Modelling of Propellant Management Systems in Early-Phase Launcher Development

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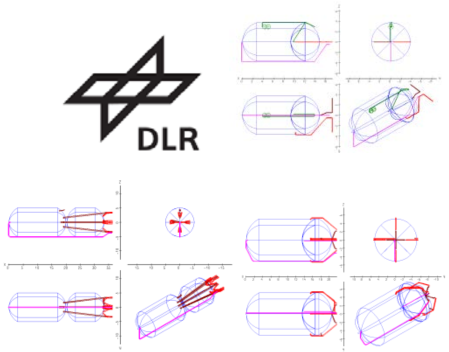
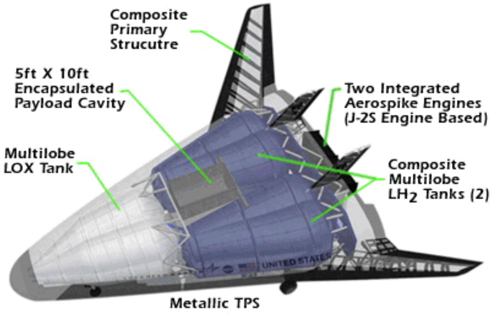
Contents

Source: NASA



Introduction



Source: NASA

Motivation

Cryogenic Stages

- High specific impulse; increase payload mass

Cryogenic tanks: critical technologies

- Typical integral structural role; large influence on overall design

Source: NASA

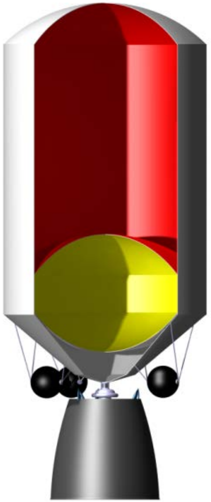
Propellant management

- Crucial functional role; highly sensitive

Saturn-V:

- Wealth of stage and flight data (e.g. AS506)
- Similar yet highly complex system

Introduction



Propellant Storage and Management Mass

- Tanks
  - Cylinders
  - Domes
  - Baffles
  - Y-Rings, Manholes
- Lines
  - Feedlines
  - Fill and Drain Lines
  - Pressurisation Lines
- Valves and Regulators
- Pressurant Gas Storage
  - Pressurant Gas
  - Tanks
  - Heaters, heat exchangers
- Thermal Management
  - Thermal Insultation

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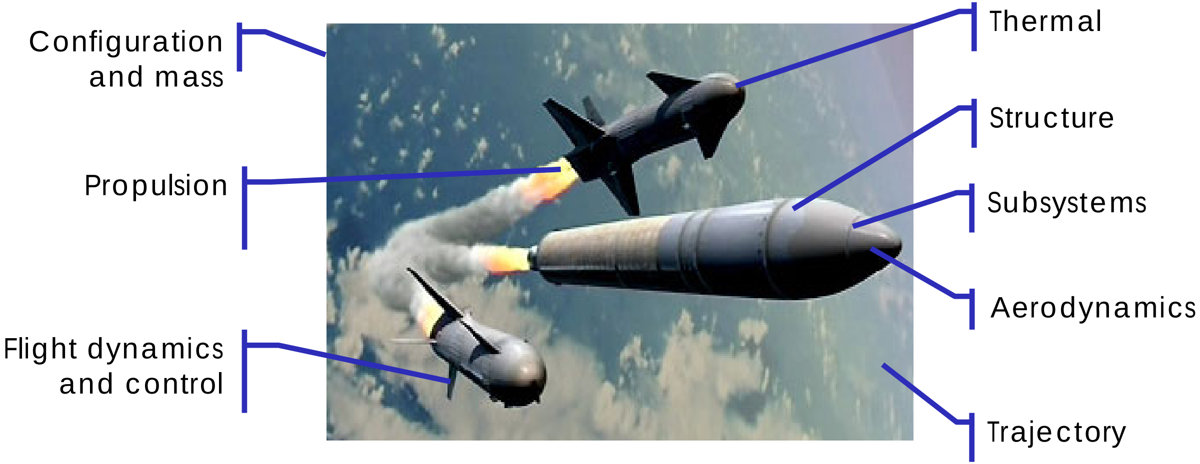
Introduction

Space Transportation System (STS) Preliminary Design

DLR-SART Tool box has been developed for preliminary space transportation system analysis and design:

- **Fast** computation time (seconds, minutes); modelling (minutes, few hours)
- **Simple**
- **Flexible**
- **Reliable**
- **Modular**



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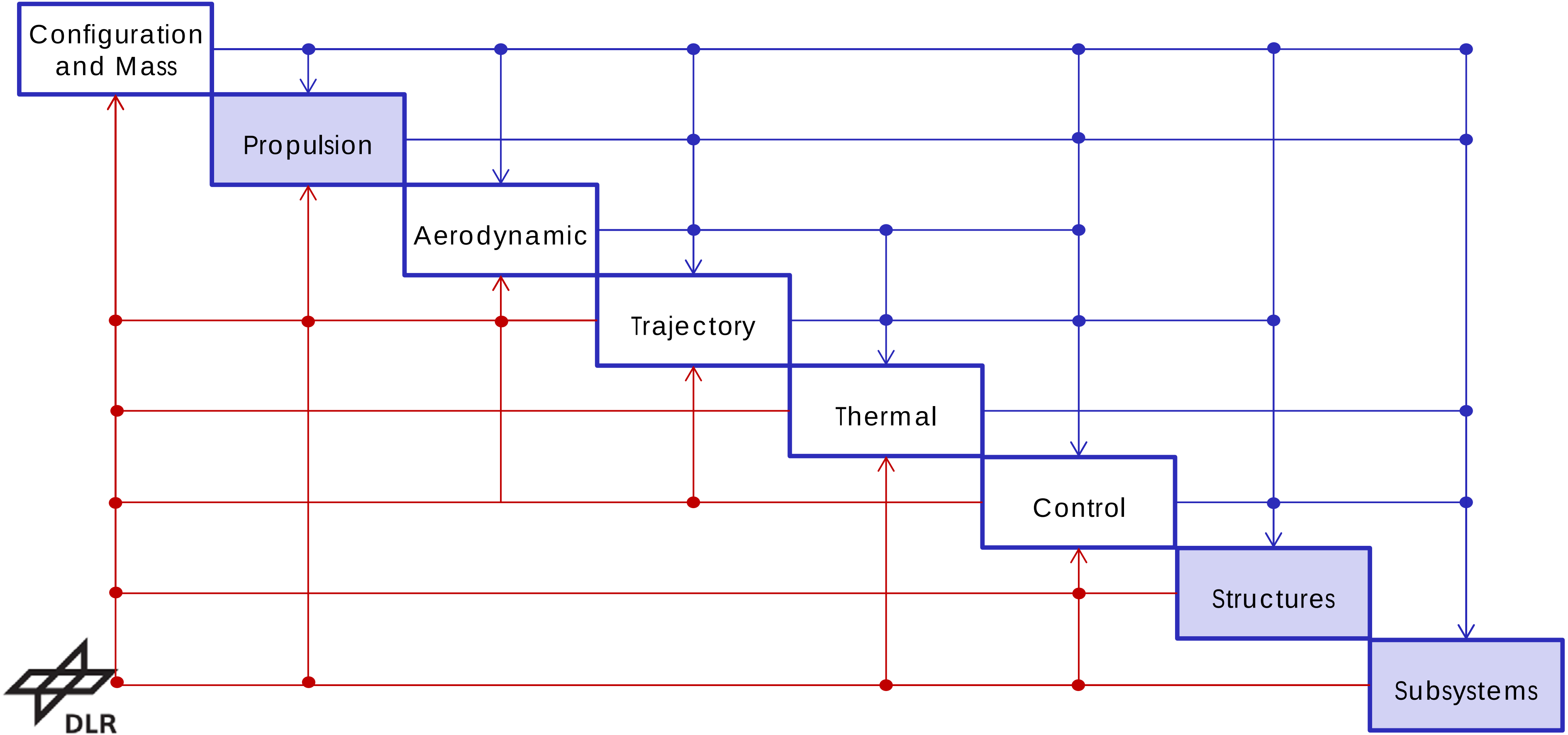

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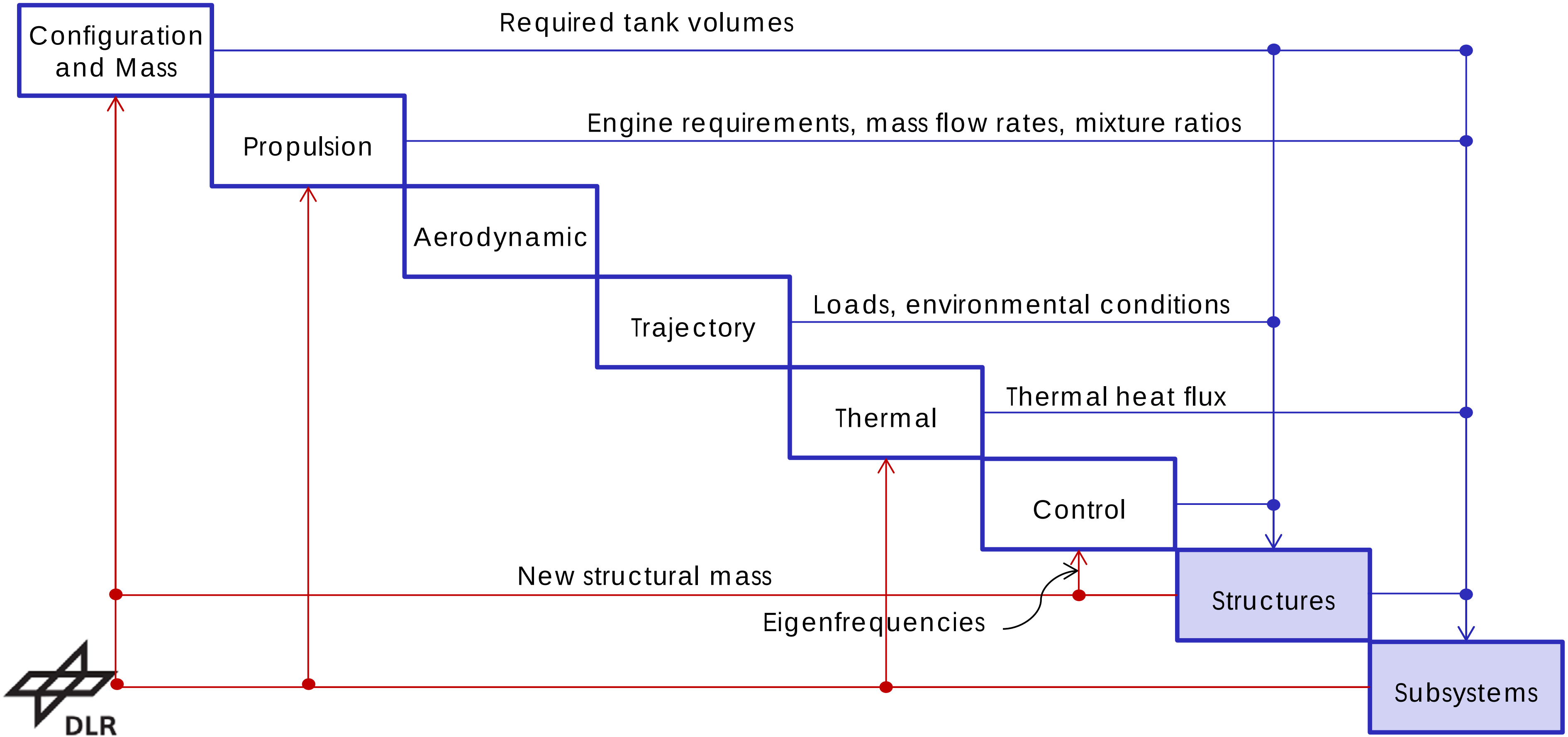
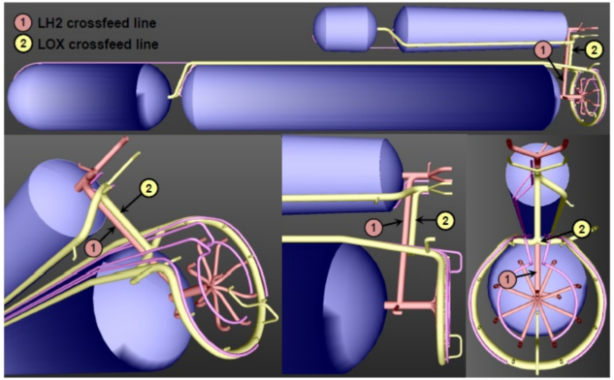


PMP Modelling Approach

Program Function

- Rapid sizing and layout of tanks (length, mass, thickness) and lines (mass)



- The layout of the pressurisation system:
  - Simulation of the entire mission, including stage loads, thermal loads, engine operation and the logical control of the ullage pressures, including both pressurant gas injection and venting.

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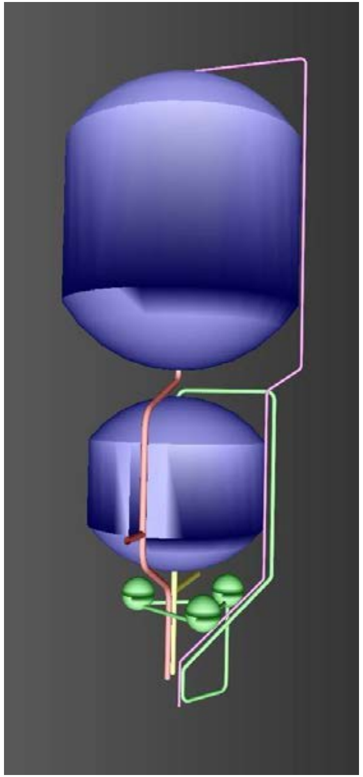
PMP Modelling Approach



Models

- The calculation methods employed in the program are 1-dimensional, and involve integral consideration of control volumes.

- Liquid stratification:
  - Heat flow over liquid-vapor interface
  - Heat input through tank walls
  - Liquid mass is divided in horizontal, discrete layers
  - Heat conduction from layer to layer
  - Sloshing implemented by increased heat transfer coefficient between layers

PMP Modelling Approach

Models

- Ullage pressure regulation simulated over the mission, with simplified control logic enacted:
  - Pressure maintained within specified operating window through venting or the injection of pressurant gas into tank ullages (bang-bang style).
  - Valve diametres, delay times can be specified.

- Currently, only ideal gas laws are considered, however real gas law implementation is foreseen.

PMP Modelling Approach

Models

- Pressure rate: $\dot{p} = \frac{T''}{V''} \cdot \left[(\dot{m}_{vap} - \dot{m}_{vent}) \cdot R'' + (m_{vap} \cdot R'' + m_{pg} \cdot R''_{pg}) \cdot \left(\frac{\dot{T}''}{T''} - \frac{\dot{V}''}{V''} \right) \right]$

- Flow rate vaporized propellant (Hertz-Knudsen):

$$\dot{m}_{vap} = 10^{-6} \cdot A_i \cdot \sqrt{\frac{1}{2\pi \cdot R'' \cdot T''}} \cdot (p_{sat} - p'') \cdot ratio$$

$$ratio = \frac{m_{vap}}{m_{vap} + m_{pg}}$$

- Mass pressurant gas: $m_{pg} = \frac{p \cdot V''}{R''_{pg} \cdot T'' \cdot Z''}$

- Internal energy ullage over time (no heatflow): $\dot{U}'' = (\dot{m}''_{vap} - \dot{m}''_{vent}) \cdot c''_v \cdot T'' - m_{vap} \cdot c''_v \cdot \dot{T}''$

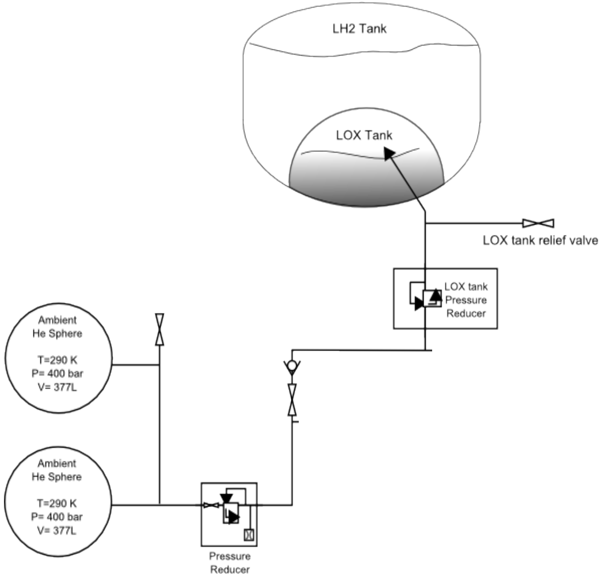
- Gasmixture temperature rate: $\dot{T}'' = \frac{\dot{U}''}{m''_{vap} \cdot c''_v}$

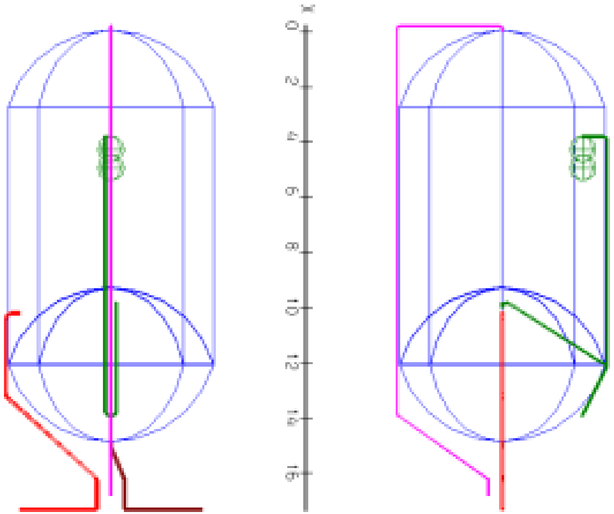
PMP Modelling Approach

Models

- Ullage volume rate: $\dot{V}'' = \dfrac{\dot{m}_{drain} + \dot{m}''_{vap}}{\rho_{liq}}$
- Ullage temperature rate: $\dot{T}'' = \dfrac{\dot{m}_{pg} \cdot c''_p \cdot (T_{pg} - T'') + \dot{Q}_{prop,wall} + \dot{Q}_{gas,wall} - \dot{Q}_{liq-gas} - \dot{m}_{vap} \cdot h_{prop}}{(m_{vap} + m_{pg}) \cdot c''_p}$
- Ullage pressure rate: $\dot{p}'' = \dfrac{\dot{m}''_{prop} - \dot{m}''_{vent}}{V''} \cdot R'' \cdot T'' + \dfrac{m''_{vap} - m''_{vent}}{V''} R'' \cdot \dot{T}''$
- Vaporised propellant volume rate: $\dot{V}''_{vap} = (\dot{m}''_{vap} - \dot{m}''_{vent}) \cdot Z'' \cdot R'' \cdot \dfrac{T''}{p''}$

PMP Modelling Approach





PMP Modelling Approach

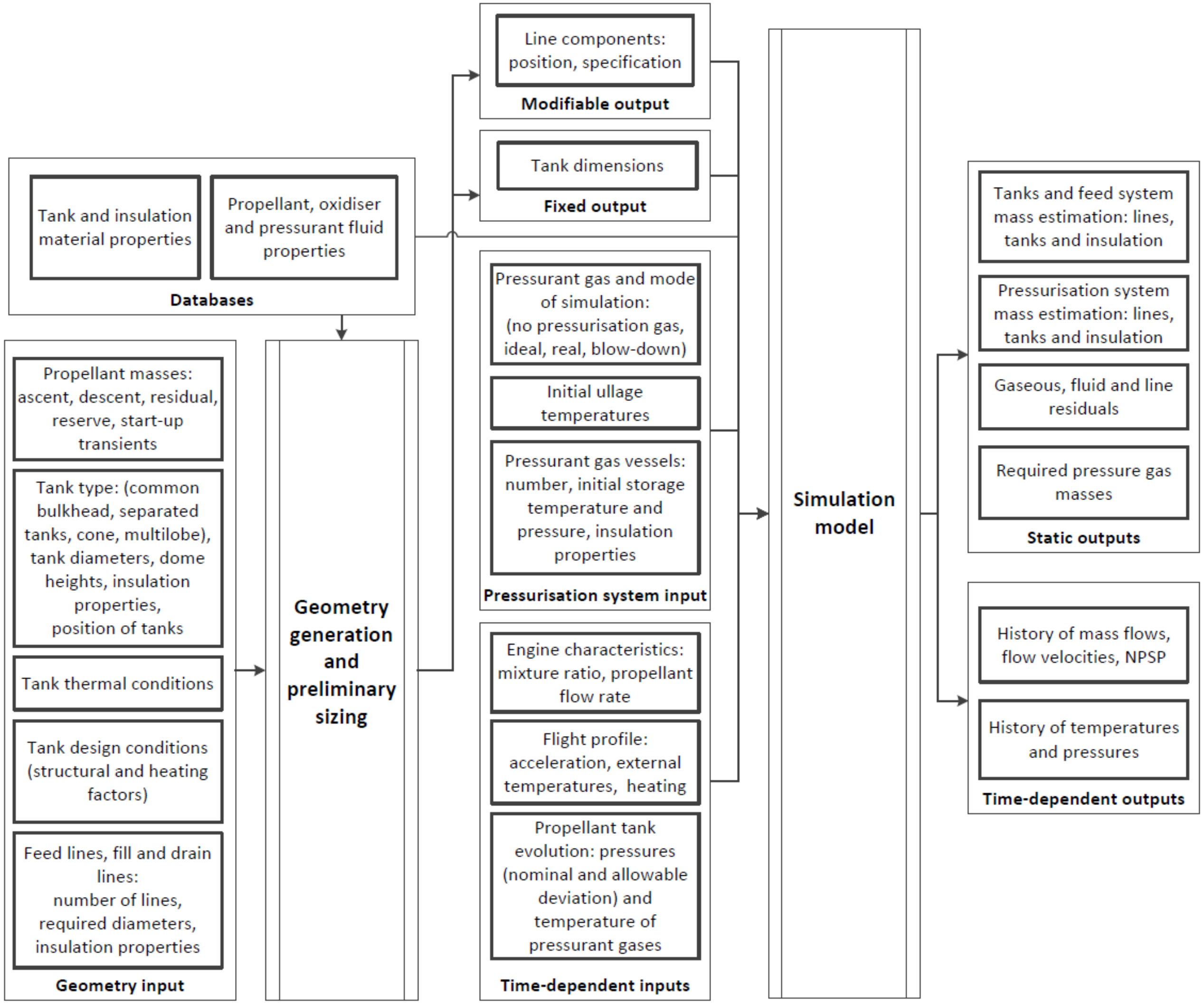
Program Functionality

Inputs:

- Geometry inputs
  - Propellant masses (ascent, descent, residual, reserve)
  - Tank type and design factors
  - Tank initial thermal conditions
- Mission history inputs
  - Ullage pressure requirements
  - Engine mass flow rate
  - Flght profile (loads, external temperature, heat fluxes)

Outputs:

- Static outputs:
  - Tank thickness, length and volume,
  - Tank, line masses,
  - Residuals (fluid and gaseous)
- Time-dependant
  - History of mass flows, velocities, pressures, NPSPs, heat transfer
  - Ullage temperatures and pressures, evaporation


Line components: position, specification
Modifiable output
Tank dimensions
Fixed output
Tank and insulation material properties
Propellant, oxidiser and pressurant fluid properties
Databases
Propellant masses: ascent, descent, residual, reserve, start-up transients
Tank type: (common bulkhead, separated tanks, cone, multilobe), tank diameters, dome heights, insulation properties, position of tanks
Tank thermal conditions
Tank design conditions (structural and heating factors)
Feed lines, fill and drain lines: number of lines, required diameters, insulation properties
Geometry input
Geometry generation and preliminary sizing
Pressurant gas and mode of simulation: (no pressurisation gas, ideal, real, blow-down)
Initial ullage temperatures
Pressurant gas vessels: number, initial storage temperature and pressure, insulation properties
Pressurisation system input
Engine characteristics: mixture ratio, propellant flow rate
Flight profile: acceleration, external temperatures, heating
Propellant tank evolution: pressures (nominal and allowable deviation) and temperature of pressurant gases
Time-dependent inputs
Simulation model
Tanks and feed system mass estimation: lines, tanks and insulation
Pressurisation system mass estimation: lines, tanks and insulation
Gaseous, fluid and line residuals
Required pressure gas masses
Static outputs
History of mass flows, flow velocities, NPSP
History of temperatures and pressures
Time-dependent outputs

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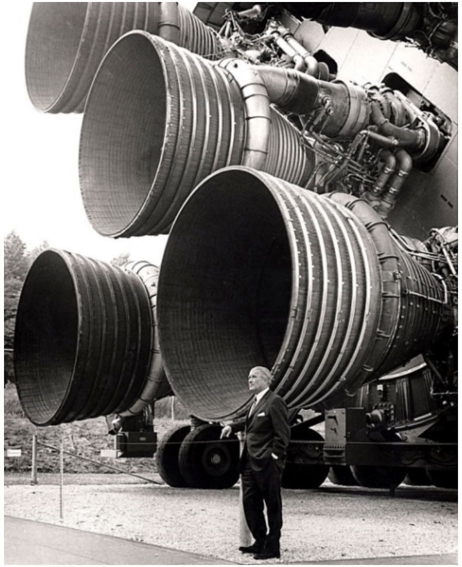
Saturn-V and AS506

Vehicle Overview

Wernher von Braun; F-1 Engines

Source: NASA



Parameter	Unit	S-IC	S-II	S-IVB
Fuel	-	RP-1 / LO_2	LH_2 / LO_2	LH_2 / LO_2
Number of engines	-	5	5	1
Mass flow rate per engine	kg/s	2647	247	215
Thrust per engine	kN	6770	1033	1033
Specific impulse	s	263	421	421
Engine mixture ratio	-	2.27	5.5	5.5
Tank mixture ratio	-	2.302	5.177	4.419
Stage dry mass	kg	137 438	43 091	15 240
Ascent propellant	kg	20 844 429	439 005	103 614

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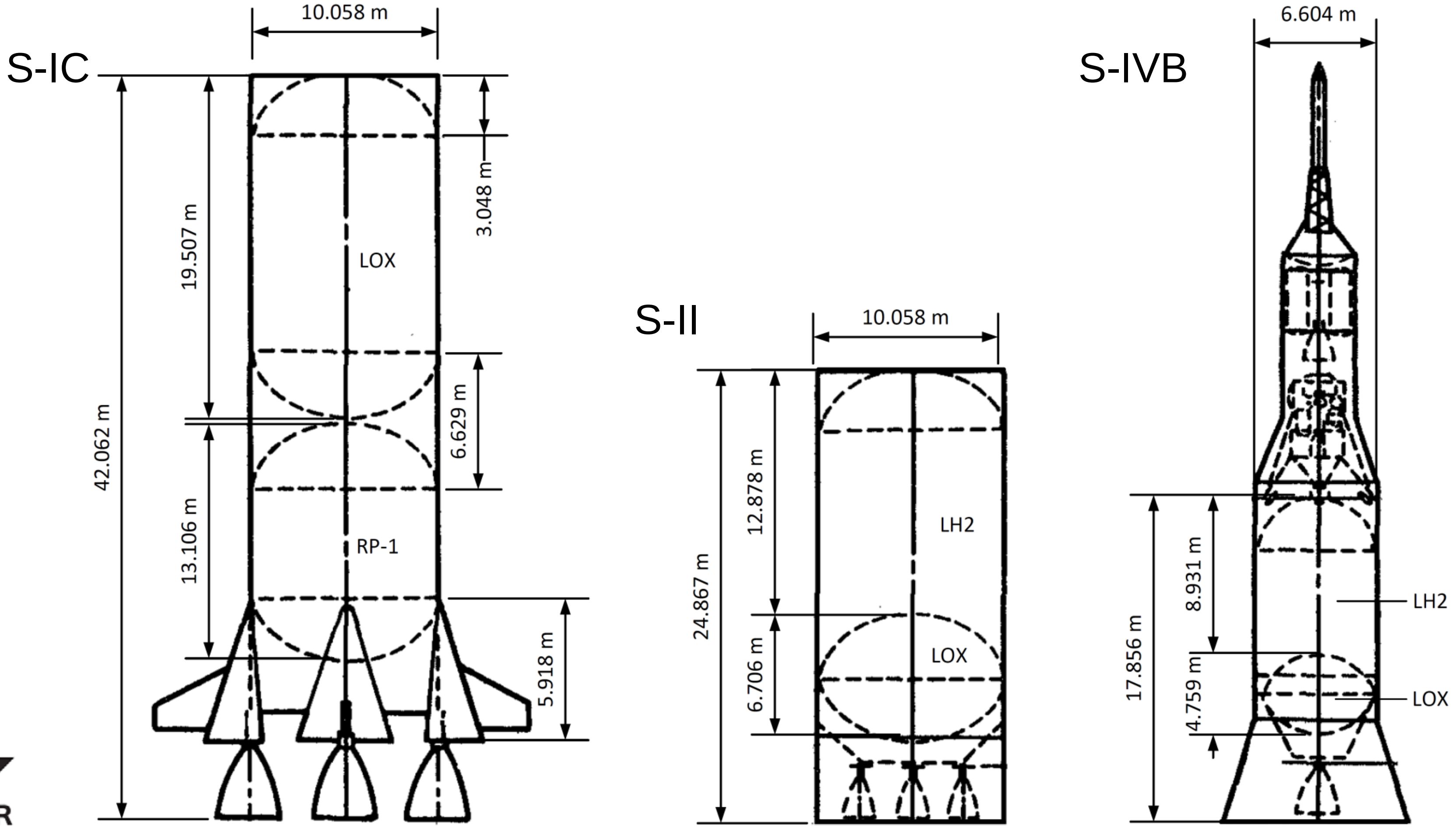
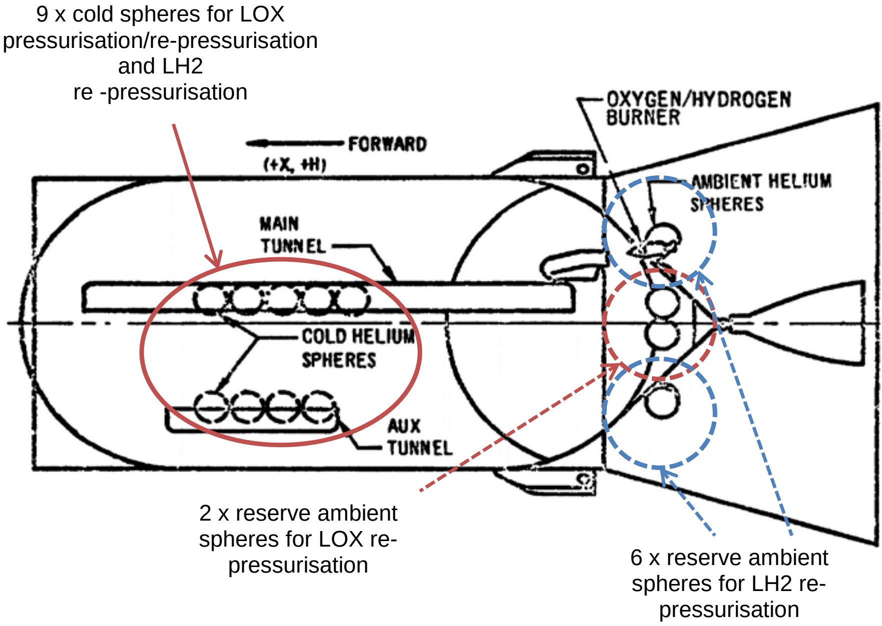

S-IC
10.058 m
42.062 m
19.507 m
3.048 m
LOX
6.629 m
13.106 m
RP-1
5.918 m
S-II
10.058 m
24.867 m
12.878 m
LH2
6.706 m
LOX
S-IVB
6.604 m
17.856 m
8.931 m
LH2
4.759 m
LOX

Saturn-V and AS506

Vehicle Overview

- S-IVB Third Stage

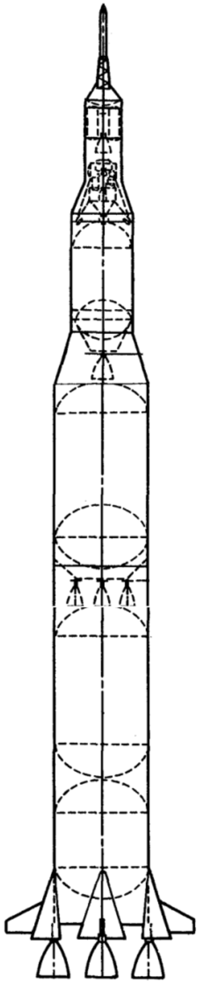
Time [seconds]	Phase	LO_2 pressurisation	LH_2 pressurisation
0 - 552.2	S-IC and S-II flight phases	GHe 27 K 0.26 - 0.28 MPa	None
552.2 - 699.6	S-IVB first flight phase	GHe 240 K 0.26 - 0.28 MPa	GH_2 110 K 0.21 - 0.23 MPa
699.6 - 9326.3	Parking orbit phase	None	None
9320.2 - 9856.2	S-IVB re-pressurisation	GHe 290 K 0.26 - 0.28 MPa	GHe 290 K 0.21 - 0.23 MPa
9856.2 - 10203.3	S-IVB second flight phase	GHe 240 K 0.26 - 0.28 MPa	GH_2 110 K 0.21 - 0.23 MPa



Saturn-V and AS506

Mission Overview

Time Base	Time [seconds]	Phase
T0	−17.0	Guidance reference release
	−8.9	Saturn-V First Stage (S-IC) engine start sequence
	−6.4	S-IC engine start
T1	0.6	Umbilical disconnect
	66.3	Mach 1
	83.0	Maximum dynamic pressure
T2	135.3	S-IC CECO
T3	161.7	S-IC OECO
	460.6	Saturn-V Second Stage (S-II) CECO
T4	548.2	S-II OECO
T5	699.6	S-IVB ECO
T6	9278.2	Restart equation solution
	9320.2	S-IVB re-pressurisation
	9856.2	S-IVB re-ignition
T7	10203.3	S-IVB ECO



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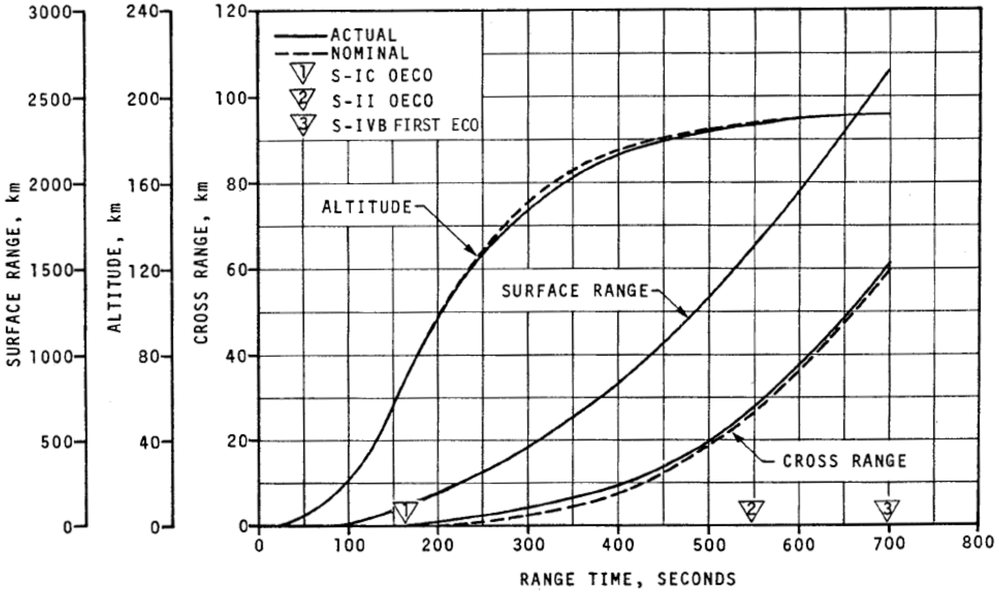
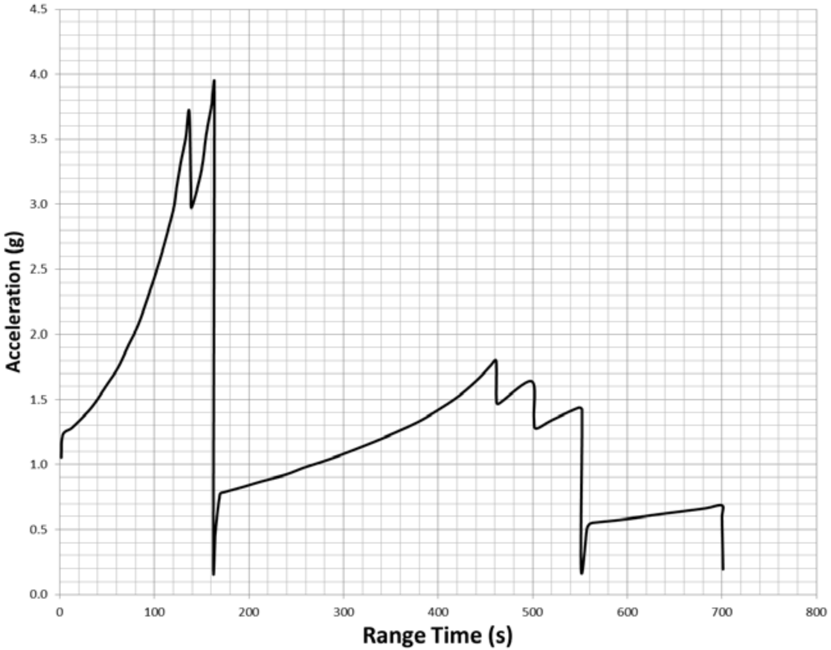
Saturn-V and AS506

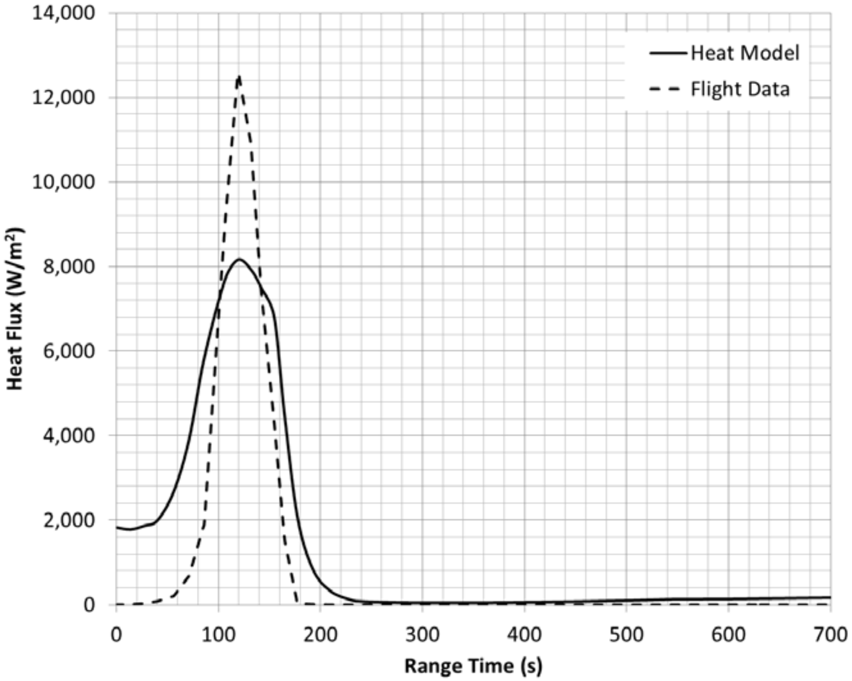
Mission Overview





Saturn-V and AS506

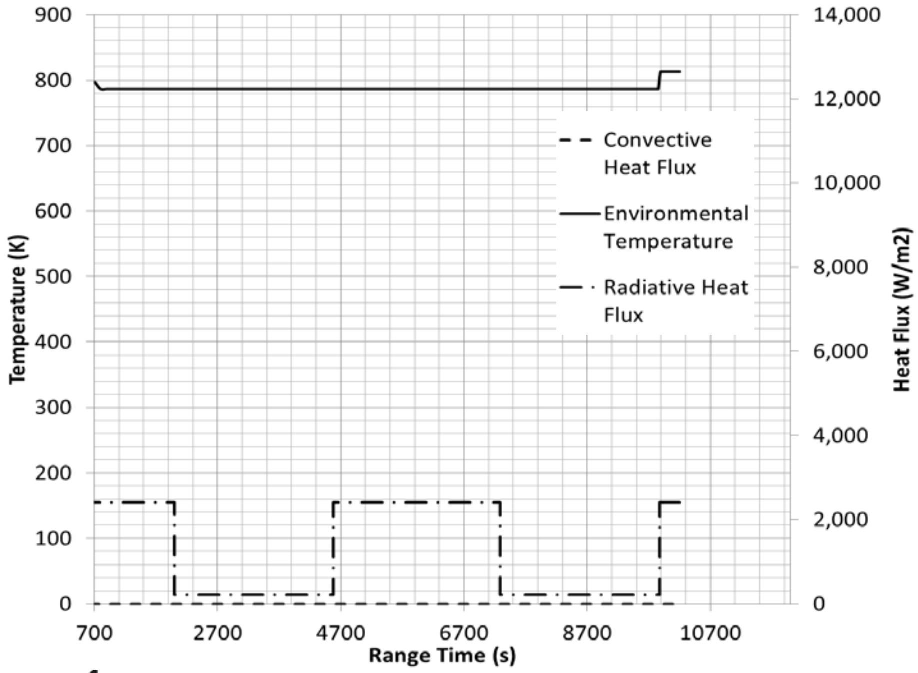
Mission Overview



$$\dot{q}_{convective} = C\sqrt{\frac{\rho R_{n,r}}{\rho_r R_n}}\left(\frac{v}{v_r}\right)^{3.05}$$

Saturn-V and AS506

Mission Overview

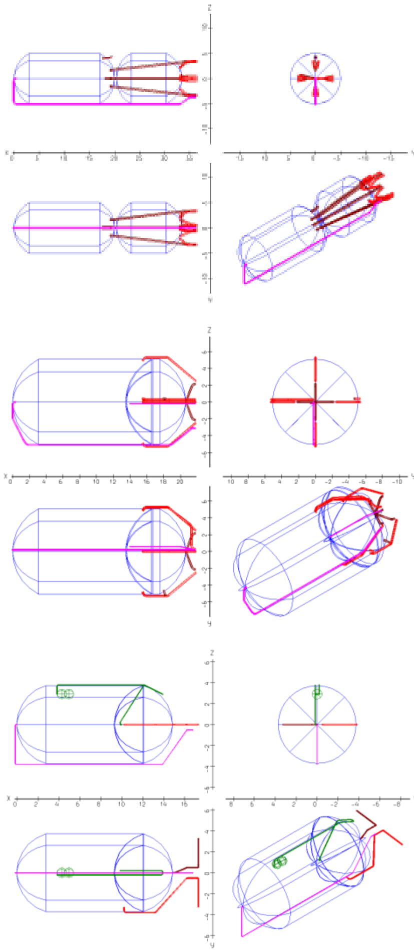


Time [seconds]	Phase	$\dot{q}_{rad,min}$	$\dot{q}_{rad,max}$
0 - 2000	Ascent / parking orbit, sun	500[a]	2403
2000 - 4585	Parking orbit, eclipse	-	218
4585 - 7293	Parking orbit, sun	-	2403
7293 - 9878	Parking orbit / S-IVB second burn, eclipse	-	218
9878 - 10213	S-IVB second burn, sun, constant	-	2403

Sizing Results

Tank Layout and Plumbing

Parameter	Unit	S-IC	S-II	S-IVB
Dimensions				
Fuel tank height	m	13.1	12.9	8.9
LO_2 tank height	m	19.5	6.7	4.8
Factors				
Fuel tank ullage factor	-	0.97	0.97	0.97
Fuel tank internal structure reduction factor	-	0.95	0.98	0.98
LOX tank ullage factor	-	0.99	0.98	0.98
LOX tank internal structure reduction factor	-	0.95	0.98	0.98

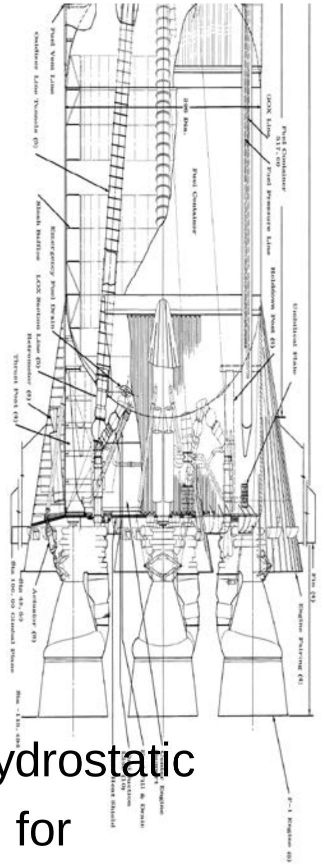


Sizing Results

Tank Layout and Plumbing

Parameter	Unit	Value PMP	Reference	Discrepancy
S-IC				
Tank mass[a]	kg	11350	25873	-56.1%
Plumbing mass	kg	3142	16100	-80.5%
S-II				
Tank mass	kg	10346	12680	-18.4%
Plumbing mass	kg	801	3480	-77.0%
S-IVB				
Tank mass	kg	3279	3947	-16.9%
Plumbing mass	kg	379	1530	-75.2%

[a] Includes wall insulation mass



Internal and hydrostatic pressure used for structural sizing

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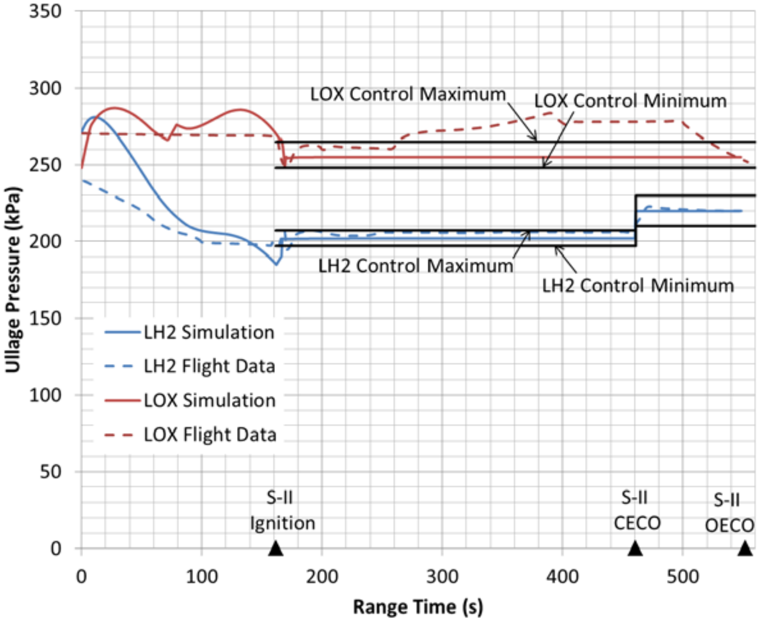
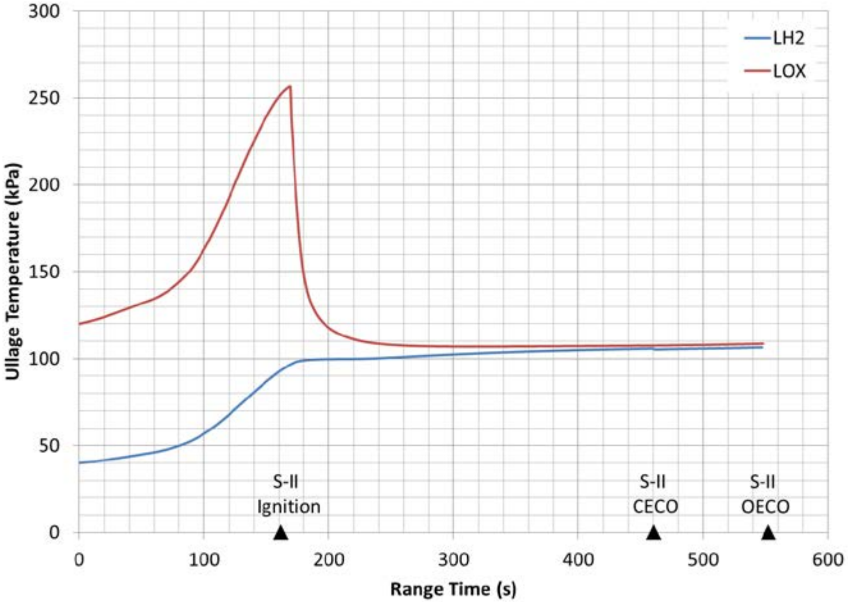
Sizing Results

Ullage Evolutions

- S-II





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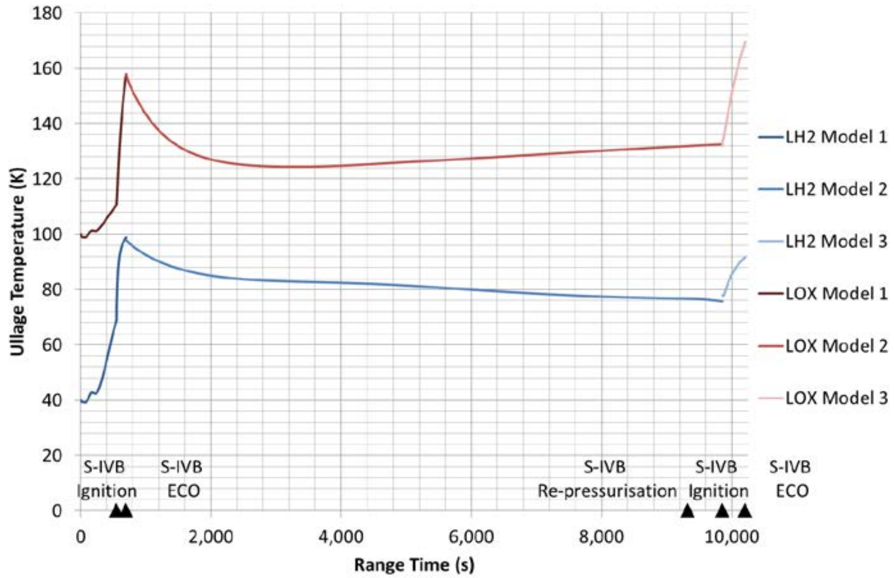
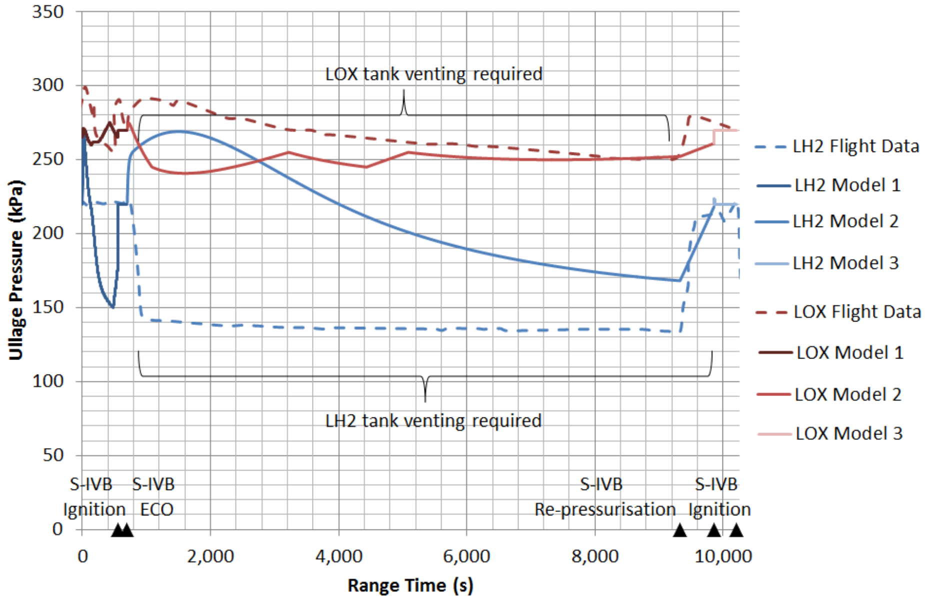
Sizing Results

Ullage Evolutions

- S-IVB





Sizing Results

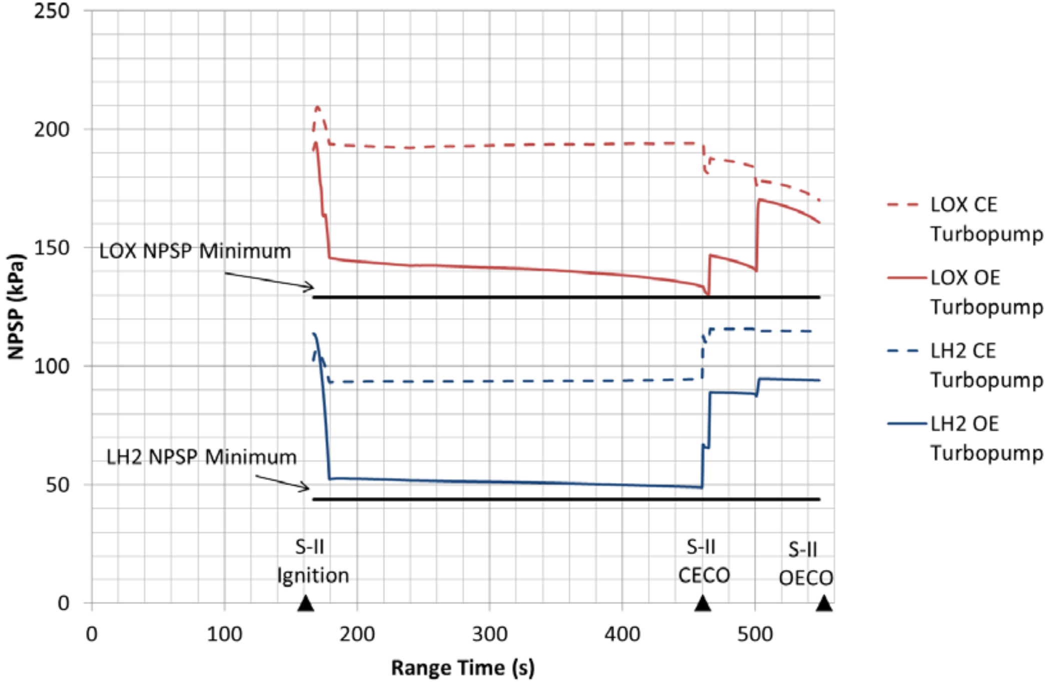
Pressurant Gas Consumption

Parameter	Unit	Value PMP	Reference	Discrepancy
S-IC				
GO_2 for pressurisation	kg	3432	3400	+0.9%
GHe for pressurisation	kg	-	240	-
S-II				
GO_2 for pressurisation	kg	2896	1900	+52.4%
GH_2 for pressurisation	kg	492	-	-
S-IVB				
GO_2 for pressurisation	kg	24	-	-
GHe for pressurisation	kg	181	171	+5.8%
GH_2 for pressurisation	kg	88	-	-

Sizing Results

NPSP

- S-II



Sizing Results

NPSP

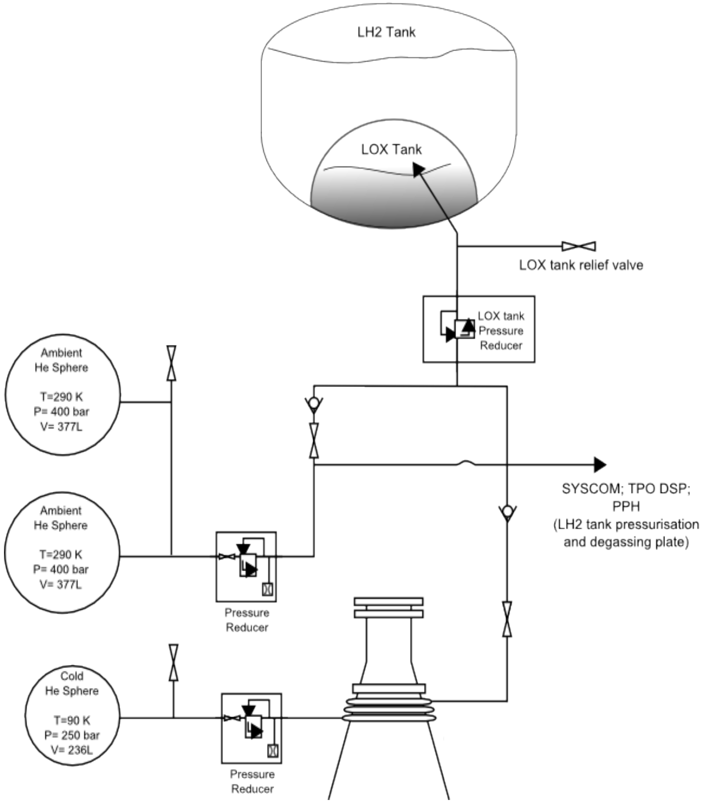
Parameter	Unit	Value PMP	Minimum Allowable[6]	Discrepancy
S-IC				
LO_2 turbopump minimum NPSP	MPa	0.57	0.56	+0.010
Fuel turbopump minimum NPSP	MPa	-	0.29	-
S-II				
LO_2 turbopump minimum NPSP	MPa	0.134	0.129	+0.005
Fuel turbopump minimum NPSP	MPa	0.049	0.044	+0.005
S-IVB				
LO_2 turbopump minimum NPSP	MPa	0.139	0.143	-0.04
Fuel turbopump minimum NPSP	MPa	0.079	0.044	+0.035

Conclusion

Future Work

- Comparison to empirical models (mass; estimation) and high-fidelity tools (2D – EcoSim Pro; CFD)

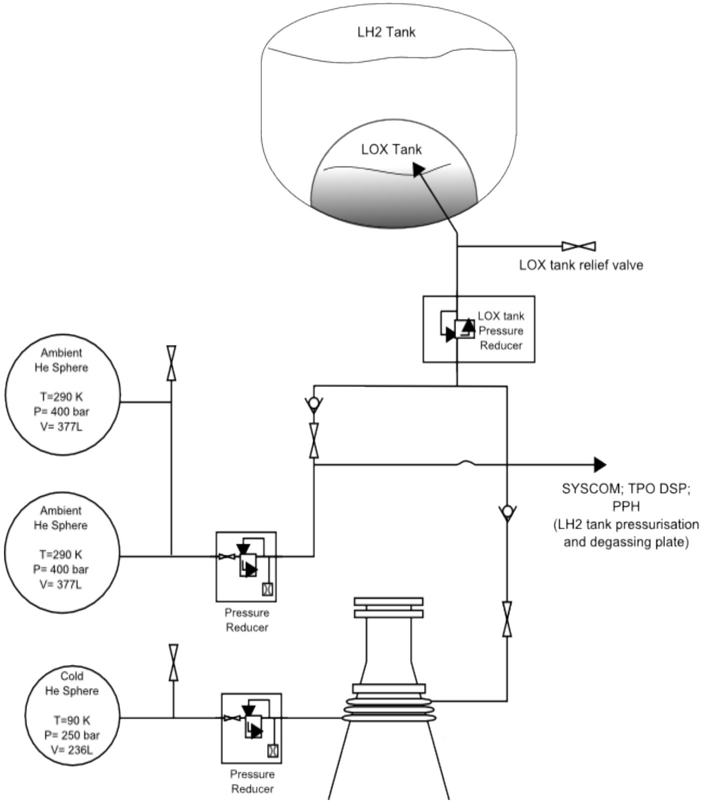
- Commonality of geometry models with e.g. strucrtural analysis program



Conclusion

Future Work

- Improved ullage pressure control logic
- Extension to multi-faceted pressurisation systems
- Refine thermal models:
  - Heat exchangers
  - Heat flux between elements: submerged lines and pressurant tanks; engine
  - Eclipse, solar beta-angle



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Conclusion

- Overview of PMP provided
- AS506 successfully modelled despite the high system complexity.
- PMP can only be utilised by experienced engineers who are able to knowledgeably adapt the input parameters and select the most relevant and realistic program outputs and discard those which are invalid.

Source: NASA

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questions?

Sizing Results

Tank Layout and Plumbing

Parameter	Unit	Value PMP	Reference	Discrepancy
S-IC				
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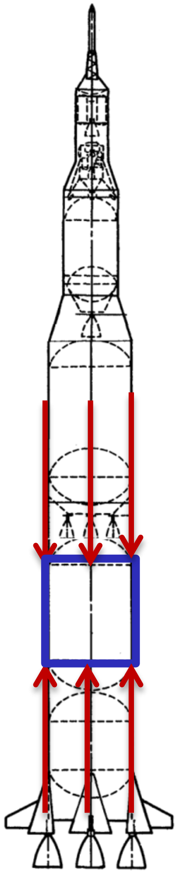
Plumbing mass	kg	379	1530	-75.2%

[a] Includes wall insulation mass

Sizing Results

Tank Layout and Plumbing

Parameter	Unit	Value PMP	Reference	Discrepancy
S-IC				
Maximum LO_2 tank thickness (bottom)	mm	4.6	6.6	-30.2%
Minimum LO_2 tank thickness (top)	mm	1.8	4.9	-63.6%
Maximum fuel tank thickness (bottom)	mm	3.0	4.9	-38.1%
Minimum fuel tank thickness (top)	mm	1.9	4.3	-55.7%
S-II				
LO_2 tank thickness (top)	mm	2.3	4.7	-50.4%
Common bulkhead thickness	mm	2.5	4.7	-45.8%
Fuel tank thickness (bottom)	mm	5.0	4.7	+6.2%
S-IVB				
LO_2 tank thickness (bottom)	mm	2.2	3.4	-34.0%
Common bulkhead thickness	mm	1.4	3.4	-60.1%
Fuel tank thickness (cylinder)	mm	1.8	3.4	-47.3%



Sizing Results

Tank Layout and Plumbing

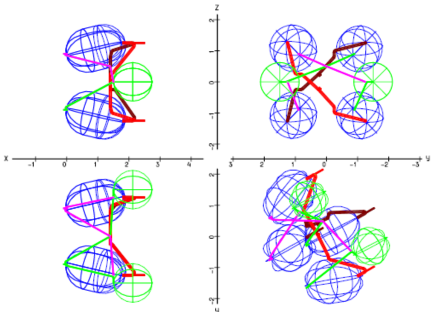
- Structural masses:
  - **Static loads** only considered; dynamic launch pad, gust or guidance and control system-driven stiffness requirements tend to be the critical loads.

  - **Second and third stage estimates closer;** the overall trend from the reference mass data:
    - Reduced structural mass higher in the vehicle due to decreasing loads,
    - The five F-1 engines act on the S-IC first stage with a force per unit area exceeding the tank pressures.
    - Furthermore, at the end of the first stage burn, the thrust to be transmitted through the entire empty stage to the S-II LOX tank, where the largest fraction of the stage mass at this time point is centred.

Sizing Results

Tank Layout and Plumbing

- Subsequent analyses for smaller stages showed a lower mass discrepancy for tanks (maximum ±12%) and lines (maximum ±12%)



- Valid range of stage sizes for mass estimations needs to be determined through extensive case studies

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