SLS Block II with AJ1E6 Advanced Boosters, 2xJ–2X optimised upper stage and heavy core. Payload to 200 km LEO = 136.2 t. 23 Aug. 2014. Author: Steven S. Pietrobon, PhD.

The dimensions of the AJ1E6 LOX/RP–1 Advanced Booster were estimated from page 13 of [1]. The AJ1E6 nozzle diameter of 1.834 m and area ratio of 31.04 was estimated from page 5 of [2]. The Isp of the AJ1E6 is not given, so this was estimated from the available values. The RD–180 [3] 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 [4], 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 [1] 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 [5], 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 [6].

Boosters	3C4J2.1	3C4J2.2
Booster Name	Aerojet	Aerojet
Engine Name	AJ1E6	AJ1E6
Number of Engines per Booster	3	3
Aft Skirt/Nacelle Diameter (m)	6.584	6.584
Booster Diameter (m)	5.125	5.125
Additional Area (m^2)	0.051	0.051
Nozzle Diameter (m)	2×1.834	2×1.834
Sea Level Thrust at 0.2 s (N)	4,893,043	4,893,043
Maximum Vacuum Thrust (N)	5,428,390	5,428,390
Vacuum Isp (m/s)	3,274.5	3,274.5
Total Mass (kg)	838,857	838,857
Startup Propellant (kg)	13,216	13,216
Usable Propellant (kg)	696,646	696,646
Residual/Reserve Propellant (kg)	11,316	11,316
Burnout/Dry Mass (kg)	117,679	117,679
Action Time (s)	140.5	140.5

The core values have been updated according to [7] and other sources with RS–25E engines. The dry mass of the heavy core in [8] is used.

Core Stage:	3C4J2.1	3C4J2.2
Stage Diameter (m)	8.407	8.407
Additional Area (m^2)	2.073	2.073
Engines	RS–25E	RS–25E
Number of Engines	4	4
Nozzle Diameter (m)	2.304	2.304
Vacuum Isp (m/s)	4,420.8	4,420.8
Engine Thrust (N)	2,320,637	2,320,637
Engine Thrust Rating (%)	111	111
Total Mass at Liftoff (kg)	1,074,908	1,089,801
Dry Mass (kg)	100,682	115,575
Usable Propellant (kg)	964,564	964,564
Reserve Propellant (kg)	7,984	7,984
Fuel Bias Propellant (kg)	1,678	1,678
Startup Propellant (kg)	8,437	8,437

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 [9] (thrust and engine mass), [10] (Isp) and [11] (nozzle diameter).

Upper Stage:	3C4J2.1	3C4J2.2
Stage Diameter (m)	8.407	8.407
Engines	J–2X	J–2X
Number of Engines	2	2
Nozzle Diameter (m)	3.048	3.048
Vacuum Isp (m/s)	4,393.4	4,393.4
Single Engine Thrust (N)	1,307,777	1,307,777
Total Mass (kg)	170,021	171,834
Usable Propellant (kg)	145,440	147,084
Reserve/Residual Propellant (kg)	2,452	2,480
Startup Propellant (kg)	771	771
RCS Propellant (kg)	127	125
Dry Mass (kg)	20,889	21,041
Ullage Motors Propellant (kg)	175	170
Ullage Motors Dry Mass (kg)	167	163
Ullage Motors Action Time (s)	3.87	3.87
Ullage Motors Thrust (N)	98,910	96,083
Ullage Motors Offset Angle (°)	30	30
Interstage Mass (kg)	9,349	9,142

The LAS/SAJ jettison time was obtained from [12]. Simulation results for 3C4J2.2 are shown in Figures 1–4. The increase in core mass results in a decrease of 6,606 kg or 4.6% of the payload from 142.9 t to 136.2 t.

	3C4J2.1	3C4J2.2
Orbit (km)	200 ± 0.1	200 ± 0.1
Liftoff Thrust at 0.2 s (N)	36,951,344	36,951,344
Liftoff Mass (kg)	3,056,726	3,066,619
Liftoff Acceleration (m/s^2)	12.09	12.05
MaxQ (Pa)	26,510	26,323
Maximum Acceleration (m/s^2)	30.46	30.24
LAS/SAJ Jettison Time (s)	330	330
Launch Abort System (kg)	7,394	7,394
Orion Jettisoned Adaptors (kg)	920	920
Total Payload (kg)	142,852	136,246
Total Delta–V (m/s)	9,681	9,713

[1] 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

[2] 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

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

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

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

[6] 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.

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

[8] 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.

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

[10] 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.

[11] 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.

[12] 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 II

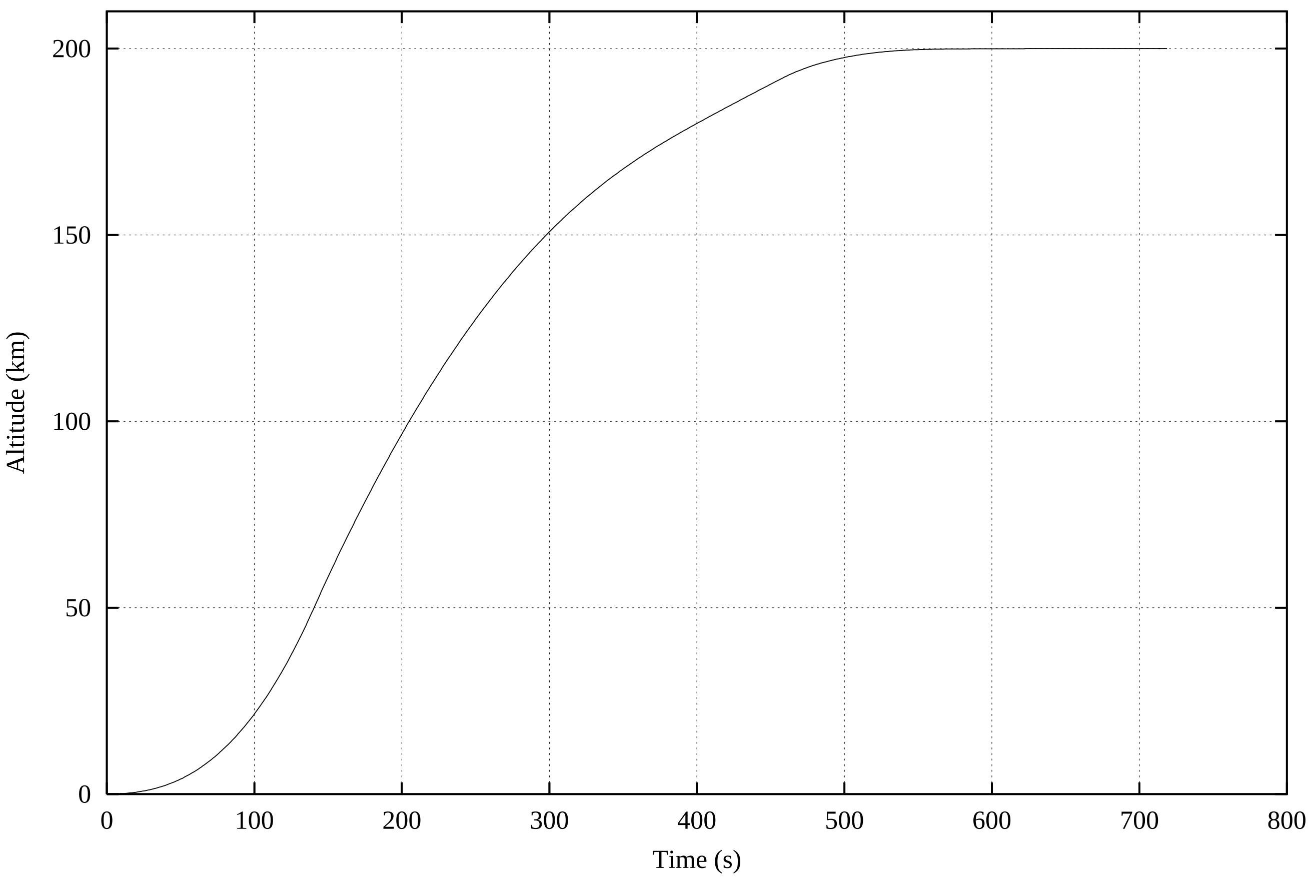

Figure 2: Speed versus time for SLS Block II

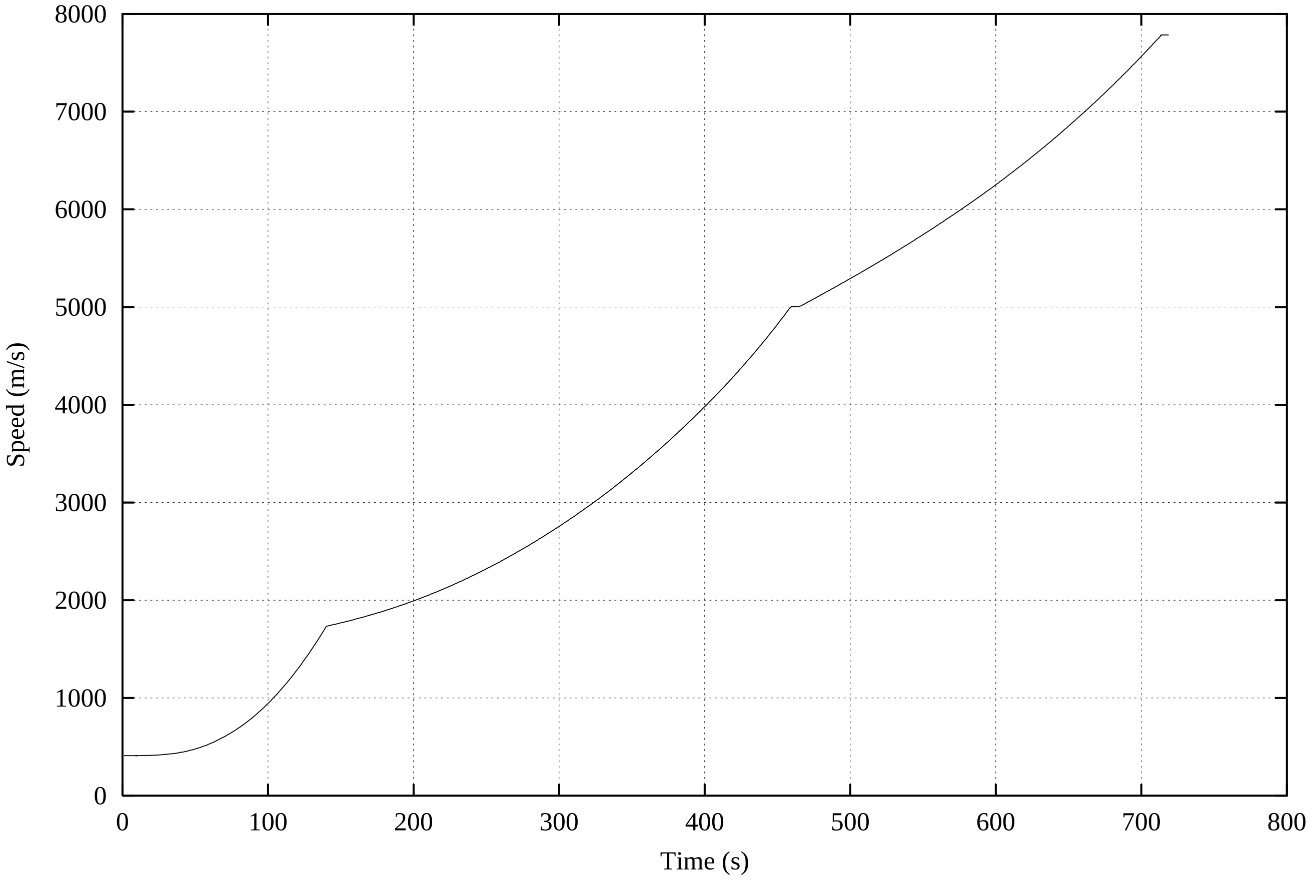

Figure 3: Acceleration versus time for SLS Block II

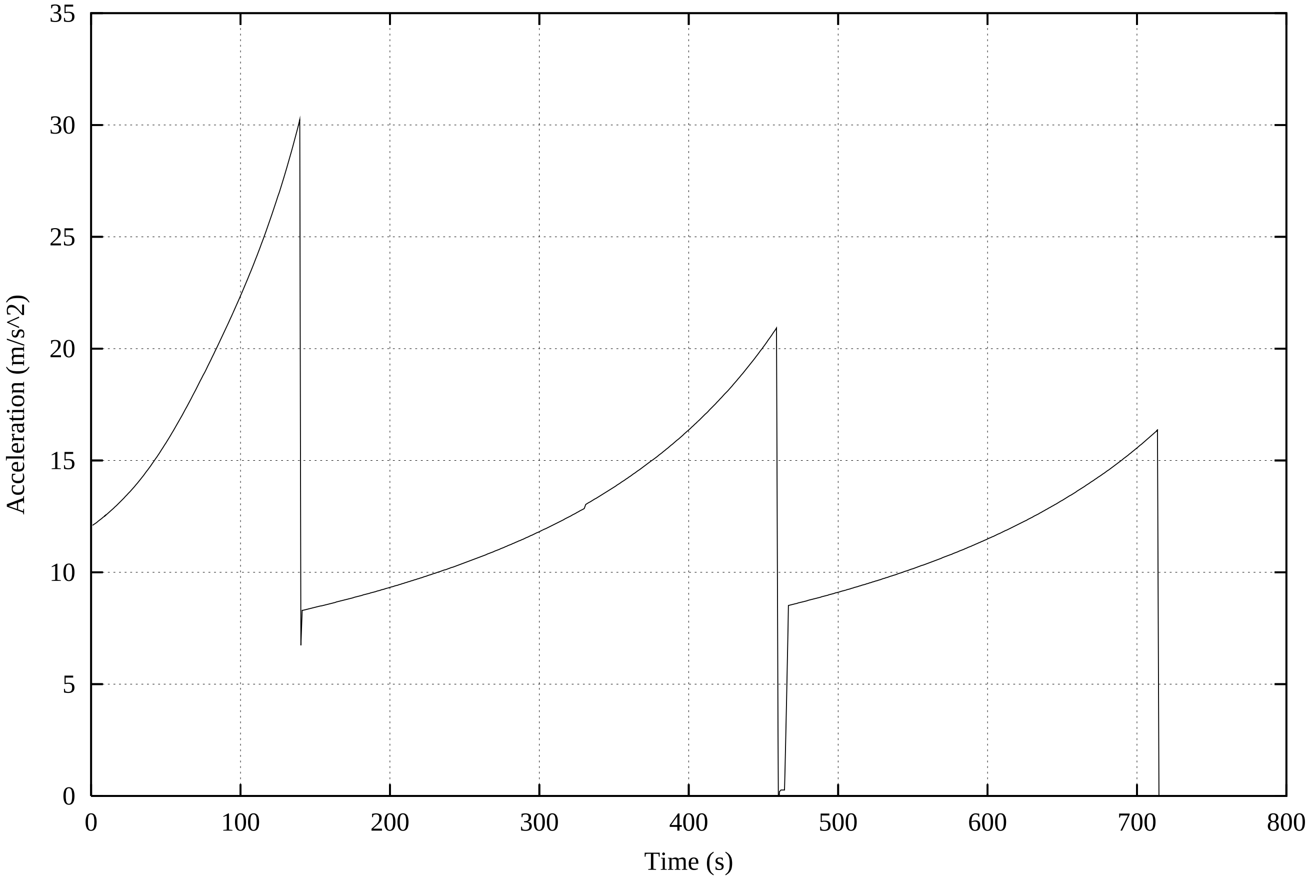

Figure 4: Dynamic pressure versus time for SLS Block II