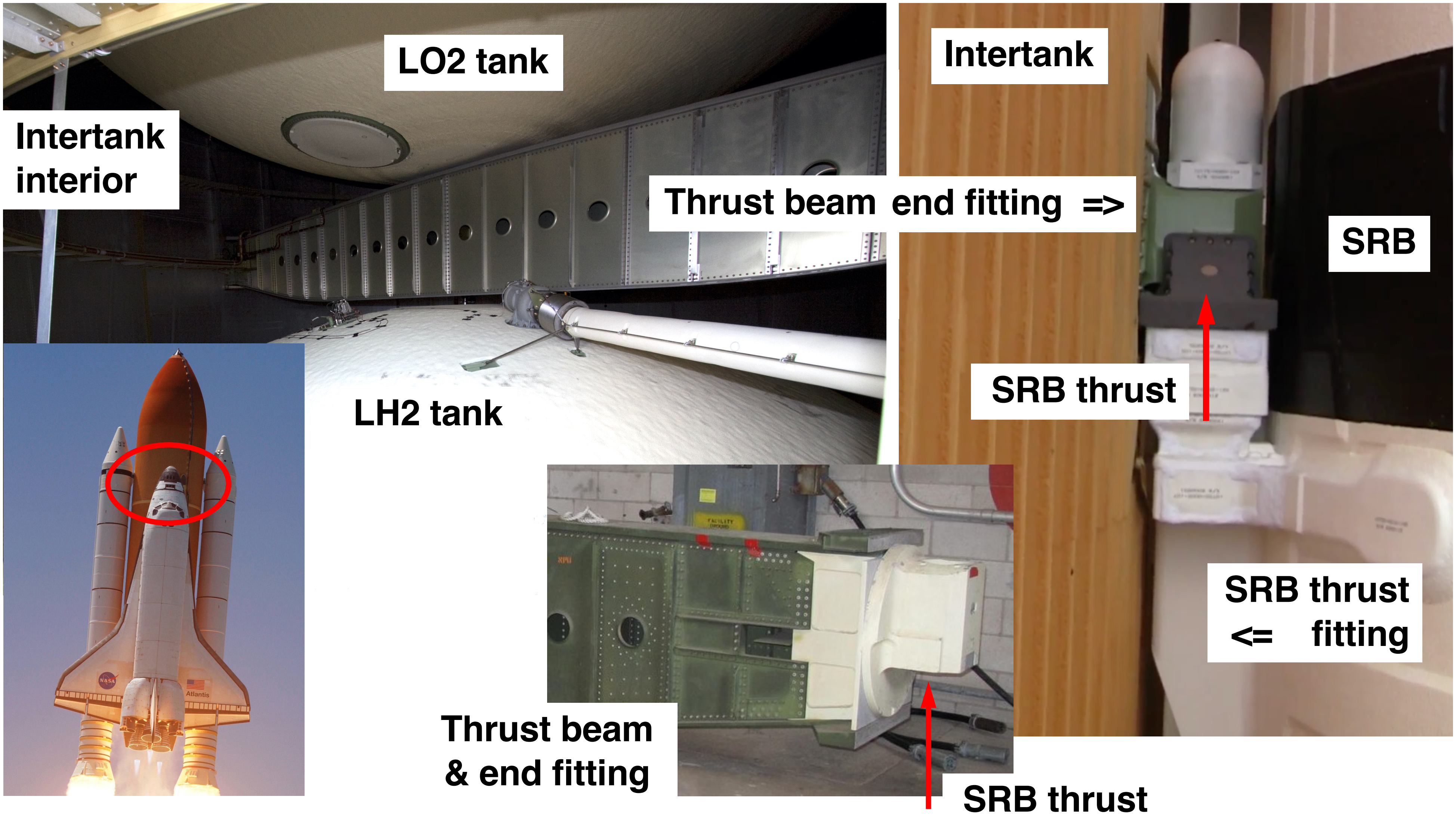
1st stage SRB
- Low Isp, High thrust
- Solid prop

1st & 2nd stage SSME
- High Isp, Low thrust
- LO2/LH2 prop

Space Shuttle Main Engine

Propellants	LO_2 - LH_2
Power level, klbf	SL/vacuum
- Rated 100%	370.0/470.8
- Nominal 104.5%	393.8/488.8
- Full 109%	417.3/513.3
Chamber pressure at 109%, Full power level	3008 psia
Specific impulse, I_{sp}, vacuum	452 seconds
Throttle range	67 to 109%
Engine mass	7480 lbm

Shuttle ET/SRB Interface Details



Shuttle Has Very Complex Load Paths

Liftoff mass

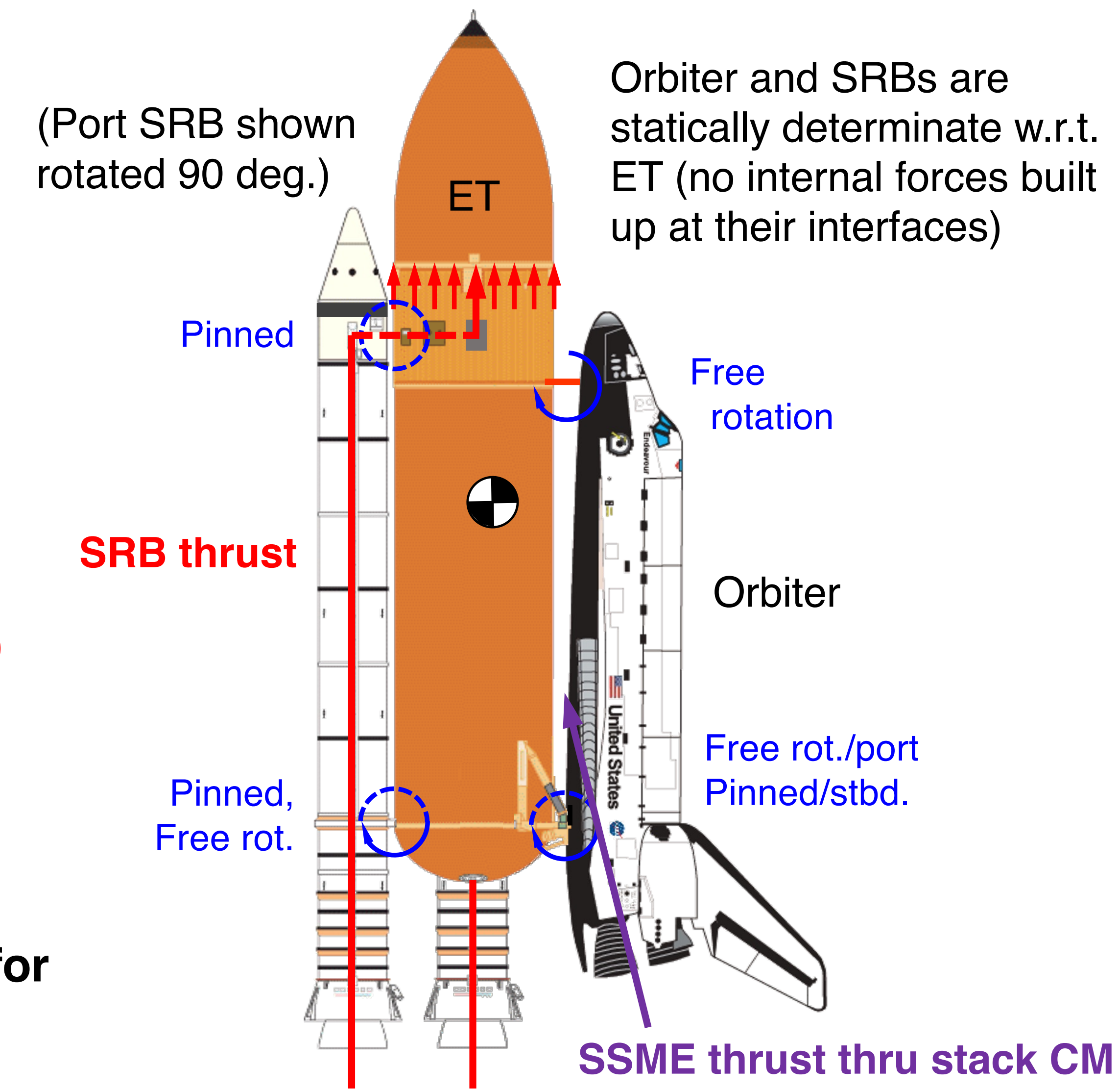
- Orbiter - 232 klbm structure
  - 32 klbm payload
- ET - 1.373 Mlbm LO2
  - 229 klbm LH2
  - 59 klbm structure
- SRBs - 2@ 1.107 Mlbm prop.
  - 2@ 192 klbm structure
- Total mass = 4.53 Mlbm

Liftoff thrust

- SSMEs - 3@ 370 klbf
- SRBs - 2@ 2.9 Mlbf (85 pct. liftoff)
- Total thrust = 6.96 Mlbf

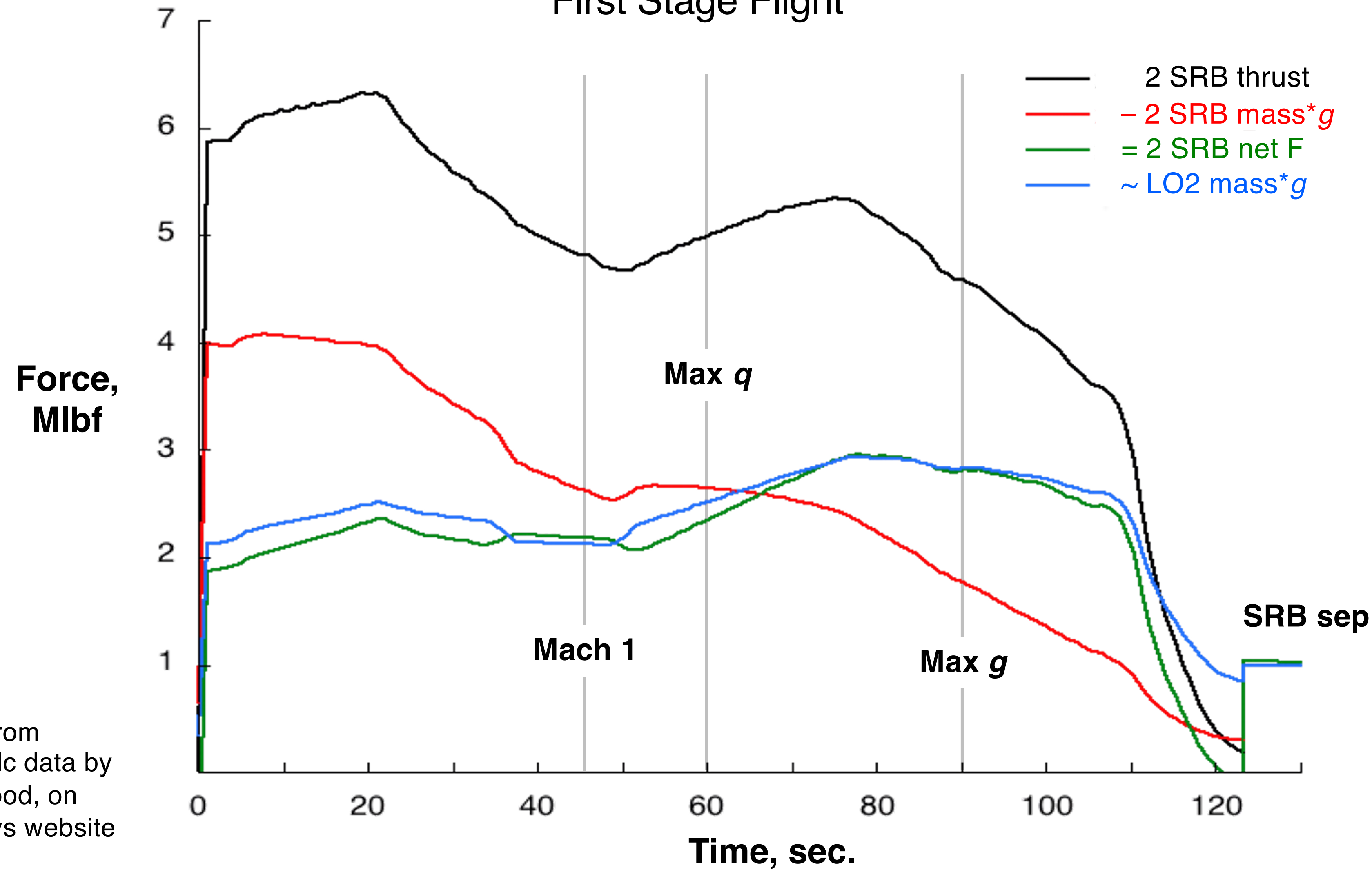
=> SRBs push themselves and LO2 mass uphill to staging

Compare to simple load paths for Saturn V and similar vehicles...



Shuttle Ascent Loads Analysis

First Stage Flight



Derived from SpaceCalc data by W. Harwood, on CBS News website

When Do The SRBs Separate?

Pc < 50 indicator light at ~ 120 sec.

- SRB chamber pressure Pc < 50 lbf/in^2
- Indicates imminent SRB separation

Est. SRB nozzle throat R = 27 in. => A = 2290 in^2

At liftoff, SRB thrust F = 2.9 Mlbf, Pc = 1000 lbf/in^2

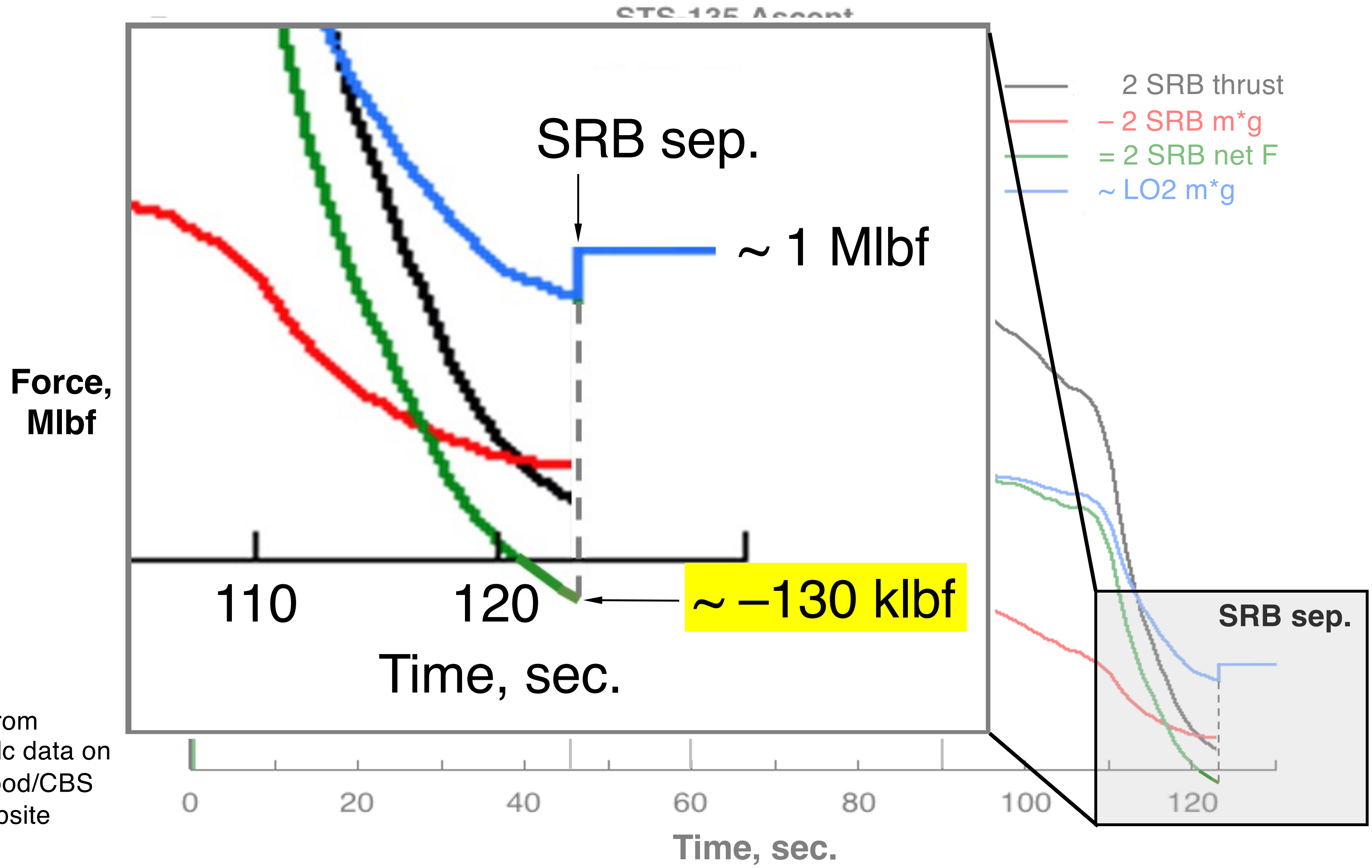
=> Nozzle efficiency e = F/Pc*A = 1.27

At separation, SRB thrust F = Pc*A*e = 145.4 klbf

- Net axial force = (145.4 klbf – SRB mass*1g)

=> Approx. –50 klbf (drag) per SRB

Shuttle Ascent Loads Analysis



Derived from SpaceCalc data on W. Harwood/CBS News website

Space Shuttle SRB Mass Estimation

Solid Rocket Booster (each)

- Assume cylinder; L = 149 ft, R = 12 ft/2
- D6AC steel; 0.284 lbm/in^3, 200 klbf/in^2 tensile yield
- 1000 lbf/in^2 peak internal pressure

From strength of materials, hoop stress = P*R/t => t = P*R/σ

Shell wall thickness t = (1 klbf/in^2*1.4 FS)*(72 in.)/200 klbf/in^2

= 0.504 in.

Shell mass = 2*π*R*t*L*ρ

= 2*π*(72 in.)*(0.504 in.)*(149 ft)*(0.284 lbm/in^3)

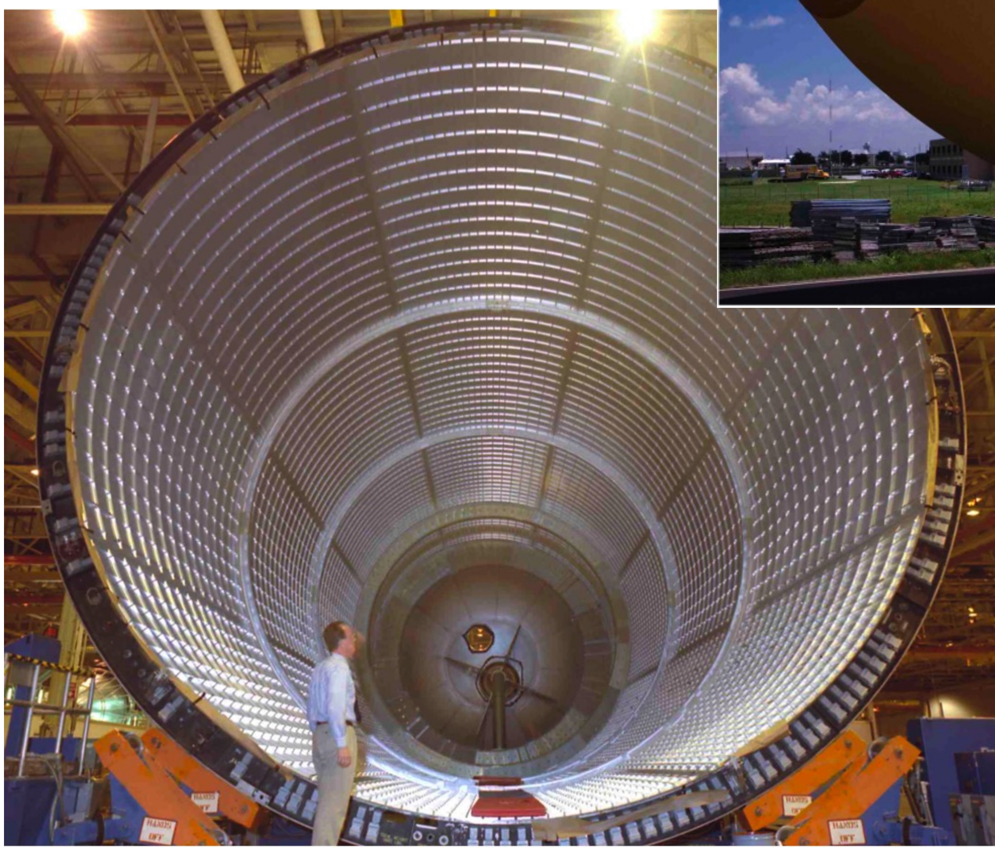
~ 115,800 lbm

Est. SRB mass = shell mass*("systems & growth" factor ~ 1.75)

~ 202,600 lbm (vs. actual SRB mass 192,946 lbm)

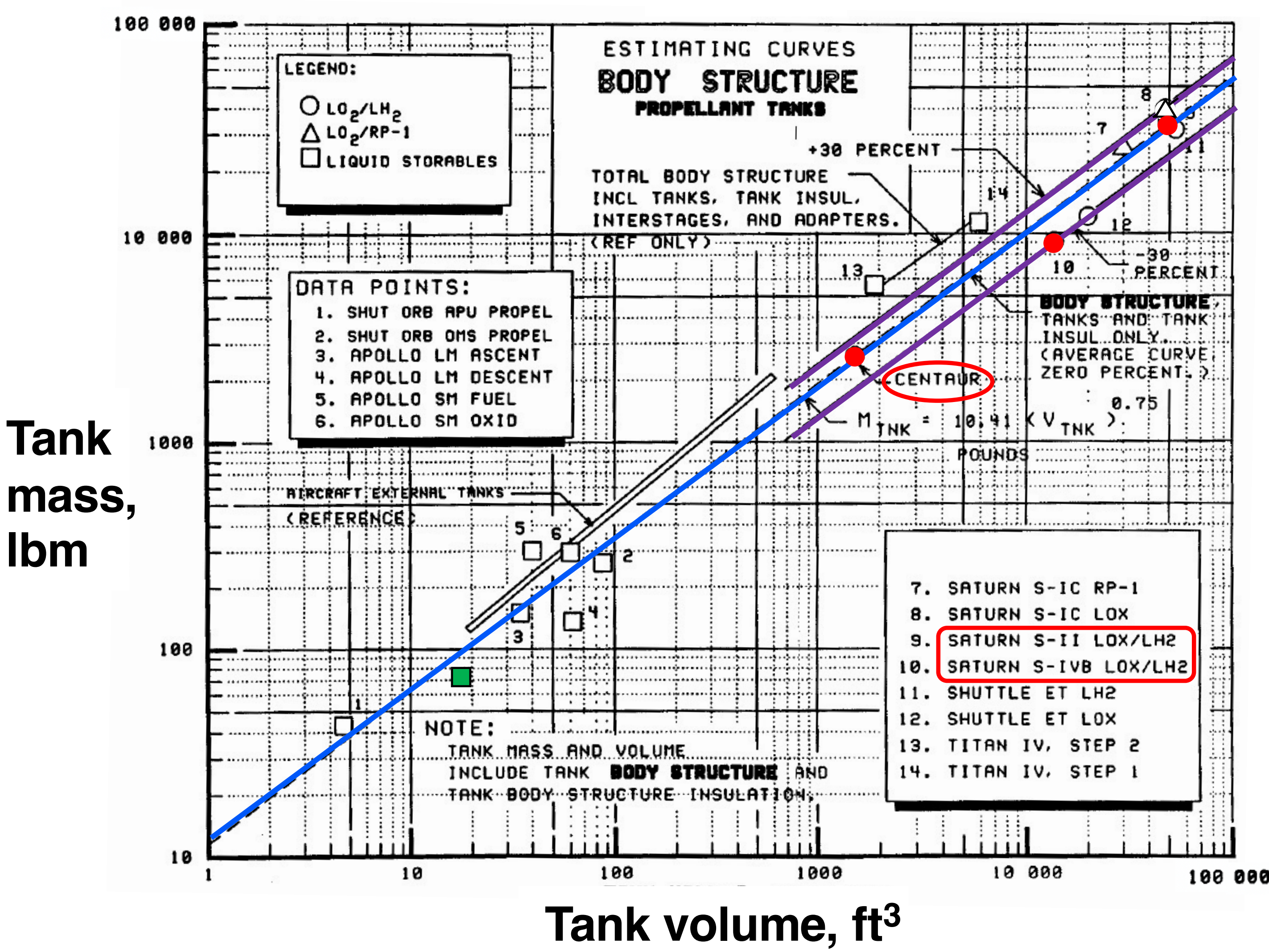
Super-Lightweight Tank (SLWT; 3rd gen. ET)

LH2 Tank Barrel



Orthogrid Details

From Heineman, JSC-26098, Nov. 1994



Average $M_{tank} = 10.41*(V_{tank})^{0.75}$ for tanks and insulation only

(±30 percent)

STS Orbiter RCS

Tanks w/ common bulkheads

SLWT Structural Sizing - "Top-down"

SLWT LH2 Tank

- Cylindrical tank, R = 331 in./2
- Barrel L = 928 in.
- Ellipsoidal domes, H = 124 in.

Calculate tank volume = $\pi * R^2 * L + 4\pi * R^2 * H/3$

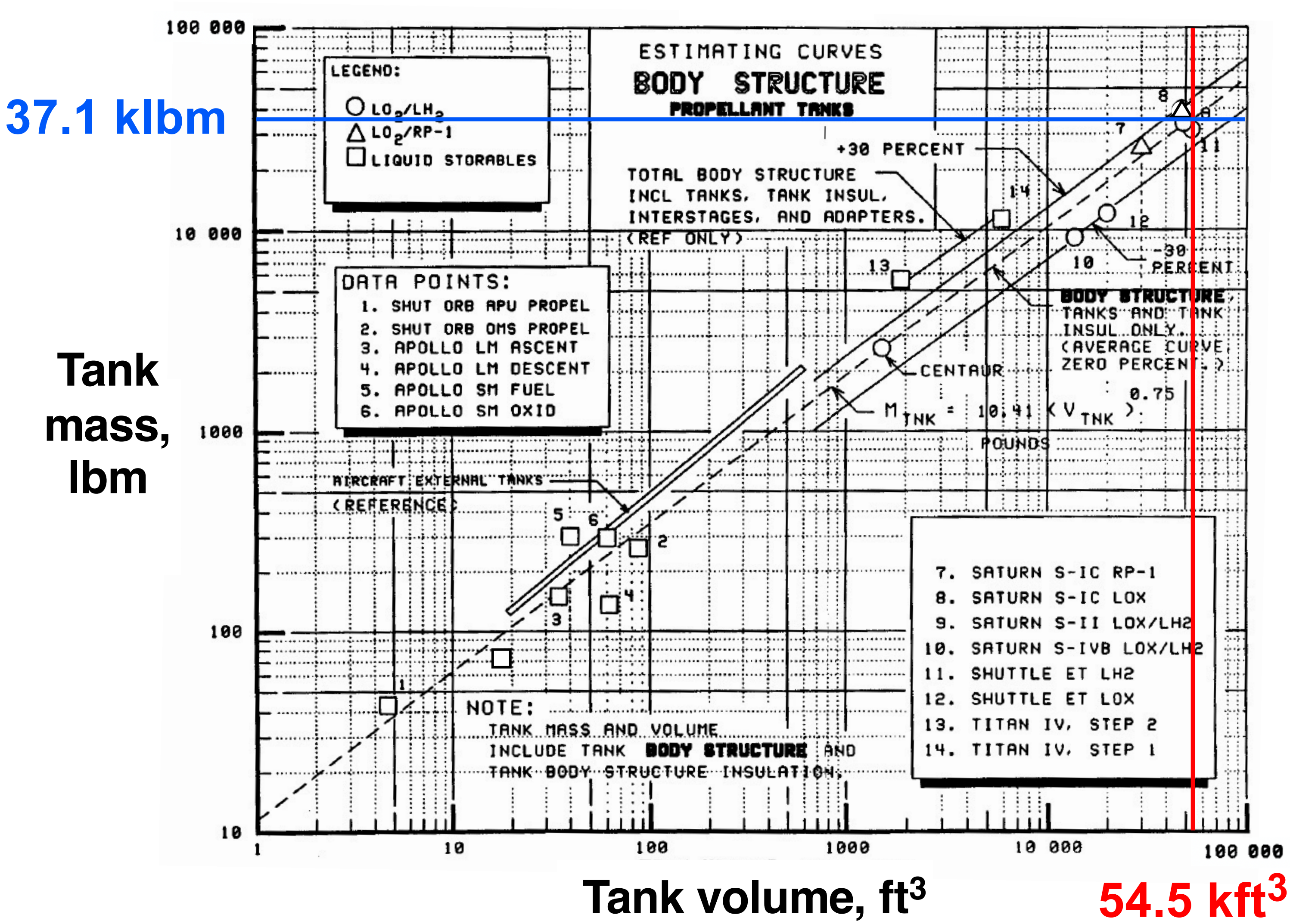
- Total tank volume = 54,452 ft^3
- Predicted tank struct. mass => 37.1 klbm

Actual tank struct. mass = 23,886 lbm

(~ 35 pct below predicted)

=> Develop correction factor = 0.65

From Heineman, JSC-26098, Nov. 1994



SLWT Structural Sizing - “Bottom-Up”

SLWT LH2 Tank Barrel

- Cylindrical tank; L = 928 in., R = 331 in./2
- 38.7 lbf/in^2 proof test pressure
- Al-Li 2195; 72 $klbf/in^2$ yield, 0.098 lbm/in^3

From strength of materials,

- Barrel skin $t = P*R / \sigma$ => $t = 0.089$ in.
- Skin mass = $2*\pi*R*L*\rho*t$ = 8417 lbm
- Apply 1.80 average NOF* => 15,151 lbm
- Apply 1.54 acreage NOF => 12,962 lbm

Actual orthogrid barrel mass = 13,477 lbm

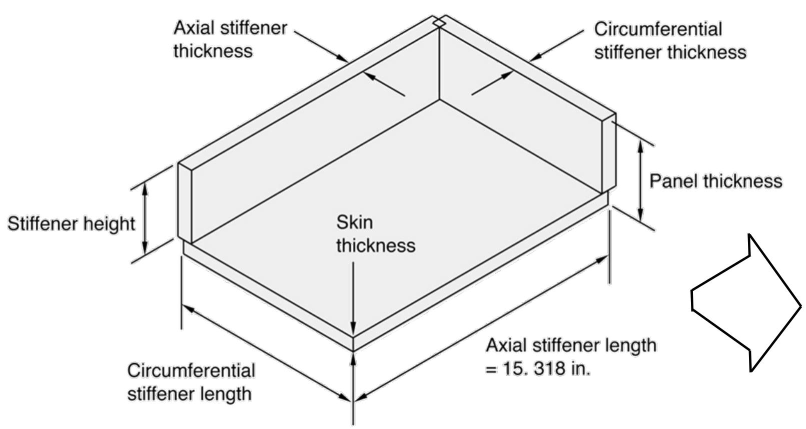
(60 pct > skin; 11 pct < avg, 4 pct > acreage)

* NOF = empirical *non-optimum factor*

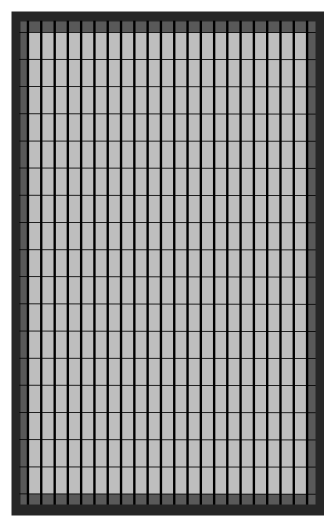
Ares V Structural Sizing - "Bottom-Up"

Core Stage LH2 Tank Barrel

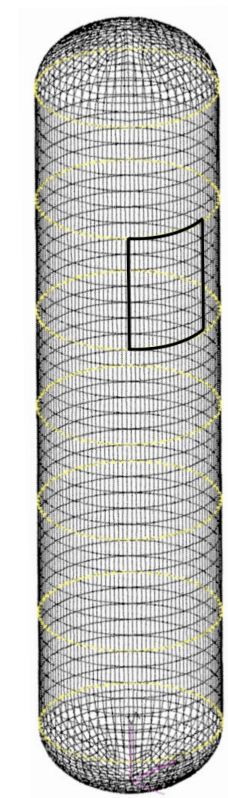
- Cylindrical tank; L = 1506 in., R = 396 in./2
- 43.4 lbf/in^2 proof test pressure
- Al-Li 2195; 72 klbf/in^2 yield, 0.098 lbm/in^3



Orthogrid unit cell

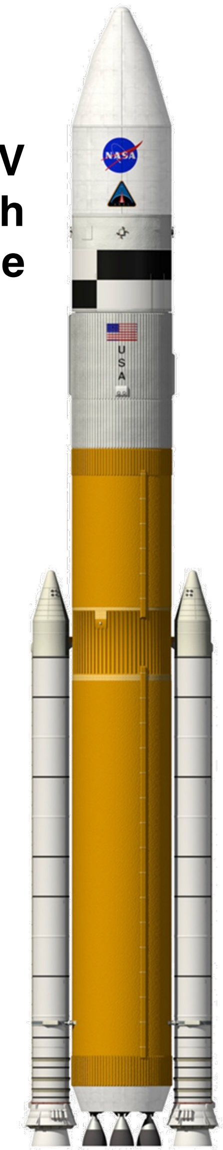


Barrel panel



Core LH2 tank

Ares V Launch Vehicle



Ares V Structural Sizing (cont'd)

HyperSizer analyses performed to size integrally-machined panel for flight load cases; 0.160-in. skin thickness

- **Proof pressure-sized skin thick. = 0.112 in.; *coarse* panel wt. = 448 lbm; 689 lbs w/ 1.54 acreage NOF**
- **Orthogrid areal wt. = 3.54 lbm/ft^2; *intermediate* panel wt. = 958 lbm; 1188 lbs w/ 1.24 NOF**
- **Orthogrid unit cell wt.= 2.25 lbm; *refined* panel wt. = 1100 lbm; 1133 lbs w/ 1.03 NOF**

Ares V load paths are *very different* from Shuttle ET

=> Proof-pressure sizing probably not appropriate…

Concluding Remarks

A brief overview of classical and other selected structural mass estimation methods is presented

Saturn V examples
- S-IC intertank (+2.1 klbm; +16%)
- S-IC / S-II interstage (–2.7 klbm; –28%)
- S-II thrust structure (–0.9 klbm; –12%)

Space Shuttle examples
- Load paths during first-stage flight
- Solid Rocket Booster (+9.7 klbm; +5%)
- SLWT LH2 tank, barrel (+13.2/–2.0 klbm; +55/–14%)

Ares V example

Use these techniques with great care and suspicion!

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Acronyms

A	Nozzle throat area, in2
avg	Average value
CM	Center of mass
CSM	Command/service module
e	Nozzle efficiency factor
E	Material elastic modulus, lbf/in2
ET	External tank
FS	Factor of safety
F-1	Saturn V 1st-stage engine
g	Standard gravitational acceleration
H	Ellipsoidal dome height, in.
Isp	Specific impulse, sec.
IU	Saturn V instrument unit
J-2	Saturn V 2nd-, 3rd-stage engine
L	Shell height, in.
lbf	Pounds (force)
lbm	Pounds (mass)
LES	Launch escape system
LH2	Liquid hydrogen
LM	Lunar module
LOR	Lunar orbit rendezvous
LO2	Liquid oxygen
LV	Launch vehicle
NOF	Non-optimum factor
Nx	Compression line load, lbf/in.
P	Internal presssure
Pc	Chamber pressure, lbf/in2
Pcr	Critical buckling load, lbf
Prop	Propellant
q	Dynamic pressure, lbf/in2
R	Radius, in.
RCS	Reaction control system
RP-1	Kerosene
sd	Standard deviation
S/C	Spacecraft
SLA	Spacecraft-LV adapter
SLWT	Super-lightweight tank
SMF	Structural mass fraction
SRB	Solid rocket booster
SSME	Space shuttle main engine
STS	Space transportation system
S-IC	Saturn V 1st stage
S-II	Saturn V 2nd stage
S-IVB	Saturn V 3rd stage
t	Shell wall thickness, in.
α	Frustum half-angle, deg.
γ	Correction factor = 1
μ	Poisson's ratio
ρ	Material density, lbm/in3
σ	Hoop stress, lbf/in2