Fly Me To The Moon On An SLS Block II

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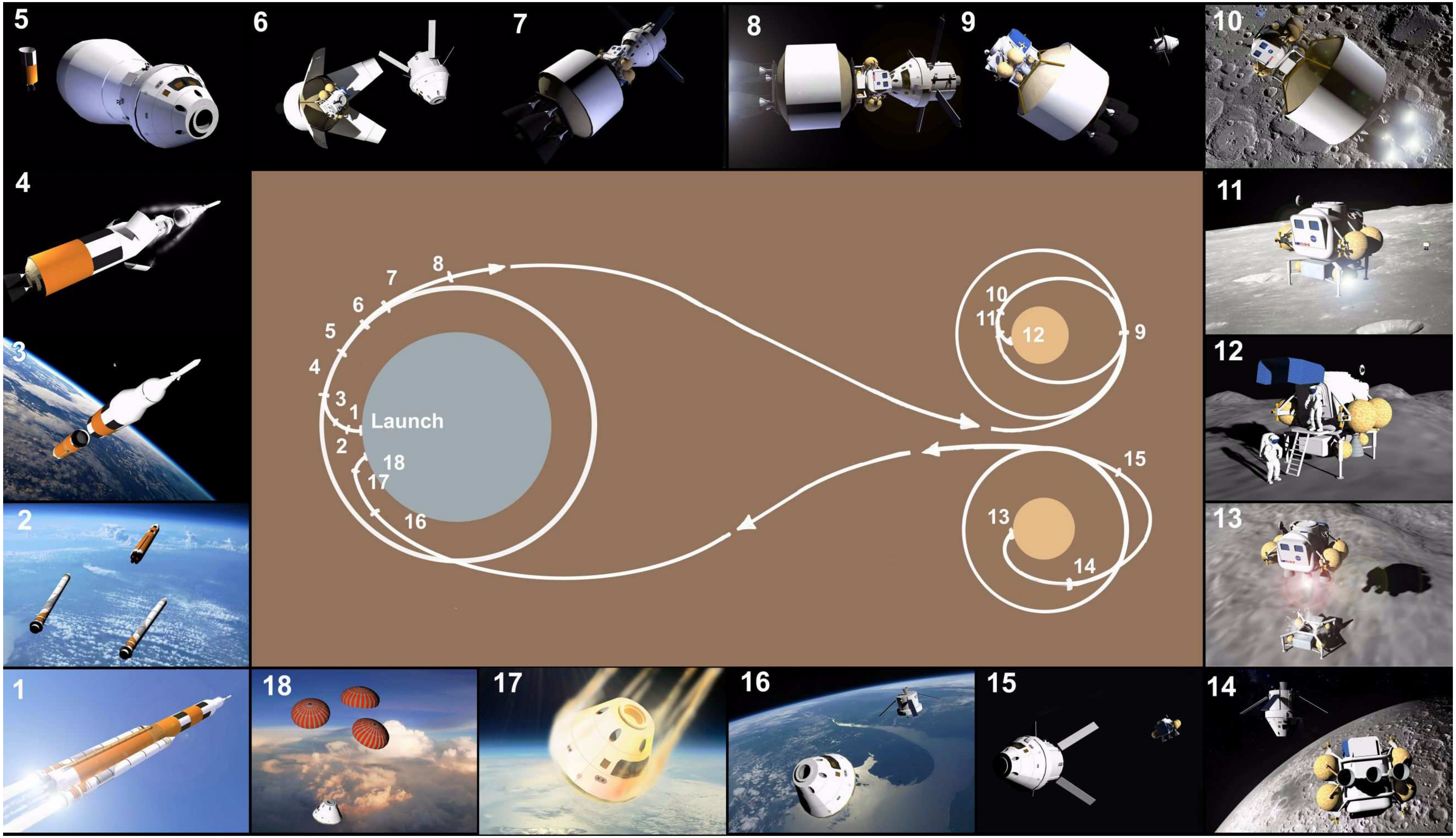
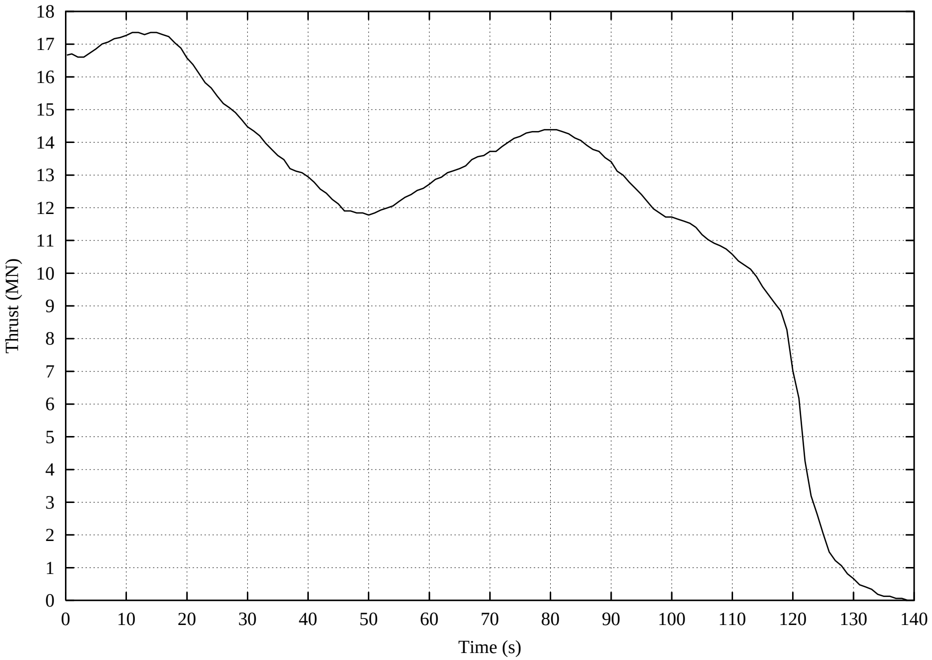
Mission Sequence



All 3D artwork courtesy of Michel Lamontagne.

RSRMV Boosters

- Five segment version of four segment RSRM booster from the Space Shuttle.
- Vacuum thrust curve manually plotted from Orbital ATK catalogue. Curve adjusted to give total impulse of 1,647,887 kNs.
- Exposed area from hold down posts, separation motors and attachments estimated to be 0.763 m^2. Overlap between aft skirt and core calculated to be 0.801 m^2. Additional area is then 0.763–0.801 = –0.038 m^2.

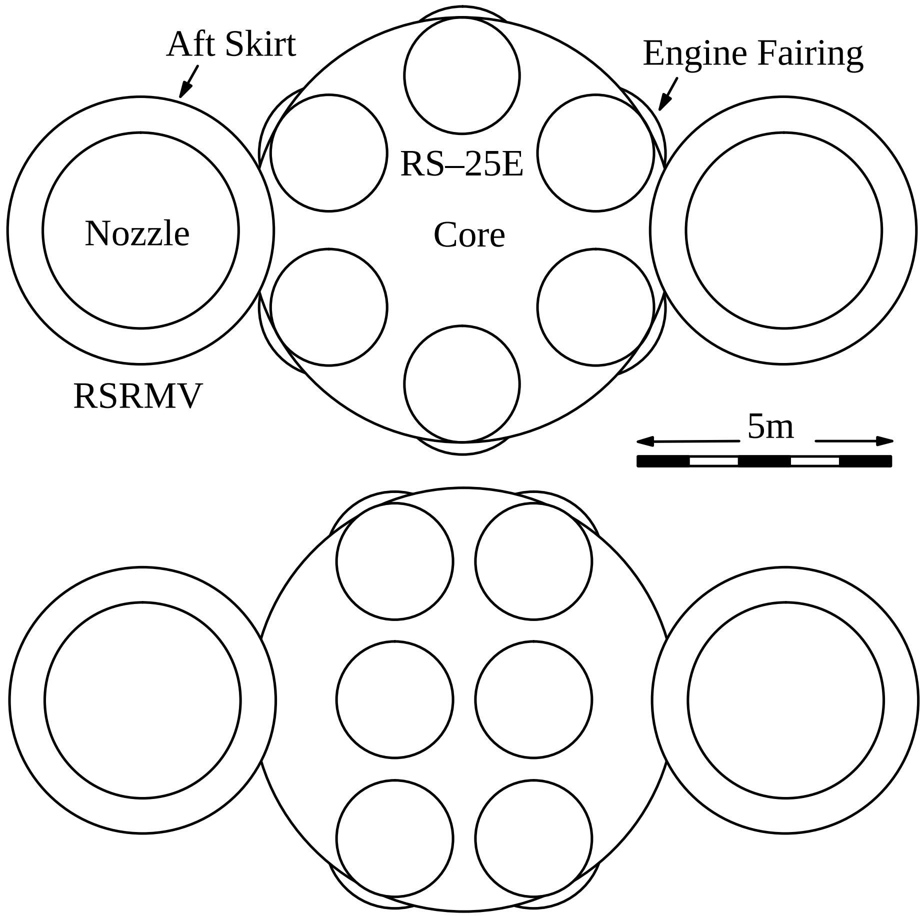


RSRMV vacuum thrust against time.

RSRMV Parameters	
Aft Skirt Diameter (m)	5.288
Additional Area (m^2)	–0.038
Nozzle Exit Diameter (m)	3.875
Sea Level Thrust at 0.2 s (N)	15,471,544
Vacuum Isp (m/s)	2605.4
Total Mass (kg)	729,240
Usable Propellant (kg)	631,185
Residual Propellant (kg)	1,304
Burnout Mass (kg)	96,751
Action Time (s)	128.4

Core Stage

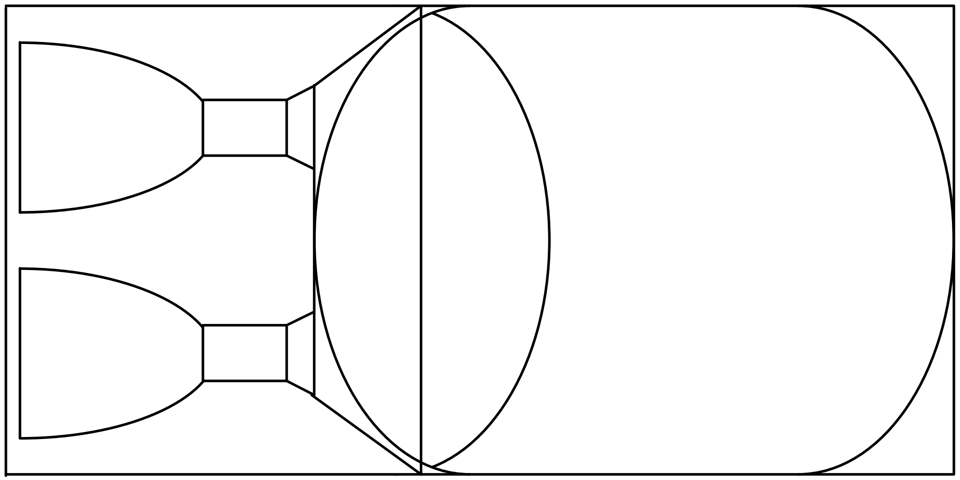
- Six engine core derived from four engine SLS Block I core. Increased dry mass (not including engines) by 15,513 kg and added mass of six RS–25E engines at 3,700 kg each.
- Examined three engine configurations. Circle of 6 has engines 0.936 m away from RSRMV nozzle, circle of 5 with 1 central is 0.5 m away and two rows of 3 engines is 1.903 m away.



Core Parameters with RS–25E engines	
Diameter (m)	8.407
Additional Area (m^2)	3.087
Nozzle Diameter (m)	2.304
Single Engine Vacuum Thrust (N) 111% RPL	2,320,637
Vacuum Isp (m/s)	4420.8
Number of Engines	6
Total Mass at Liftoff (kg)	1,093,602
Dry Mass (kg)	123,595
Usable Propellant (kg)	959,506
Reserve Propellant (kg)	7,984
Nonusable Propellant (kg)	2,517
Startup Propellant (kg)	12,656

Large Upper Stage (LUS)

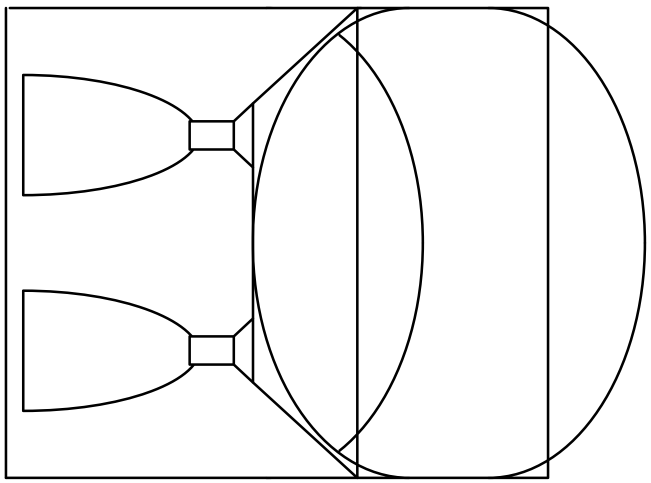
- Stage size determined in an iterative fashion. Start with fixed total interstage, LUS and payload mass (m_t). Adjust turn time and maximum angle of attack of core and LUS for 37x200 km orbit. Then adjust m_t and repeat process until payload is maximised.
- Uses two J–2X engines for maximum payload into LEO. Due to vehicle height restrictions had to reduce payload mass from 143,165 kg to 140,667 kg and use a common bulkhead.



LUS Parameters with J–2X engines	
Diameter (m)	8.407
Nozzle Diameter (m)	3.048
Single Engine Vacuum Thrust (N)	1,307,777
Vacuum Isp (m/s)	4393.4
Number of Engines	2
Total Mass at Liftoff (kg)	186,716
Dry Mass (kg)	16,894
Total Propellant (kg)	169,426
Startup Propellant (kg)	771
Main Stage Propellant (kg)	166,048
Reserve Propellant (kg)	449
Ullage Gas Propellant (kg)	1,067
Below Tank Propellant (kg)	435
Fuel Bias Propellant (kg)	656
Ullage Motors Propellant (kg)	205
Ullage Motors Dry Mass (kg)	191
Ullage Motors Thrust (N)	141,615
Ullage Motors Action Time (s)	3.87
Ullage Motors Offset Angle (°)	30
Interstage Mass (kg)	4,624

Cryogenic Propulsion Stage (CPS)

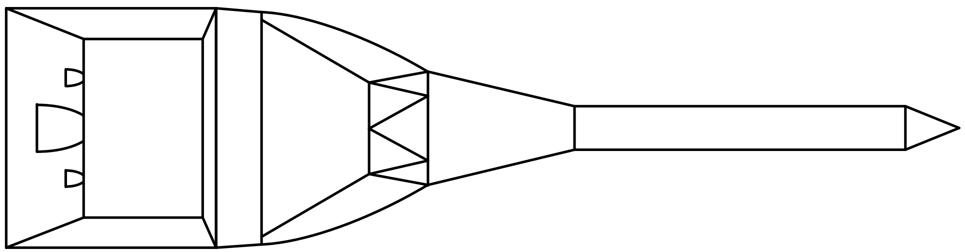
- Uses common bulkhead due to vehicle height restrictions. Iterative program used to determine CPS size. Uses four RL–10C–2 engines for Earth Orbit Insertion (EOI), Trans Lunar Injection (TLI), Lunar Orbit Insertion (LOI) and 75% of Powered Descent (PD).
- Reaction control system (RCS) uses GH_2/GO_2 thrusters (3432.3 m/s Isp) for trans Lunar (TL) trajectory correction manoeuvres (TCM) and powered descent initiation (PDI). Boiloff rate assumed at 0.17% per day.



CPS Parameters with RL–10C–2 engines		
Diameter (m)		8.407
Nozzle Diameter (m)		2.146
Single Engine Vacuum Thrust (N)		110,093
Vacuum Isp (m/s)		4535.6
Number of Engines		4
Total Mass at Liftoff (kg)		104,330
Dry Mass (kg)		9,000
Total Propellant (kg)		95,330
EOI Propellant (kg)	49.0 m/s	1,528
TLI Propellant (kg)	3184.9 m/s	70,038
TCM RCS Propellant (kg)	3.8 m/s	76
LOI Propellant (kg)	960.4 m/s	13,004
PDI RCS Propellant (kg)	24.9 m/s	213
PD Propellant (kg)	1531.2 m/s	8,383
PD RCS Propellant (kg)	5.5 m/s	47
Reserve Propellant (kg)	60.8 m/s	460
Propellant Boiloff (kg)	5 days	811
Ullage Gas Propellant (kg)		599
Below Tank Propellant (kg)		71
Fuel Bias Propellant (kg)		101
Interstage Mass (kg)		1,738

Orion Multipurpose Crew Vehicle (MPCV)

- For initial missions a crew of three astronauts is used. The service module fairing (SMF) and launch abort system (LAS) are ejected at 375 s and 380 s after launch, respectively.
- Orion 220 N RCS (2650 m/s Isp) used for transposition and docking (TAD), low Lunar orbit (LLO) control and trans Earth (TE) TCM.
- Due to limited propellant, the plane change (PC) allows latitudes up to 12° to be reached.
- At TLI the maximum load on the docking ring is 164.6 kN, less than the maximum of 300 kN of the International Docking System Standard.

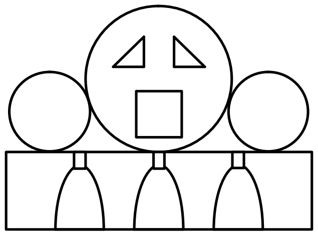


Orion Parameters		
Diameter (m)		5.029
Vacuum Isp (m/s)		3069.5
Total Mass at Liftoff (kg)		35,259
Launch Abort System Mass (kg)		7,643
Crew Mass (kg)		375
Crew Module Mass (kg)		9,887
Service Module Inert Mass (kg)		6,858
Service Module Fairing Mass (kg)		1,384
Service Module Adaptor Mass (kg)		510
Total Propellant (kg)		8,602
TAD Propellant (kg)	0.6 m/s	6
PC Propellant (kg)	46.2 m/s	380
LLO RCS Propellant (kg)	5.5 m/s	53
TEI Propellant (kg)	1168.7 m/s	8,037
TCM RCS Propellant (kg)	1.7 m/s	11
Reserve Propellant (kg)	12.2 m/s	69
Unusable Propellant (kg)		45
Spacecraft Launch Adaptor Mass (kg)		1,285

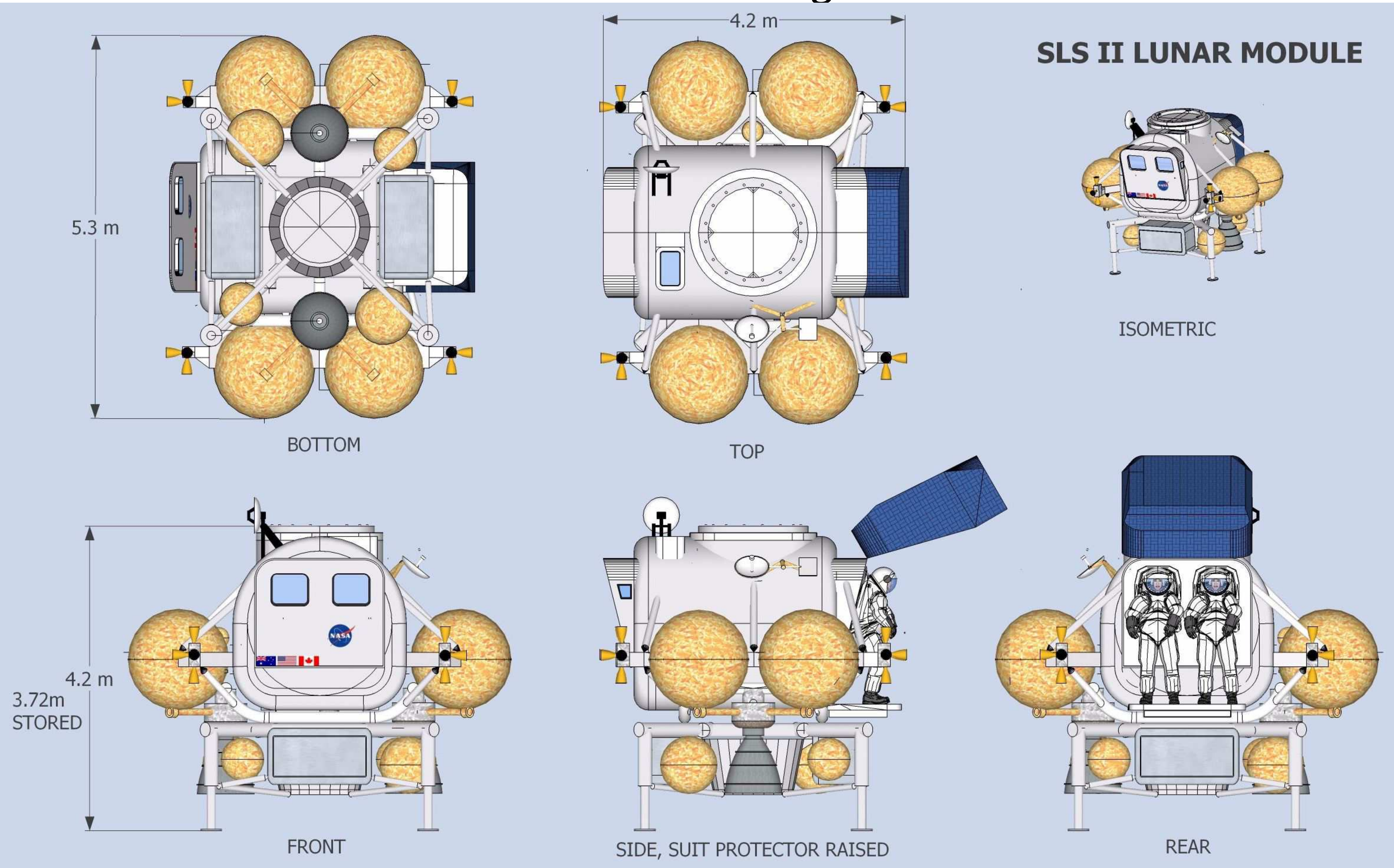
Lunar Module (LM)

- The LM initially carries two crew, but is sized for up to four crew. Consists of the crew and propulsion module (CPM) and non–propulsive landing and cargo module (LCM).
- Storable N_2O_4/Aerozine–50 propellants are used. LM performs last 25% of PD. Four equal sized spherical tanks of 1.314 m diameter are used.
- Two outer steerable and throttleable engines used for descent and one fixed position and thrust inner engine used for ascent.
- If LCM fails to separate from CPS, CPM separates and performs abort. If ascent engine fails can use descent engines as backup.
- Cabin diameter is 2.4 m. LCM height (not including landing legs) is 1.265 m. LCM has large cargo volume for experiments, tools and Lunar roving vehicle.

LM Parameters		
Landing Engines Isp (m/s)		2991.0
Ascent Engine Isp (m/s)		3040.1
Total Mass at Liftoff (kg)		10,348
CPM Dry Mass (kg)		3,558
LCM Mass (kg)		588
LM Adaptor Mass (kg)		602
Cargo Mass (kg)		509
Total Propellant (kg)		5,092
Descent RCS Propellant (kg)	5.5 m/s	19
Descent Propellant (kg)	510.4 m/s	1,568
Ascent RCS Propellant (kg)	5.5 m/s	14
Ascent Propellant (kg)	1890.0 m/s	3,432
Reserve Propellant (kg)	24.1 m/s	33
Unusable Propellant (kg)		27
Crew Mass (kg)		250
Return Sample Mass (kg)		100



Lunar Module Configuration



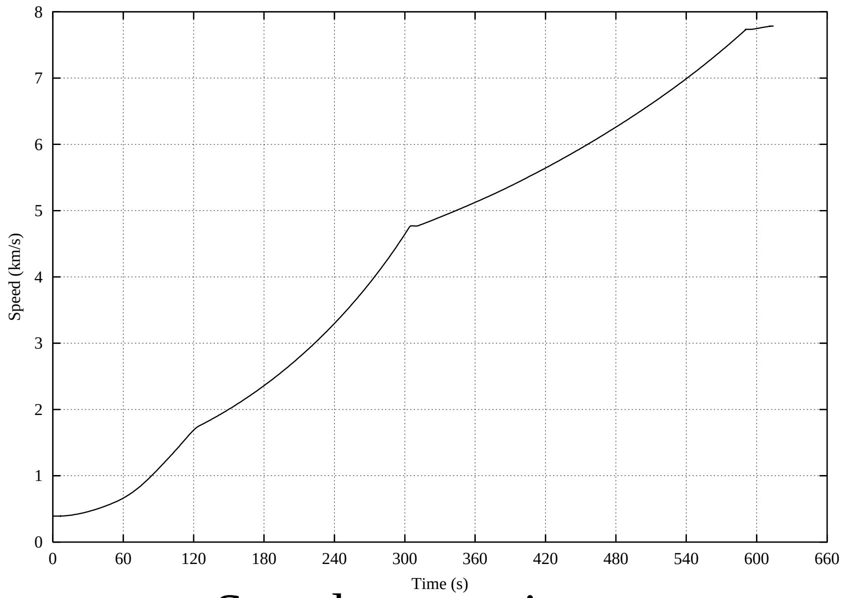
Trajectory Simulations

- Used custom two dimensional (2D) trajectory simulation program. Runga–Kutta fourth order method used to solve differential equations. Can model changing thrust. Standard atmosphere used.
- Launch from Kennedy Space Center at 28.45° latitude into 32.55° orbit. As 2D program used, adjusted Earth's rotation from 408.9 m/s to 391.1 m/s.
- Two parameters used to get into orbit, the time at which vehicle is made to follow gravity turn after launch (turn time) and maximum angle of attack for LUS and CPS.
- Typically require 100 to 200 iterations to find optimum payload mass. Found turn time of 5.051 s and maximum angle attack of 10.9612° for chosen vehicle.
- For RSRMV and Core Stage, gravity turn has zero air angle of attack. For LUS and CPS, use algorithm that gradually increases angle of attack until maximum value reached. Centrifugal forces then gradually reduce angle of attack to zero.

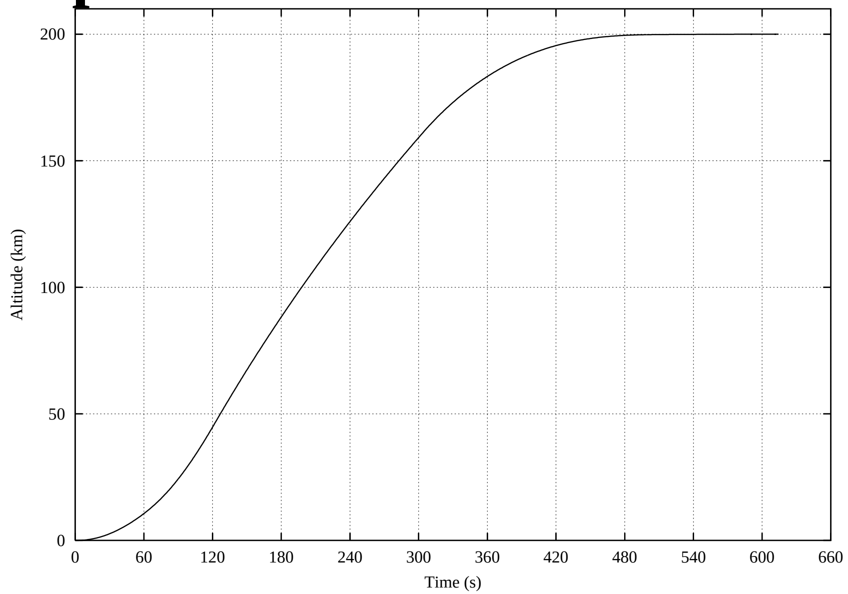
SLS Block II Summary	
Orbit (km)	200±0.0
Inclination (°)	32.55
Liftoff Thrust at 0.2 s (N)	42,332,715
Liftoff Mass (kg)	2,895,882
Liftoff Acceleration (m/s^2)	14.63
Maximum Dynamic Pressure (Pa)	28,878
Maximum Acceleration (m/s^2)	29.02
LAS Jettison Time (s)	375
SMF Jettison Time (s)	380
Total Payload (kg)	140,667
Total Delta–V (m/s)	9,155

- SLS1C6J2C4 software freely available from http://www.sworld.com.au/steven/space/sls/

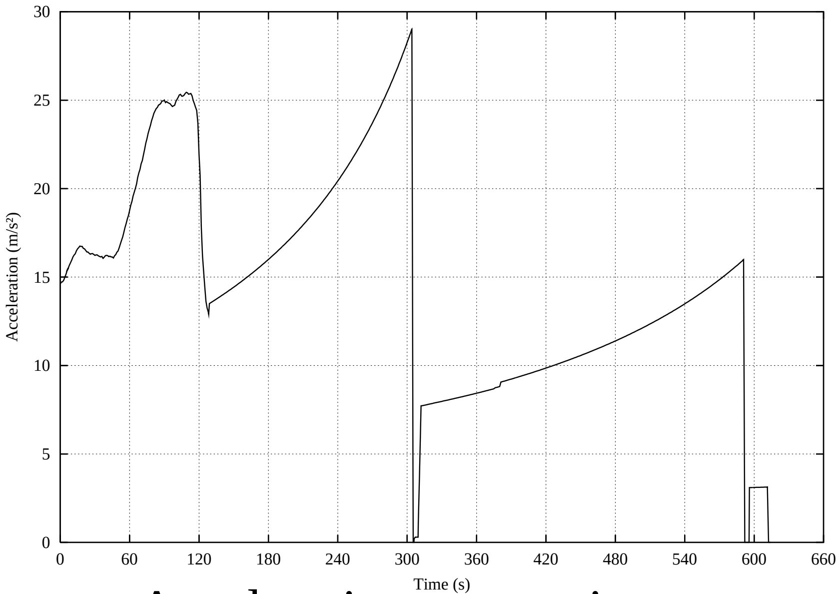
Simulation Output



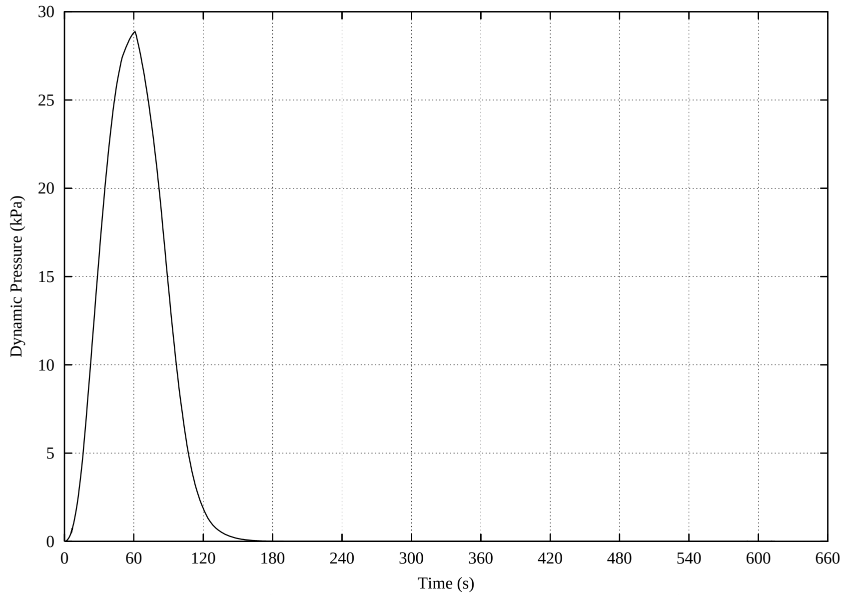
Speed versus time.



Altitude versus time.



Acceleration versus time.



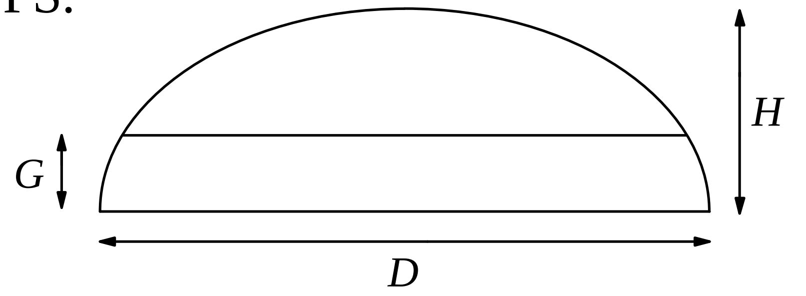
Dynamic pressure versus time.

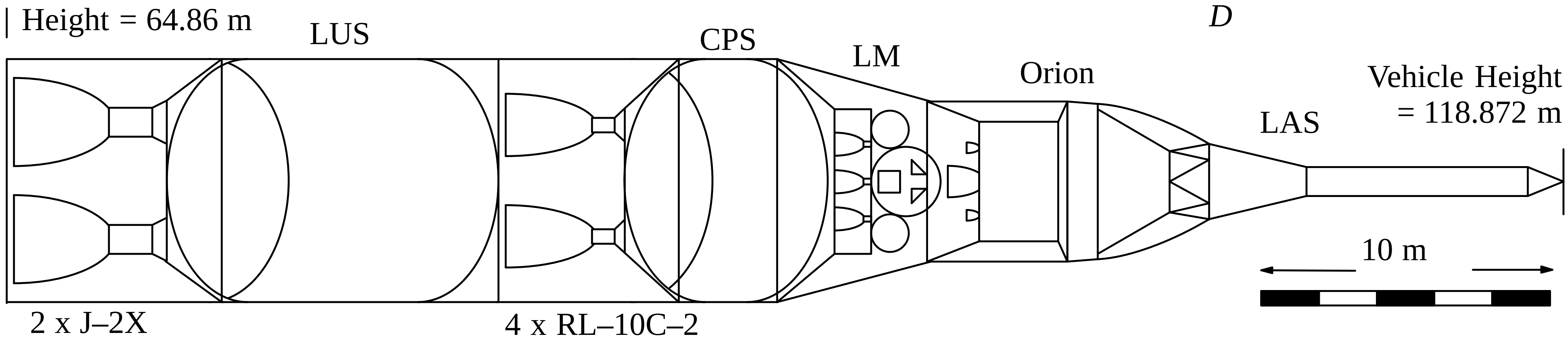
Vehicle Height

- Maximum vehicle length for Kennedy Space Center Vehicle Assembly Building is 118.872 m. With D = 8.407 m diameter and three LOX/LH_2 stages, vehicle is too tall with a separate tank design for the LUS and CPS.
- Designed LUS and CPS with forward facing common bulkhead design to reduce vehicle length. Has added benefit of increased payload at the expense of increased development and production cost.
- Even with common bulkheads, vehicle height was exceeded by over two meters. Reduced propellant load in LUS and CPS to meet vehicle height requirement. LEO payload loss was only 2,498 kg.
- Assumed dome height $H = D/3$. Calculated tank side wall lengths of 5.887 m for LUS and 1.422 m for CPS. LOX tank bishell volume is

$$V_o = \pi D^2(2H + G^3/H^2 - 3G)/6.$$

- Calculated G = 0.688 m for LUS and 1.274 m for CPS.





Lunar Mission Costs

- Used Spacecraft/Vehicle Level Cost Model derived from NASA/Air Force Cost Model (NAFCOM) database. Amounts adjusted to 2017 US dollars. All amount in $M.

Element	Dry Mass Each (kg)	Devel. Cost	Prod. Cost 11	Prod. Cost 29
2×RSRMV	96,751	2,023.9	1,854.2	3,894.5
1×Core	101,395	5,933.6	3,214.5	6,751.7
1×LUS	11,950	2,105.1	897.6	1,885.2
1×CPS	7,796	1,664.3	676.4	1,420.8
1×LM	4,145	2,592.3	1,300.1	2,730.7
1×Orion	16,745	5,587.0	3,276.3	6,881.5
1×LAS	5,044	797.3	308.6	648.3
6×RS–25E	3,700	3,880.0	1,324.4	2,781.7
2×J–2X	2,472	3,108.1	437.3	918.5
4×RL–10C	301	976.2	184.4	387.4
Total*	250,299	12,497.7	13,473.8	28,300.3

*Total development cost excludes RSRMV, Orion, LAS, RS–25E, J–2X, RL–10C–2 and Block I core development costs. Includes 10% of RSRMV development cost ($202.1M) to restart steel segment production.

- Comparison to dual Block IB mission with EUS delivering Orion and LM to LLO in separate missions. Assume LM mass same as Orion mass of 25,848 kg.

Element	Dry Mass Each (kg)	Devel. Cost	Prod. Cost 11	Prod. Cost 29
4×RSRMV	96,751	2,023.9	3,152.1	6,620.7
2×Core	85,898	5,416.3	4,896.5	10,284.3
2×EUS	10,650	1,718.1	1,229.4	2,582.2
1×LM	7,758	3,659.4	1,968.7	4,135.1
1×Orion	16,745	5,587.0	3,276.3	6,881.5
1×LAS	5,044	797.3	308.6	648.3
8×RS–25E	3,700	3,880.0	1,650.6	3,467.0
8×RL–10C	301	976.2	313.6	658.6
Total*	226,847	5,579.9	16,795.8	35,277.7

- Total cost for Block II is $25,971.5M for 11 missions and $40,798.0M for 29 Missions. Total cost for Block IB is $22,376.7M for 11 missions and $40,857.6M for 29 Missions. Block II is cheaper for 29 or more missions. Block II per mission costs are 20% cheaper.

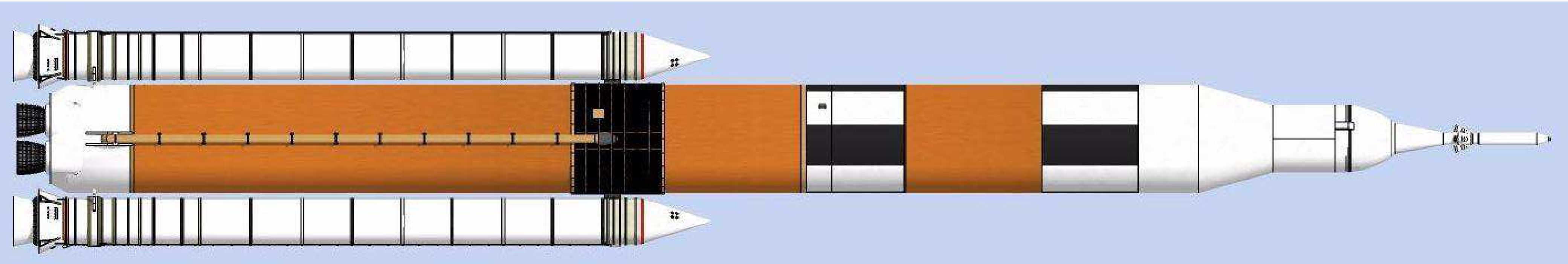
Comparison With Other Block II Configurations

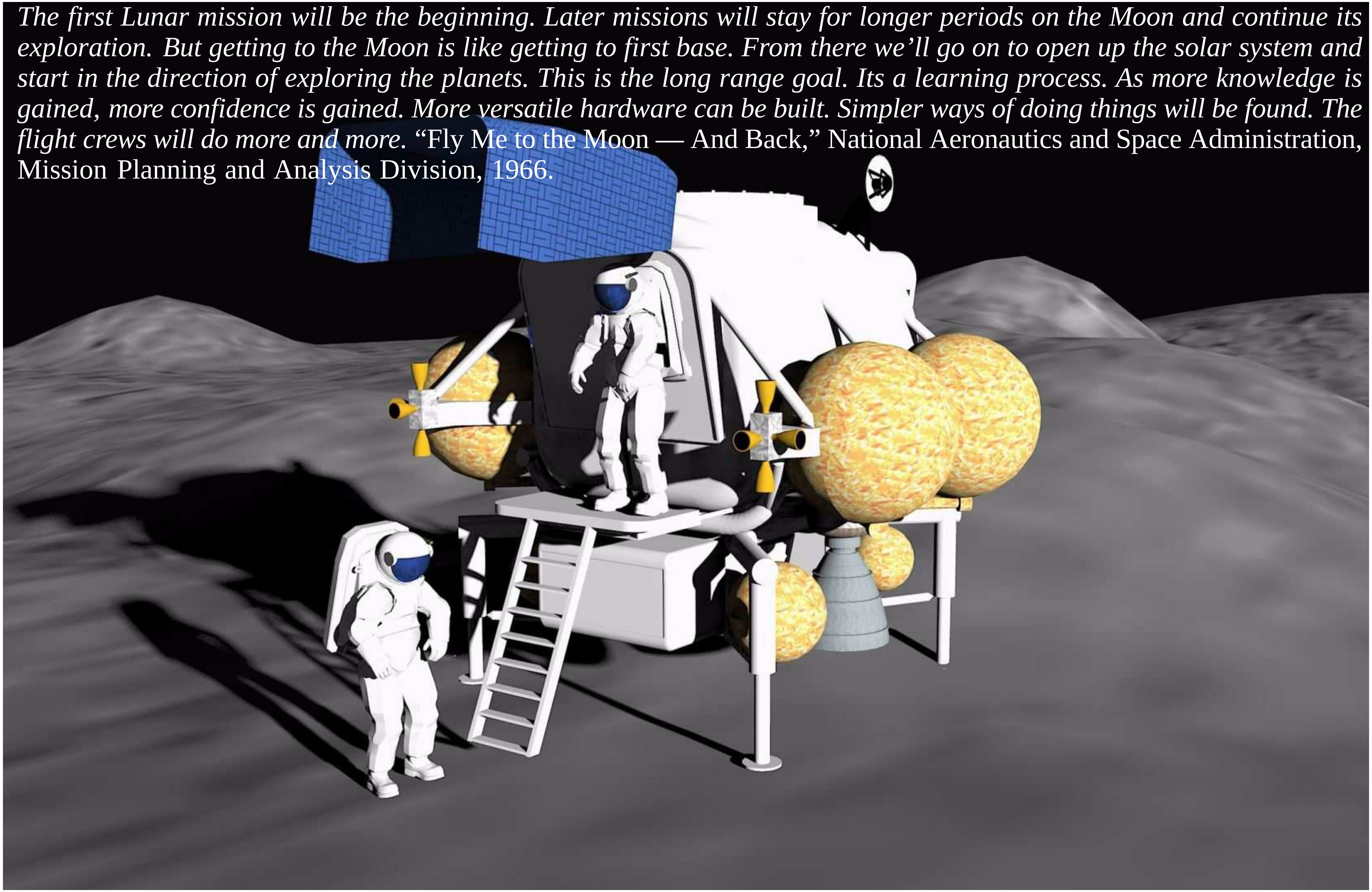
- Examined various Block II configurations that achieved 130 t payload (not IMLEO) to LEO. Used earlier lighter versions of LAS and SMF ejected at 300 s. Dry mass of LUS used heavier separate tank design. Orbit inclination of 28.45°. All configurations used an LUS with two J–2X engines
- SLS1C6J2.1 – 2×RSRMV, 6×RS–25E Core.
- SLS2C4J2.2 – 2×Pyrios Boosters each with 2×F–1B engines, 4×RS–25E Core.
- SLS3C4J2.2 – 2×Liquid Boosters each with 3×AJ1E6 engines, 4×RS–25E Core.
- SLS4C5J2.2 – 2×Solid Advanced Boosters, 5×RS–25E Core.

SLS Block II Costs for 11 Flights ($M)

Config.	Payload (t)	Total*	Per Flight
SLS1C6J2.1	137.0	16,559.4	722.8
SLS2C4J2.2	133.2	27,358.7	1,174.2
SLS3C4J2.2	136.2	25,595.2	1,157.1
SLS4C5J2.2	144.1	18,025.8	701.2

- Total costs excludes RSRMV, Block I Core, RS–25E and J–2X development costs. Includes 10% of RSRMV development cost to restart steel segment production.
- Cheapest Block II option is the one we have chosen with RSRMV boosters and six engine core. Advanced Solid Boosters is next cheapest at 9% greater total. Per flight costs are only 3% cheaper.





The first Lunar mission will be the beginning. Later missions will stay for longer periods on the Moon and continue its exploration. But getting to the Moon is like getting to first base. From there we'll go on to open up the solar system and start in the direction of exploring the planets. This is the long range goal. Its a learning process. As more knowledge is gained, more confidence is gained. More versatile hardware can be built. Simpler ways of doing things will be found. The flight crews will do more and more. "Fly Me to the Moon — And Back," National Aeronautics and Space Administration, Mission Planning and Analysis Division, 1966.