SLS 1C with AJ1E6 Advanced Boosters and 4xMB–60 optimised upper stage. Payload to 200 km LEO = 132.6 t. 7 Dec. 2013. Author: Steven S. Pietrobon, PhD.

RSRMV thrust curve obtained from page 56 of [1]. There is a discrepancy in that Loaded Mass minus Burnout Mass in [1] is 650,743 kg compared to 633,233 kg in [2] and 628,701 kg in [3]. Therefore, we have adjusted the propellant mass and impulse in [1] to match the values in [2].

The dimensions of the AJ1E6 LOX/RP–1 Advanced Booster were estimated from page 13 of [4]. The AJ1E6 nozzle diameter of 1.834 m and area ratio of 31.04 was estimated from page 5 of [5]. The Isp of the AJ1E6 is not given, so this was estimated from the available values. The RD–180 [6] nozzle efficiency of $\eta = 0.8936$ allowed an estimation of the chamber pressure of P_c = 17,665.7 kPa and the sea level thrust coefficient of C_f = 1.821 using the formula $F_{sl} = P_c\ A_t\ C_f\ \eta$ and an Isp calculation program [7], where F_{sl} is the sea level thrust and A_t is the throat area. The estimated AJ1E6 chamber pressure is 34% less than the RD–180 at 26,670 kPa. The RD–180 Isp efficiency of 94.01% was then used to estimate the AJ1E6 Isp of 3274.5 m/s. This is 1.2% less than the RD–180 Isp due to the lower chamber pressure and reduced area ratio (31.04 instead of 36.87).

Using the figures in [4] allowed an estimation of the main booster diameter to be 5.125 m. This was used along with other measurements to give a total propellant mass of m_p = 721.178 t and oxidiser to fuel ratio of 2.693. The engine mass was derived using Figure 9 from [8], using the formula $m_e/R_v = 3.5428 + 2\times10^{-7}F_v$ where R_v = 1613.2 L/s is the propellant volume flow rate and F_v = 5,428,390 N is the vacuum thrust. This gave an estimated engine mass for the AJ1E6 of m_e = 7,467 kg. The dry mass of the stage less engines was estimated using the formula $m_s = \alpha V_p^{0.848}$, where V_p is the propellant volume in m^3. The constant α = 0.367626 was determined from the dry mass less engine mass and propellant volume of the Pyrios stage [9].

Boosters	1C4J2.2	2C4J2	2C4B4	3C4B4
Booster Name	RSRMV	Pyrios	Pyrios	Aerojet
Number of Boosters	2	2	2	2
Engine Name	–	F–1B	F–1B	AJ1E6
Number of Engines per Booster	1	2	2	3
Aft Skirt Diameter (m)	5.156	9.340	9.340	6.584
Booster Diameter (m)	3.711	5.486	5.486	5.125
Nozzle Diameter (m)	3.875	3.185	3.185	2×1.834
Sea Level Thrust at 0.2 s (N)	15,599,386	8,029,040	8,029,040	4,893,043
Maximum Vacuum Thrust (N)	17,866,606	8,836,221	8,836,221	5,428,390
Vacuum Isp (m/s)	2,622.3	2,932.7	2,932.7	3,274.5
Total Mass (kg)	733,776	942,030	942,030	838,857
Startup Propellant (kg)	0	17,940	17,940	13,216
Usable Propellant (kg)	632,791	787,311	787,311	696,646
Residual/Reserve Propellant (kg)	442	12,789	12,789	11,316
Burnout/Dry Mass (kg)	100,543	123,990	123,990	117,679
Action Time (s)	131.9	131.8	131.8	140.5

The simulations have no thrust bucket and reduced the thrust rating to 109%, as reported in [10].

Core Stage: 4xRS–25 Engines	1C4J2.2	2C4J2	2C4B4	3C4B4
Stage Diameter (m)	8.407	8.407	8.407	8.407
Nozzle Diameter (m)	2.304	2.304	2.304	2.304
Vacuum Isp (m/s)	4,436.5	4,436.5	4,436.5	4,436.5
Engine Thrust (N)	2,278,824	2,278,824	2,278,824	2,278,824
Engine Thrust Rating (%)	109	109	109	109
Thrust Bucket (%)	109	109	109	109
Total Mass (kg)	1,091,525	1,091,525	1,091,525	1,091,525
Usable Propellant (kg)	966,061	966,061	966,061	966,061
Reserve Propellant (kg)	8,210	8,210	8,210	8,210
Fuel Bias Propellant (kg)	1,678	1,678	1,678	1,678
Startup Propellant (kg)	7,439	7,439	7,439	7,439
Dry Mass (kg)	115,575	115,575	115,575	115,575

The size of the upper stage was optimised to maximise payload delivered into a 200 km orbit. The interstage mass was adjusted according to total maximum weight carried by the core. Ullage motors were added to ensure propellant settling, similar to that used by the Saturn V. MB–60 parameters were obtained from [11] (thrust and engine mass), [12] (Isp) and [13] (nozzle diameter).

Upper Stage:	1C4J2.2	2C4J2	2C4B4	3C4B4
Engines	J–2X	J–2X	MB–60	MB–60
Number of Engines	2	2	4	4
Stage Diameter (m)	8.407	8.407	8.407	8.407
Nozzle Diameter (m)	3.048	3.048	2.286	2.286
Vacuum Isp (m/s)	4,275.7	4,275.7	4,560.1	4,560.1
Single Engine Thrust (N)	1,281,088	1,281,088	266,700	266,700
Single Engine Mass (kg)	2,472	2,472	590	590
Total Mass (kg)	147,516	156,359	97,334	94,423
Usable Propellant (kg)	125,292	133,184	83,083	80,479
Reserve Propellant (kg)	2,114	2,247	1,399	1,355
Startup Propellant (kg)	771	771	300	300
Residual Propellant (kg)	0	0	0	0
RCS Propellant (kg)	102	116	92	92
Dry Mass (kg)	19,005	19,748	12,264	12,001
Ullage Motors Propellant (kg)	115	148	96	96
Ullage Motors Dry Mass (kg)	117	145	100	100
Ullage Motors Action Time (s)	3.87	3.87	3.87	3.87
Ullage Motors Thrust (N)	65,032	83,178	54,017	54,149
Ullage Motors Offset Angle (°)	30	30	30	30
Interstage Mass (kg)	5,944	8,910	7,494	7,192

The LAS/SAJ jettison time was obtained from [14]. Simulation results for 3C4B4 are shown in Figures 1–4. The AJ1E6 powered boosters were able to increase payload by 2.5% or 3.2 t from 129.4 t to 132.6 t over the F–1B powered boosters.

	1C4J2.2	2C4J2	2C4B4	3C4B4
Orbit (km)	200 ± 0.4	200 ± 0.4	200 ± 0.4	200 ± 0.5
Liftoff Thrust at 0.2 s (N)	38,623,742	39,541,132	39,541,132	36,783,231
Liftoff Mass (kg)	2,823,613	3,242,240	3,182,240	2,985,342
Liftoff Acceleration (m/s^2)	13.69	12.20	12.43	12.32
MaxQ (Pa)	21,877	28,287	30,746	28,644
Maximum Acceleration (m/s^2)	23.80	31.65	33.06	31.85
LAS/SAJ Jettison Time (s)	330	330	330	330
Launch Abort System (kg)	7,394	7,394	7,394	7,394
Orion Jettisoned Adaptors (kg)	920	920	920	920
Other Spacecraft (kg)	102,762	128,953	129,394	132,607
Remaining Propellant (kg)	0	0	0	0
Total Payload (kg)	102,762	128,953	129,394	132,607
Total Delta–V (m/s)	9,905	9,689	9,583	9,564

[1] Alliant Techsystems Inc., "ATK space propulsion products catalog," Aug. 2012.

[2] B. Donahue and J. Bridges, "The Space Launch System capabilities for enabling crewed Lunar and Mars exploration," *63rd Int. Astronautical Congress*, Naples, Italy, IAC–12–D2.8.7, Oct. 2012.

[3] P. Phillips, "Ground systems development and operations," NASA, July 2012.

[4] S. Crumbly, "NASA's Space Launch System: Partnering for tomorrow," *ASEE Eng. Research Council*, Washington, DC, USA, Mar. 2013. http://www.asee.org/Crumbly_ASEE_Final.pdf

[5] S. Crumbly, "NASA's Space Launch System: Partnering for tomorrow," *Space & Missile Defense Symp*, Huntsville, AL, USA, Aug. 2013. http://smdsymposium.org/wp–content/uploads/2013/09/Crumbly–presentation.pdf

[6] NPO Energomash, "RD–180 rocket engine," in Russian. http://www.lpre.de/energomash/RD–180/index.htm

[7] C. Selph, "United States Air Force chemical equilibrium specific impulse (Isp) code," Mar. 1992. http://www.dunnspace.com/isp.htm

[8] S. S. Pietrobon, "A flexible reusable space transportation system," *J. of the British Interplanetary Society*, vol. 53, pp. 276–288, May/June 2000.

[9] S. Cook, K. Doering, A. Crocker and R. Bachtel, "Enabling an affordable advanced liquid booster for NASA's Space Launch System," *63rd Int. Astronautical Congress*, Naples, Italy, IAC–12–D2.8.10, Oct. 2012.

[10] M. Davidson, "RS–25: The Clark Kent of engines for the Space Launch System," 13 Sep. 2013. http://www.nasa.gov/exploration/systems/sls/rs25–engine–powers–sls.html

[11] Mitsubishi Heavy Industries, Ltd., "MB–XX," http://www.mhi.co.jp/en/products/detail/space_rocket_engine_mb–xx.html

[12] B. Donahue and S. Sigmon, "The Space Launch System capabilities with a new large upper stage," *AIAA Space 2013 Conf. & Exposition.*, San Diego, CA, USA, Sep. 2013.

[13] J. R. Bullock, M. Popp and J. R. Santiago, "Program status of the Pratt & Whitney RL60 engine," *AIAA/ASME/SAE/ASEE Joint Propulsion Conf. & Exhibit*, Indianapolis, IN, USA, July 2002.

[14] S. Creech, J. Holladay and D. Jones, “SLS dual use upper stage (DUUS) opportunities,” *Partnership Study with JAXA*, Huntsville, AL, USA, Apr. 2013.

Figure 1: Altitude versus time for SLS Block 1C

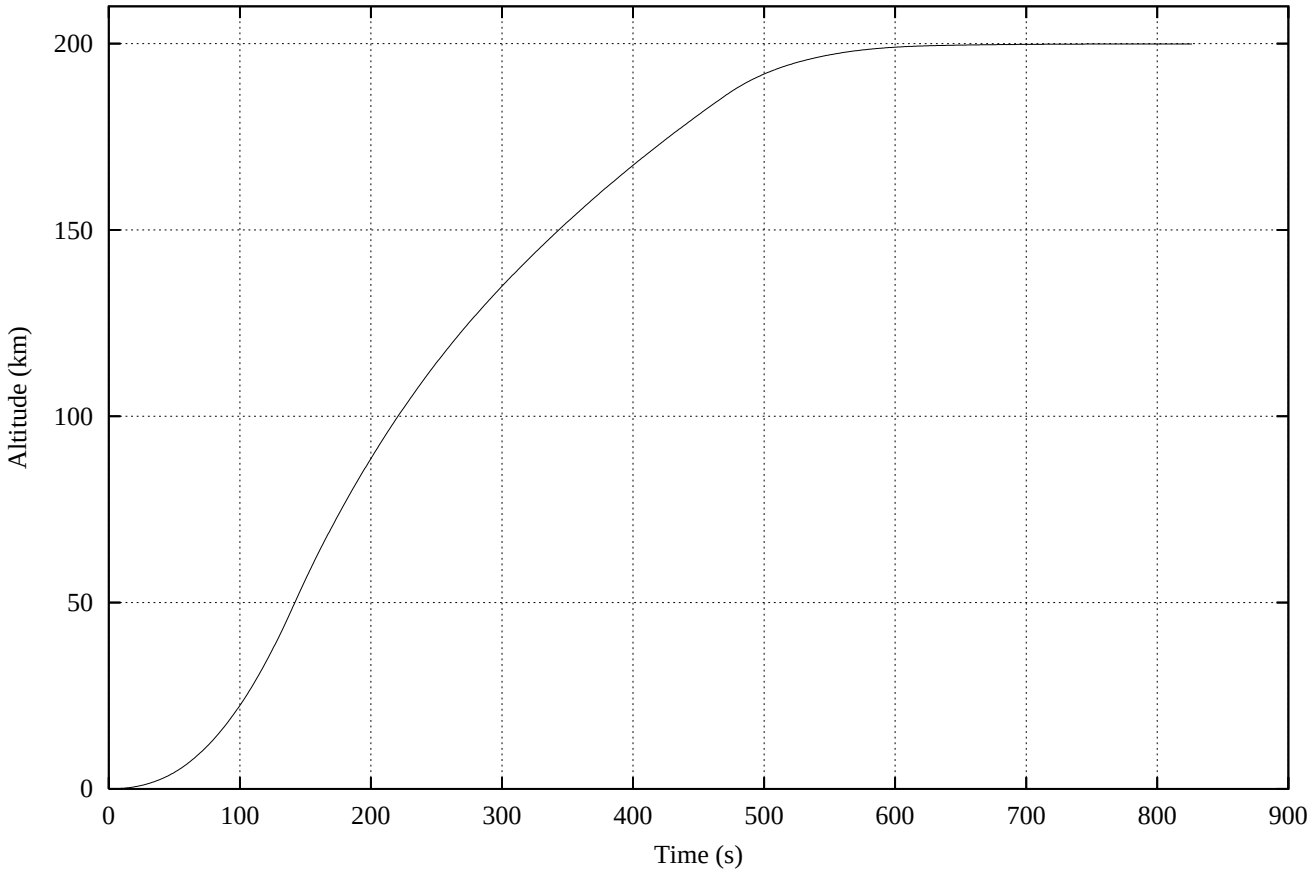

Figure 2: Speed versus time for SLS Block 1C

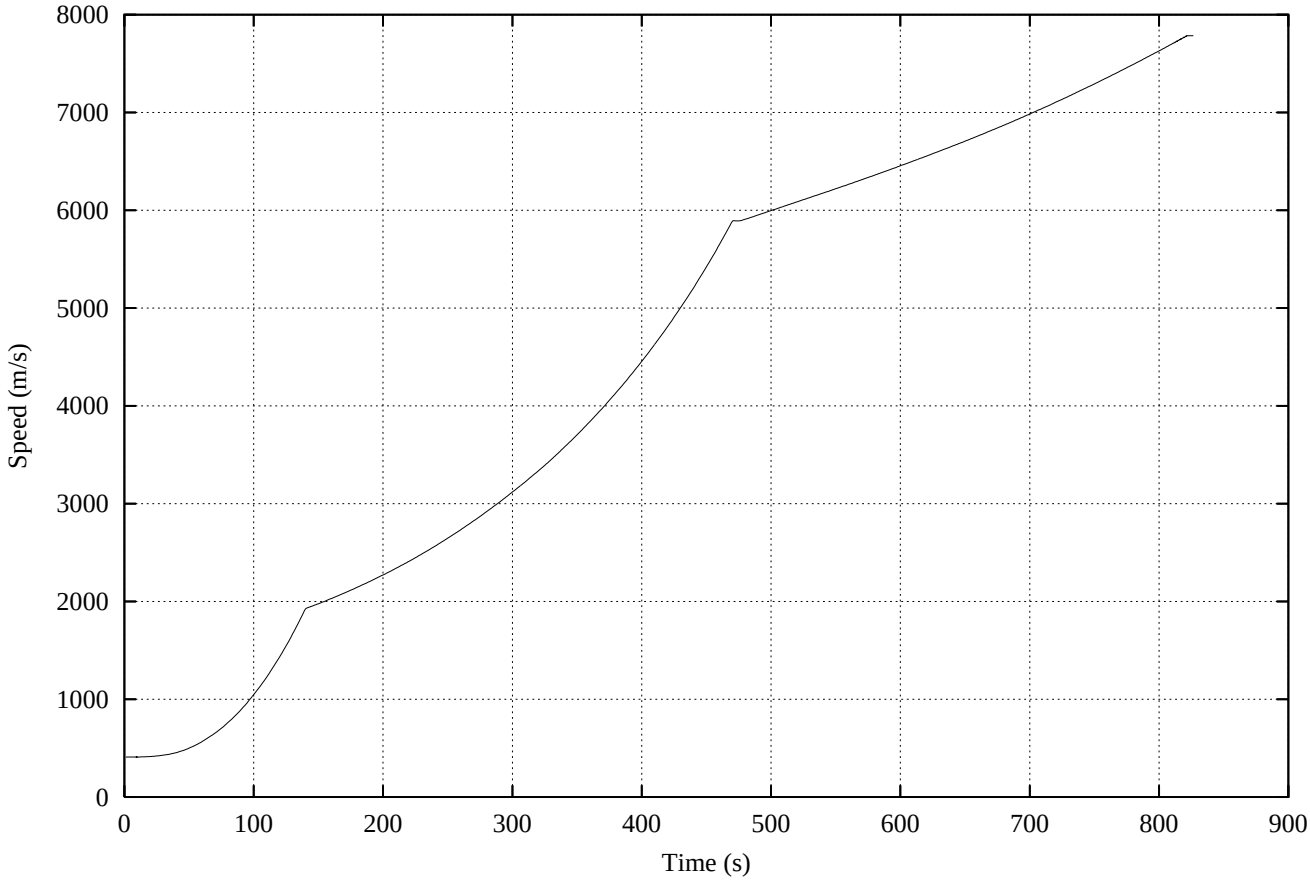

Figure 3: Acceleration versus time for SLS Block 1C

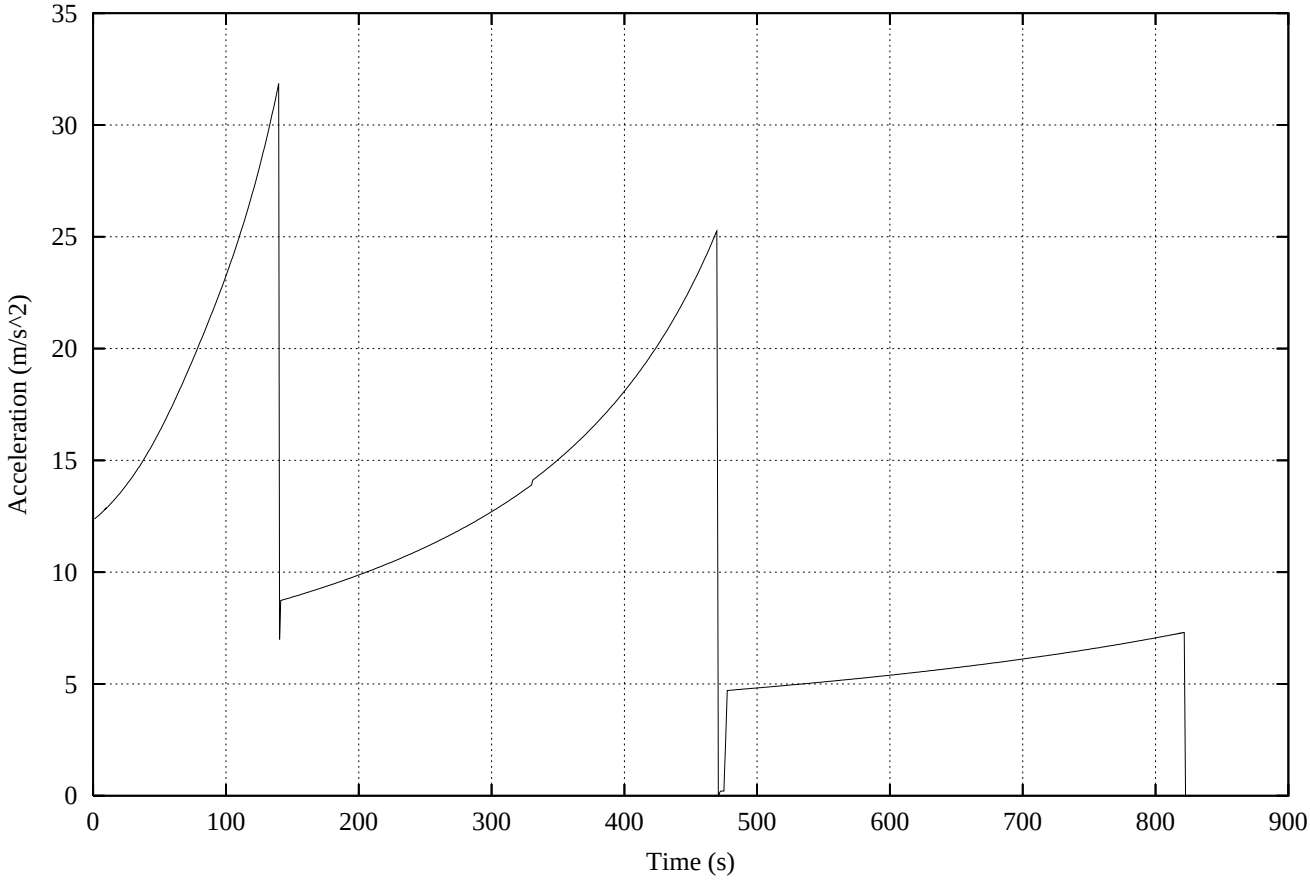

Figure 4: Dynamic pressure versus time for SLS Block 1C