Past Discrete Event Simulations

Summary of past lunar, asteroid, and Mars mission campaign analyses

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Past Discrete Event Simulations

Crewed Mission – Campaign Analysis for Lunar, Asteroid and Mars Missions

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    - “The Exploration of Mars Launch & Assembly Simulation”

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Discrete Event Simulation (DES) Introduction

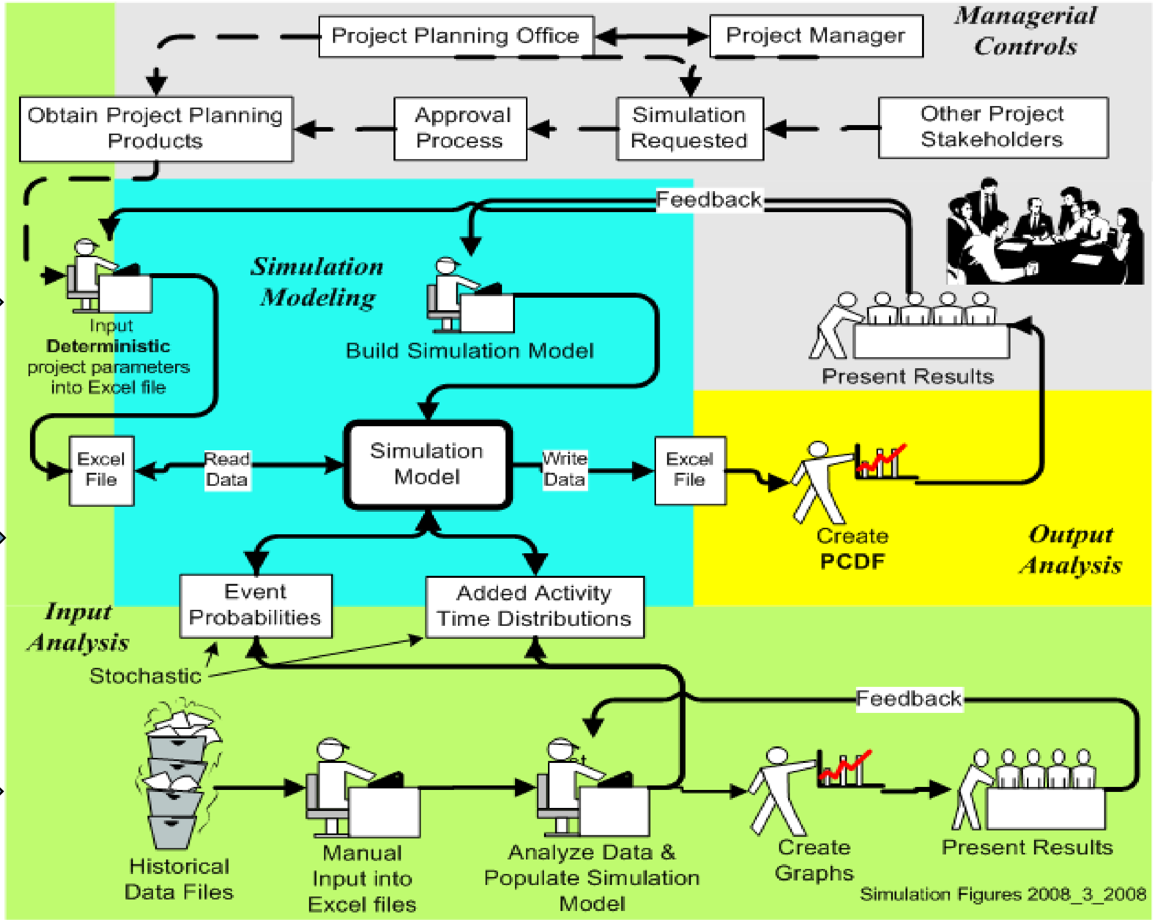
"Discrete-event simulation concerns the modeling of a system at it evolves over time by a representation in which the state variables change instantaneously at separate points in time."*

The software tool (Arena) enables modeling of resource constraints, complex logic, equations, and continuous processes.

Examples of planning products include:
- Launch Countdown & Ground Turnaround Timelines
- Mission Specific Launch Windows
- On-orbit operations
- Launch Vehicle, Spacecraft and Ground Architecture Assumptions

Modeling guidelines:
- Model at the level of detail for which there is data.
- Model at the level of detail required to provide the answer.
- Complete the analysis in time to be useful.

Input analysis sources:
- Historical Data
- Subject Matter Experts
- Program Analysis Products



Simulation, Modeling and Analysis, 5th Edition, by Averill M. Law, McGraw Hill, 2015, pg. 6

Selected list of previously published papers

1. Cates, Grant R., William M. Cirillo, and Chel Stromgren. "**Low earth orbit rendezvous strategy for lunar missions**." *Proceedings of the 38th conference on Winter simulation*. Winter Simulation Conference, 2006.

2. Stromgren, Chel, Grant Cates, and William Cirillo. "**Launch Order, Launch Separation, and Loiter in the Constellation 1½-Launch Solution**," *2009 IEEE Aerospace Conference*, Big Sky, MT, March 7-14, 2009.

3. Cirillo, William M., Chel Stromgren, and Grant R. Cates. "**Risk analysis of on-orbit spacecraft refueling concepts**." *AIAA Space 2010 Conference & Exposition*, AIAA-2010-8832. Vol. 30. 2010.

4. Cates, G., Gelito, J., Stromgren, C., Cirillo, W., & Goodliff, K. "**Launch and Assembly Reliability Analysis for Human Space Exploration Missions**," *2012 IEEE Aerospace Conference*, Big Sky, MT, March 2012.

5. Cates, G., Stromgren, C., Cirillo, W., & Goodliff, K. (2013, March). "**Launch and assembly reliability analysis for Mars human space exploration missions**." *In Aerospace Conference, 2013 IEEE* (pp. 1-20). IEEE.

6. Cates, G., Stromgren, C., Arney, D., Cirillo, W., & Goodliff, K. (2014, March), "**International human mission to Mars: Analyzing a conceptual launch and assembly campaign**." *In Aerospace Conference, 2014 IEEE* (pp. 1-18). IEEE.

7. Cates, G., Stromgren, C., Mattfield, B., Cirillo, W., & Goodliff, K., "**The Exploration of Mars Launch & Assembly Simulation**." *Aerospace Conference, 2016 IEEE*. IEEE, 2016.

Authors: Bill Cirillo, Kandyce Goodliff, and Dale Arney (NASA Langley Research Center); Justin Gelito (SAIC); Chel Stromgren and Bryan Mattfield (Binera)

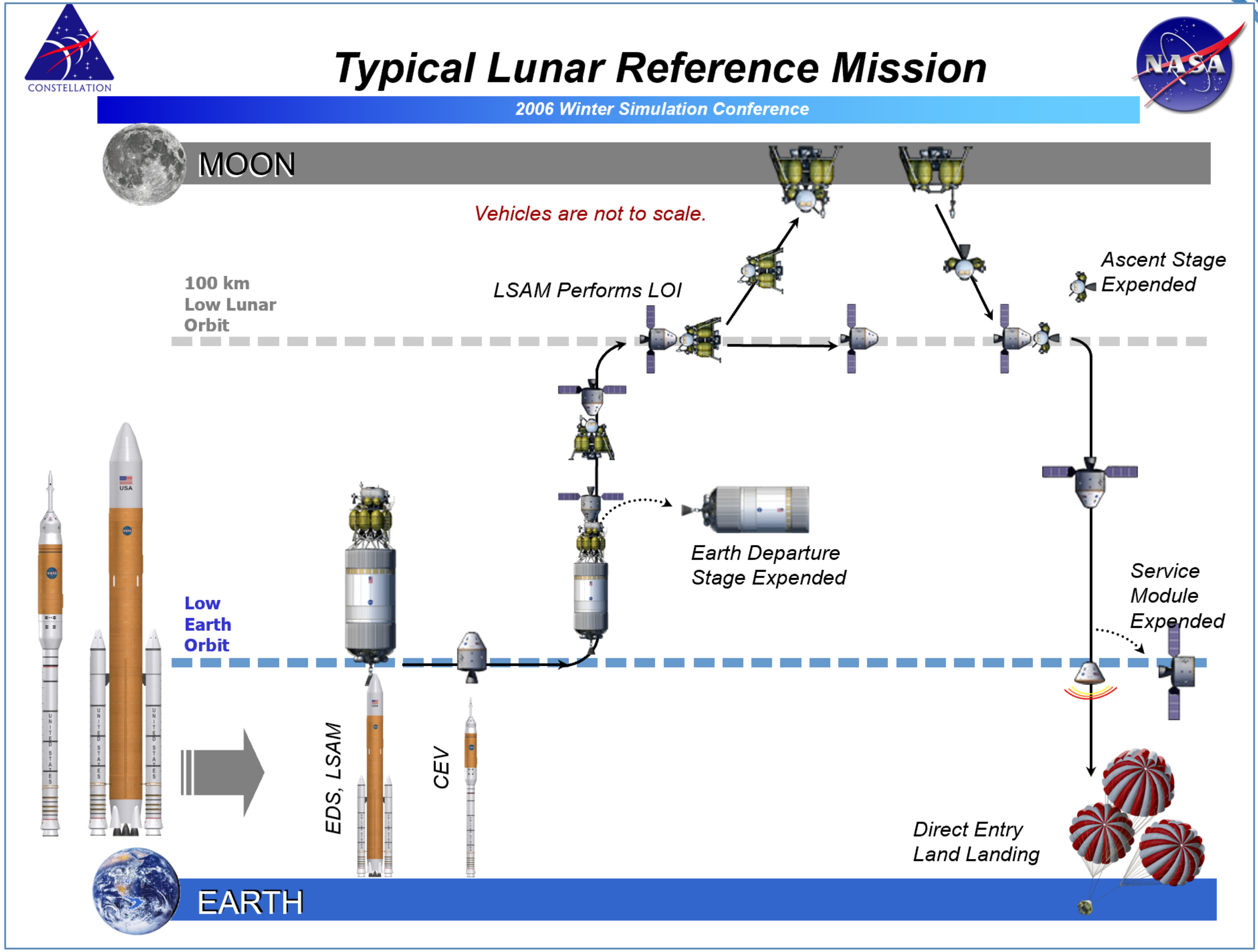
Low Earth Orbit Rendezvous for Lunar Missions (2006)

Overview

- On January 14, 2004, President George W. Bush announced a new Vision for Space Exploration calling for NASA to return humans to the moon.
- In 2005 NASA decided to use a Low Earth Orbit (LEO) rendezvous strategy for the lunar missions developed by the Exploration Systems Architecture Study (ESAS).
- The LEO rendezvous strategy called for NASA to develop two rockets using heritage Shuttle hardware.
  - A human rated Crew Launch Vehicle (CLV) that will loft the crew exploration vehicle (CEV → Orion) into LEO.
  - A Cargo Launch Vehicle (CaLV) to carry an Earth Departure Stage (EDS) and a Lunar Surface Access Module (LSAM → Altair).
- A Discrete Event Simulation (DES) based model of the LEO rendezvous strategy was constructed.
  - The Constellation-Manifest Assessment Simulation Tool (C-MAST)
  - The Constellation-Requirement Assessment Simulation Technique (C-RAST)
  - C-MAST and C-RAST are discrete event simulations using Rockwell Software's Arena, plus ExpertFit by Averill M. Law and Associates and the Microsoft Office suite of Excel, Word, PowerPoint, and Visio.
- Explored the ramifications of the LEO rendezvous strategy.

Low Earth Orbit Rendezvous for Lunar Missions (2006)

- As the EDS and LSAM wait in LEO for the CEV, their cryogenic propellants are boiling off.
- The EDS was to have enough propellant to provide 95 days of loiter capability in LEO.
  - *If the CEV fails to dock with the EDS such that a TLI burn can't be initiated during that 95-day period, then the lunar mission would be lost.*
- Is 95 days sufficient?
- The 95-day requirement had a significant impact upon the design of the EDS.
  - *A large volume of propellants is required, and this increases size, weight, and cost.*
  - *Reducing the 95-day requirement would allow a smaller, lighter, cheaper EDS.*



EDS = Earth Departure Stage; LSAM = Lunar Surface Access Module → Altair;
CEV = Crew Exploration Vehicle → Orion; LEO = Low Earth Orbit; TLI = Trans Lunar Injection

Low Earth Orbit Rendezvous for Lunar Missions (2006)

Low Earth Orbit Rendezvous for Lunar Missions (2006)

Model Architecture

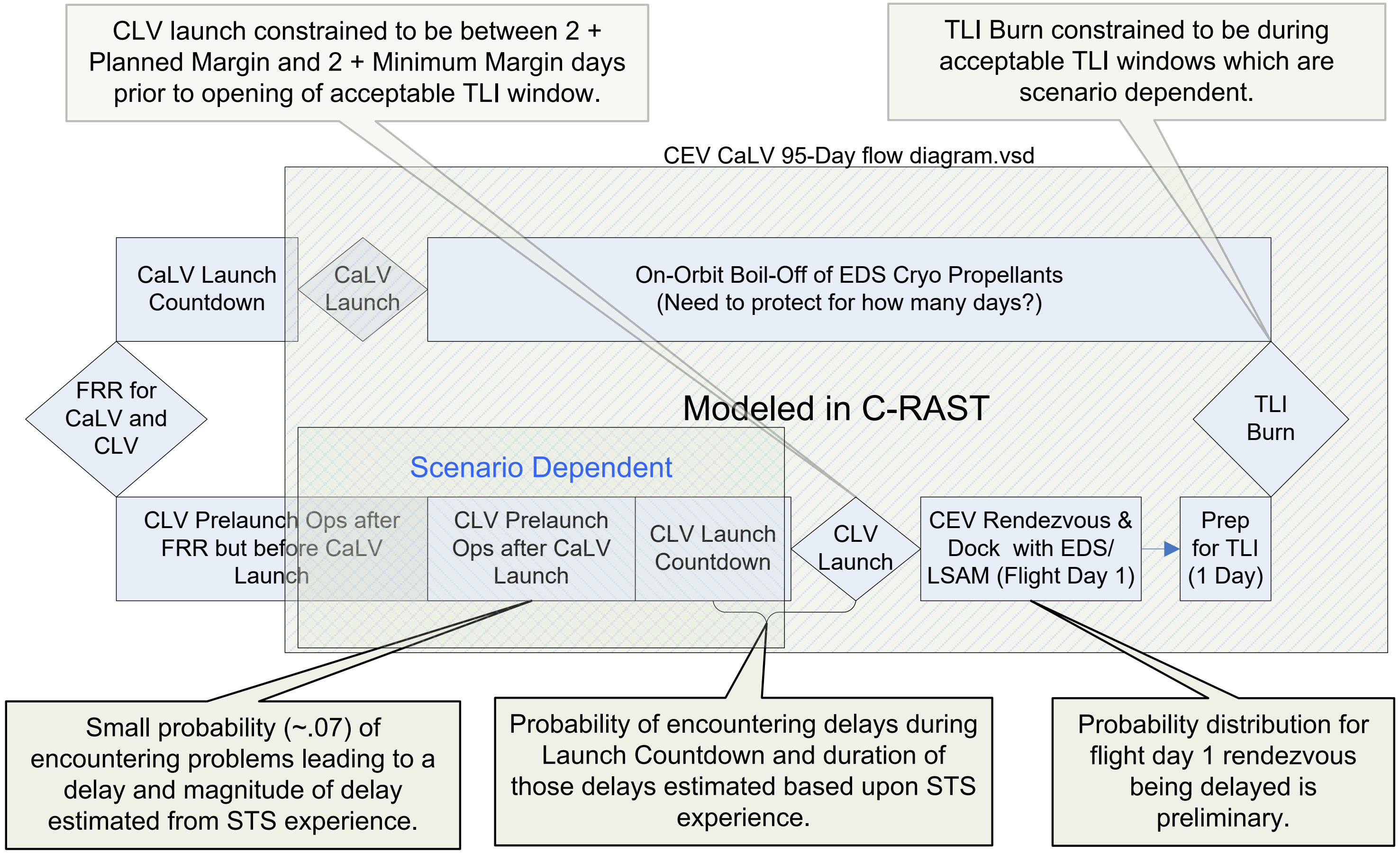
- The model picks up at the point in time in which the CaLV has launched
- Assumed the CLV is on the launch pad in a position to launch in as few as two days.
- Space Shuttle historical data was reviewed to determine the risk of a delay during a two-day period of Pre-Launch Count Ops. A discrete distribution was developed:

  DISC (0.925,0, 0.935,1, 0.944,2, 0.949,3, 0.958,4, 0.964,5, 0.971,6, 0.975,7, 0.976,8, 0.978,9, 0.981,10, 0.984,12, 0.989,14, 0.994,21, 0.999,28, 1.0,31)

  The discrete distribution consists of ordered pairs. The first ordered pair (0,925,0) indicates that the probability of no delay is 0.925.

  The second ordered pair (0.935,1) indicates that the probability of a 1-day delay is 0.01 (the difference between 0.935 and 0.925).

- Additional delay risks are described on subsequent charts.



CLV = Crewed Launch Vehicle → Ares I; CaLV = Cargo Launch Vehicle → Ares V; TLI = Trans Lunar Injection; STS = Space Transportation System (Space Shuttle)
C-RAST = Constellation Requirement Assessment by Simulation Technique; FRR = Flight Readiness Review; CEV = Crew Exploration Vehicle → Orion

Low Earth Orbit Rendezvous for Lunar Missions (2006)

Launch Probability and Delay Durations for Launch Scrubs

- Should a delay or scrub occur during the launch countdown, there will then be a delay of some number of days before the next launch attempt.
- Space Shuttle historical data was reviewed to develop discrete distributions for three of the delay categories:
  - *Weather*

    DISC(0.79,1, 0.90,2, 0.95,3, 0.97,5, 1.0,23)
  - *Flight Hardware*

    DISC(0.35,1, 0.46,2, 0.49,3, 0.54,4, 0.62,5, 0.65,6, 0.70,7, 0.78,8, 0.81,10, 0.84,11, 0.87,12, 0.89,14, 0.92,18, 0.95,19, 0.97,75, 1.0,99)
  - *Infrastructure*

    DISC(0.53,1, 0.73,2, 0.80,3, 0.93,4, 1.0,7)
- A delay caused by a problem with the upper stage engine is modeled as requiring the launch vehicle to be returned to the Vehicle Assembly Building. The upper stage would be changed out and the vehicle would then return to the launch pad.

The STS historical data through June of 2006 was used to derive launch probabilities probabilities by category for the CLV and CaLV.

		Delays or Scrubs During Launch Countdown				
	Launch Occurs	Weather	Flight Hardware (Less Engine Abort)	Infrastructure or Operational Prerogative	Main Engine Abort	Total
STS Experience	0.54	0.18	0.18	0.07	0.02	1.00
CLV Estimate	0.62	0.17	0.15	0.06	0.01	1.00
T-90 Minutes to Launch	0.90	0.02	0.05	0.03	0.01	1.00
T-9 Minutes to Launch	0.94	0.00	0.03	0.02	0.01	1.00
CaLV Estimate	0.65	0.12	0.15	0.05	0.02	1.00

Low Earth Orbit Rendezvous for Lunar Missions (2006)

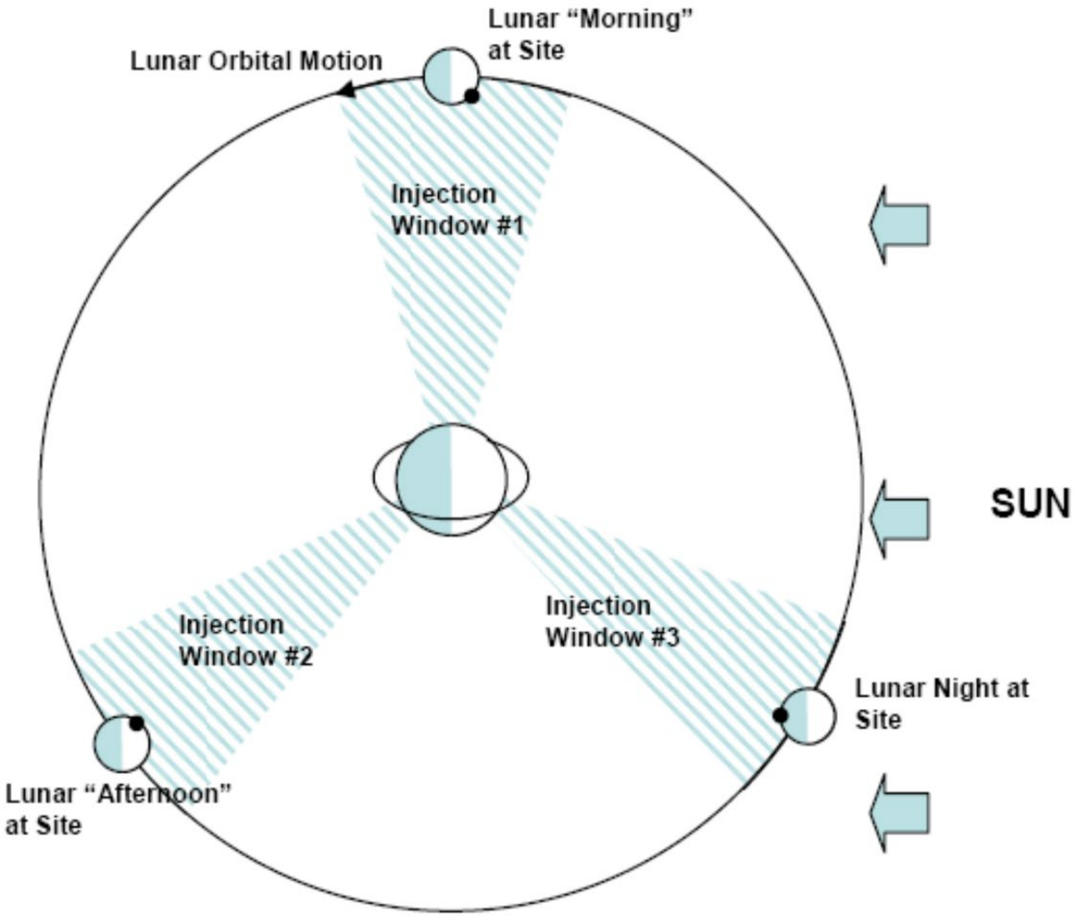
Delay risks after launch

- The estimated delay in days to Rendezvous & Dock was estimated with a discrete distribution
  - *DISC(0.80,0, 0.90,1, 0.96,2, 0.99,3, 1.0,4) based upon consideration of various potential sources of delay:*
    - When the CLV is launched within its launch window can influence how long it takes to achieve rendezvous with the EDS/LSAM.
    - An ascent anomaly or performance delta resulting in achieving a different orbit than planned can delay rendezvous. Shuttle examples include engine out with abort-to-orbit, and an early MECO.
    - Problems with the rendezvous and docking systems such as the secondary propulsion systems, radar systems, flight control systems, docking mechanisms, and hatches can delay docking.
      - *Gemini, Apollo, and Shuttle have experienced such problems. Likewise for Russian space vehicles.*
- Risks that were not modeled
  - *Problems with the Service Module, Crew Module, EDS, or LSAM after docking but prior to TLI burn.*
    - Integration and checkout operations of complex systems with humans in the loop will have the potential to experience delays.
  - *Crew health problems resulting in additional time in LEO to make sure crew is OK to press on to moon.*
    - High occurrence of motion sickness during first few days in orbit. Potential to mask other serious conditions, or indications of other conditions that could cause flight surgeons to place hold on go for TLI burn.

Low Earth Orbit Rendezvous for Lunar Missions (2006)

Translunar Injection Window Opportunities

- Mission requirements / constraints provide lunar injection windows from LEO approximately every 9 days as shown in the figure.
- Injection Window 1 puts the lunar landing site in the highly desired “morning” lighting conditions.
- The planned landing site would be available on a 27-day cycle.
- Window 2 puts the landing site in acceptable “afternoon” lighting conditions.
- Window 3 puts the landing site in unacceptable darkness. This Window is not available.

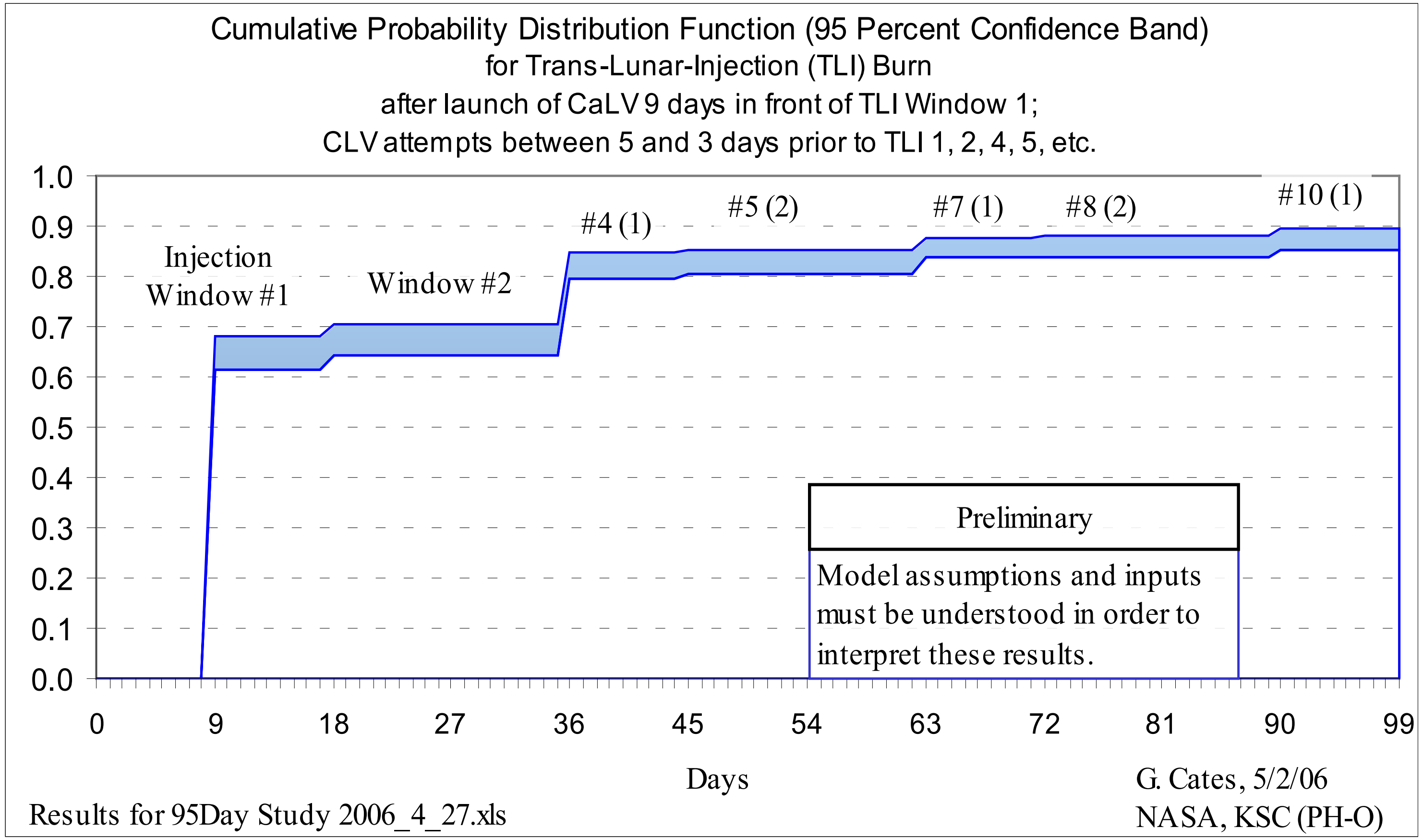


Opportunities to perform the translunar injection are limited.

Low Earth Orbit Rendezvous for Lunar Missions (2006)

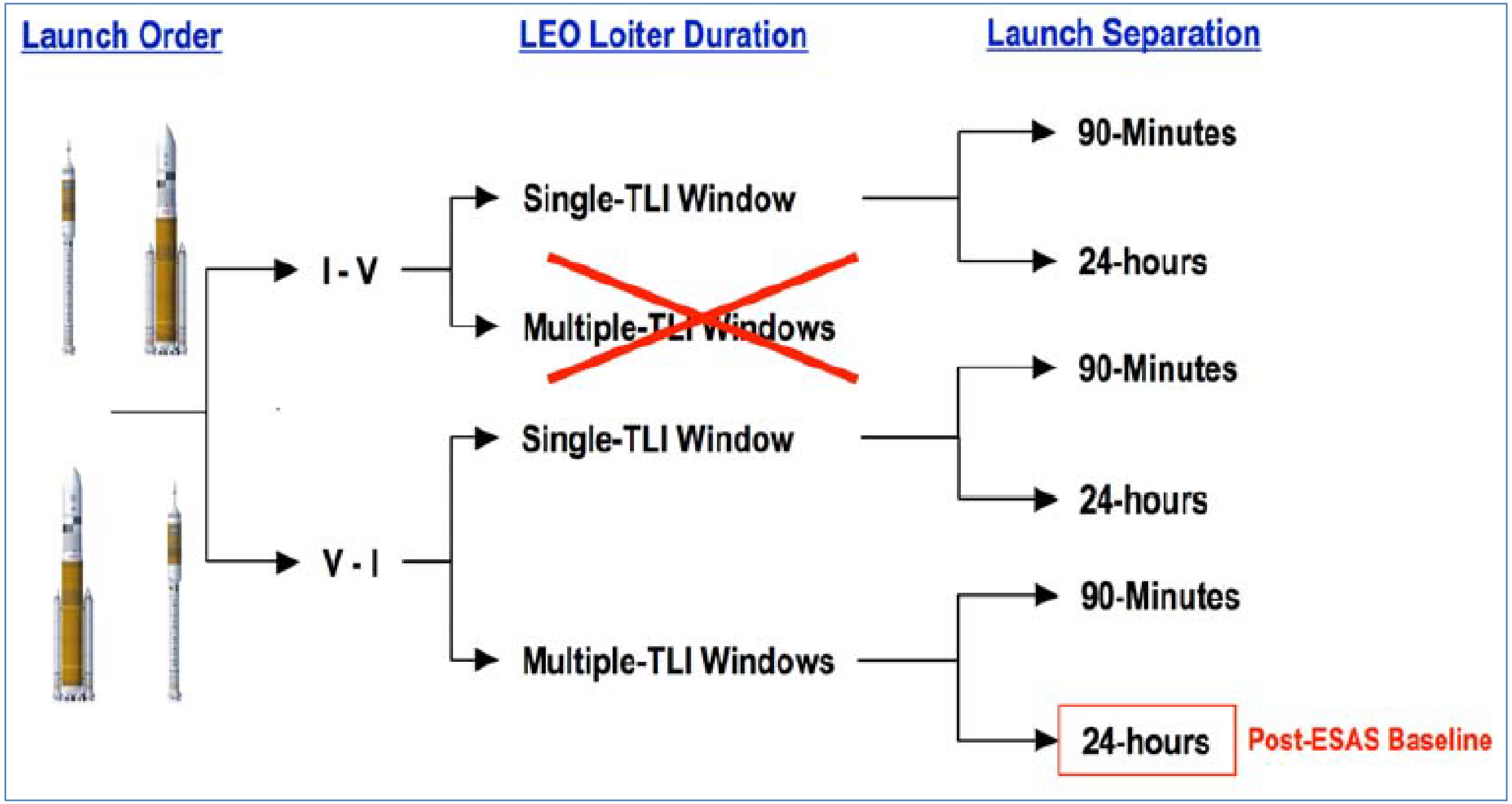
Simulation Results – Cumulative Probability of Achieving Trans-Lunar-Injection

- The cumulative probability increases stairstep fashion based upon the ability to perform TLI for Window 1 or Window 2 but not Window 3.
- If the loiter capability was only 18 days (not enough to go the Window 2 as a backup) the likelihood of achieving TLI is between 0.62 and 0.71.
- A 45-day capability would provide an increased probability range of 0.79 to 0.85.
- Increased capability beyond 45 days provides only modest improvement.
  - *However, in terms of reducing loss of mission risk, the additional loiter capability would be important.*



Launch Order, Launch Separation, and Loiter in the Constellation 1½-Launch Solution (2009)

- Initial plans called for the Ares V (EDS and Altair) to be launched first, followed the next day by the Ares I (Orion).
- Orion docks with Altair.
- The integrated vehicle loiters in LEO until the TLI window opportunity opens, at which time the EDS propels the integrated Orion–Altair to the Moon.
- Successful completion of this "1½-launch" solution carried risks related to
  - *orbital lifetime of the assets*
  - *probability of not launching the second vehicle within the orbital lifetime of the first.*
- Evaluated the launch strategy, including the order of launch and the planned time period between launches.



Launch Order, Launch Separation, and Loiter in the Constellation 1½-Launch Solution (2009)

Probability of No Second Launch (PnSL)

Table 1. 1½-Launch Options

Launch Order	Launch Separation	Orion LEO Loiter	EDS LEO Loiter	Launch Opportunities for Second Vehicle
V-I	24-Hour	1 Day	2 Days	1
		2 Days	3 Days	2
		3 Days	4 Days	3
		4 Days	5 Days	4
		4 Days	15 Days	8
		4 Days	25 Days	12
	90-Minute	1 Day	1 Day	1
		2 Days	2 Days	2
		3 Days	3 Days	3
		4 Days	4 Days	4
		4 Days	14 Days	8
		4 Days	24 Days	12
I-V	24-Hour	2 Days	1 Day	1
		3 Days	2 Days	2
		4 Days	3 Days	3
	90-Minute	1 Day	1 Day	1
		2 Days	2 Days	2
		3 Days	3 Days	3
		4 Days	4 Days	4

Table 6. Comparison of PnSL for 90-Minute and 24-Hour Separation Cases

90-Minute Separation	PnSL
I-V 4-Day Orion 4-Day EDS	5.4%
V-I 4-Day Orion 4-Day EDS	4.7%
V-I 4-Day Orion 14-Day EDS	1.9%

24-Hour Separation	PnSL
I-V 4-Day Orion 3-Day EDS	13.0%
V-I 4-Day Orion 5-Day EDS	14.1%
V-I 4-Day Orion 15-Day EDS	5.5%

90-Minute planned launch separation is better than 24-Hour.

Launch order favors V-I, if the EDS has extended loiter capacity.

Launch Order, Launch Separation, and Loiter in the Constellation 1½-Launch Solution (2009)

Replacement Costs for Transportation Elements – Loss of Crew Risk for a missed TLI Opportunity.

Table 4. Replacement Cost Estimates for Transportation Elements

Element	Per Unit Cost (Ares I Stack Equiv.)
Ares I – Marginal Cost	0.40 AI
Orion SM & CM Refurbishment – Marginal Cost	0.60 AI
Ares V (51.0.48) – Marginal Cost	0.90 AI
Ares V (51.0.47) – Marginal Cost	1.13 AI
Altair – Fixed Cost	1.19 AI
Altair - Marginal Cost	0.79 AI
Altair - Total	1.98 AI

Table 5. PLOC Estimates for 4-Day Orion LEO Mission

Phase	Current PLOC	CARD Requirement
Ares I Launch	0.00077 ($^1/_{1300}$)	0.00011 ($^1/_{9168}$)
LEO Loiter (4-Days)	0.00071 ($^1/_{1400}$)	0.00010 ($^1/_{9873}$)
EDL from LEO	0.00104 ($^1/_{960}$)	0.00015 ($^1/_{6770}$)
Total	**0.00253 ($^1/_{396}$)**	**0.00036 ($^1/_{2793}$)**

Launching the Ares I first minimizes expected cost. However, additional risk to crew needs to be considered.

Launch Order, Launch Separation, and Loiter in the Constellation 1½-Launch Solution (2009)

Comparisons of Figures of Merit (FOMs)

Table 7. Comparison of FOMs Across Loiter Period Options for V-I Launch Order (90-Minute Launch Separation)

Ares V Loiter, Days	PnSL	Cost of No Second Launch (Ares I Stack Equiv.)	Expected Vehicle Replacement Cost, per Crewed Mission (Ares I Stack Equiv.)	Change in Propellant Mass, kg	Cost to Provide Added Loiter
1	8.7% ($^1/_{11.5}$)	2.88 AI	0.25 AI	-119	0
2	6.8% ($^1/_{14.7}$)	2.88 AI	0.20 AI	-79	0
3	5.9% ($^1/_{16.9}$)	2.88 AI	0.17 AI	-40	0
4	4.7% ($^1/_{21.3}$)	2.88 AI	0.14 AI	0	0
14	1.9% ($^1/_{52.6}$)	3.11+ AI	0.06 AI	395	>$1B+
24	1.2% ($^1/_{83.3}$)	N/A	N/A	834	N/A

Table 8. Comparison of FOMs Across Loiter Period Options for I-V Launch Order (90-Minute Launch Separation)

Ares I Loiter, Days	PnSL	Cost of No Second Launch (Ares I Stack Equiv.)	Expected Vehicle Replacement Cost, per Crewed Mission (Ares I Stack Equiv.)	Added Loiter Mass	Added PLOC
1	10.8% ($^1/_{9.2}$)	1.00 AI	0.11 AI	-119	0.00030
2	8.1% ($^1/_{12.3}$)	1.00 AI	0.08 AI	-79	0.00023
3	7.0% ($^1/_{14.3}$)	1.00 AI	0.07 AI	-40	0.00020
4	5.4% ($^1/_{18.5}$)	1.00 AI	0.05 AI	0	0.00016

I-V order appears optimal if the added loss of crew risk is acceptable.

Risk analysis of on-orbit spacecraft refueling concepts (2010)

Concept of Operations

- EDS is launched into LEO.
- Multiple expendable tanker missions fuel the EDS.
- The lunar lander and a crew module are launched separately.
- The entire stack, including the EDS, lander, and crew module are then propelled to the Moon by the EDS.

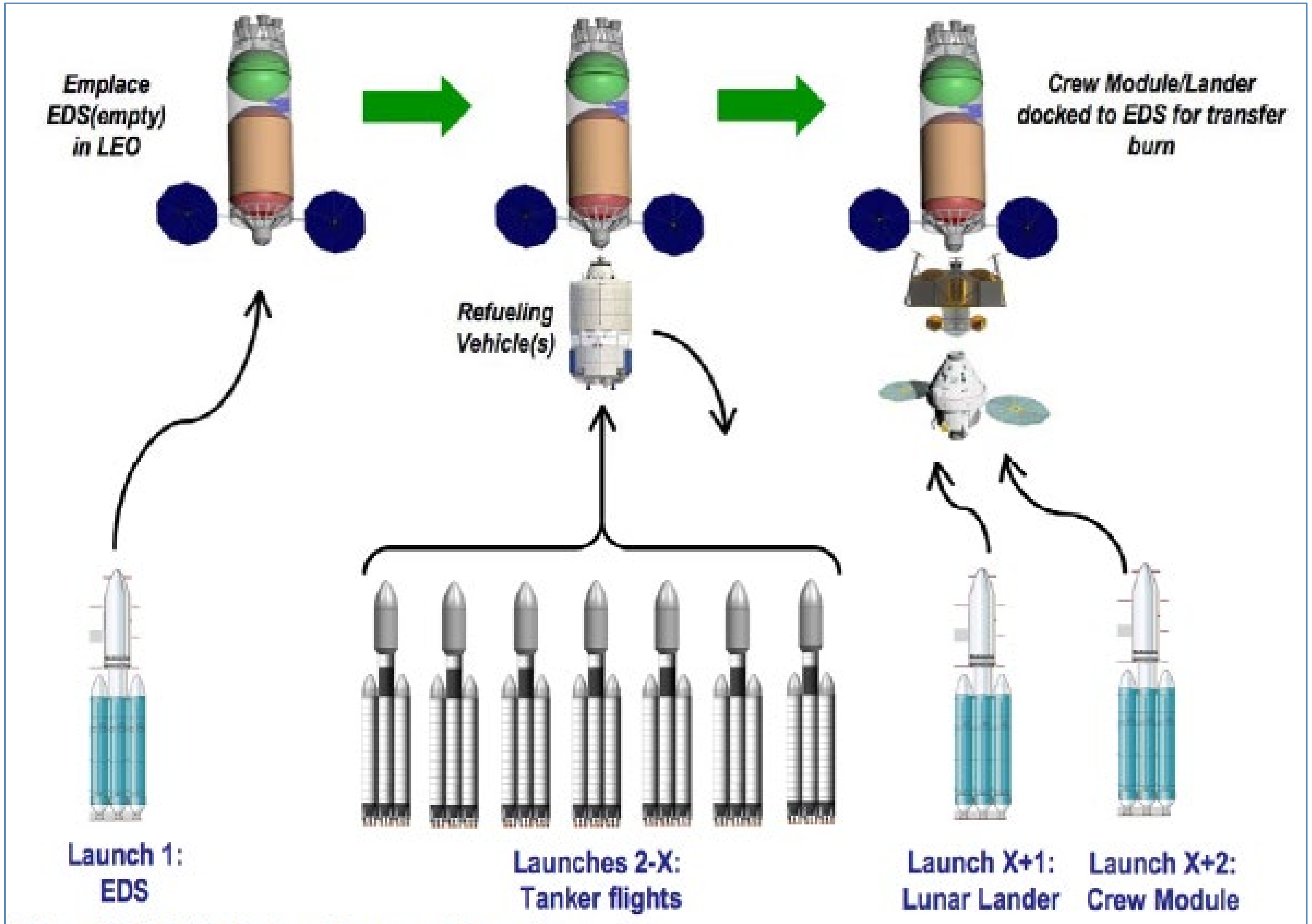
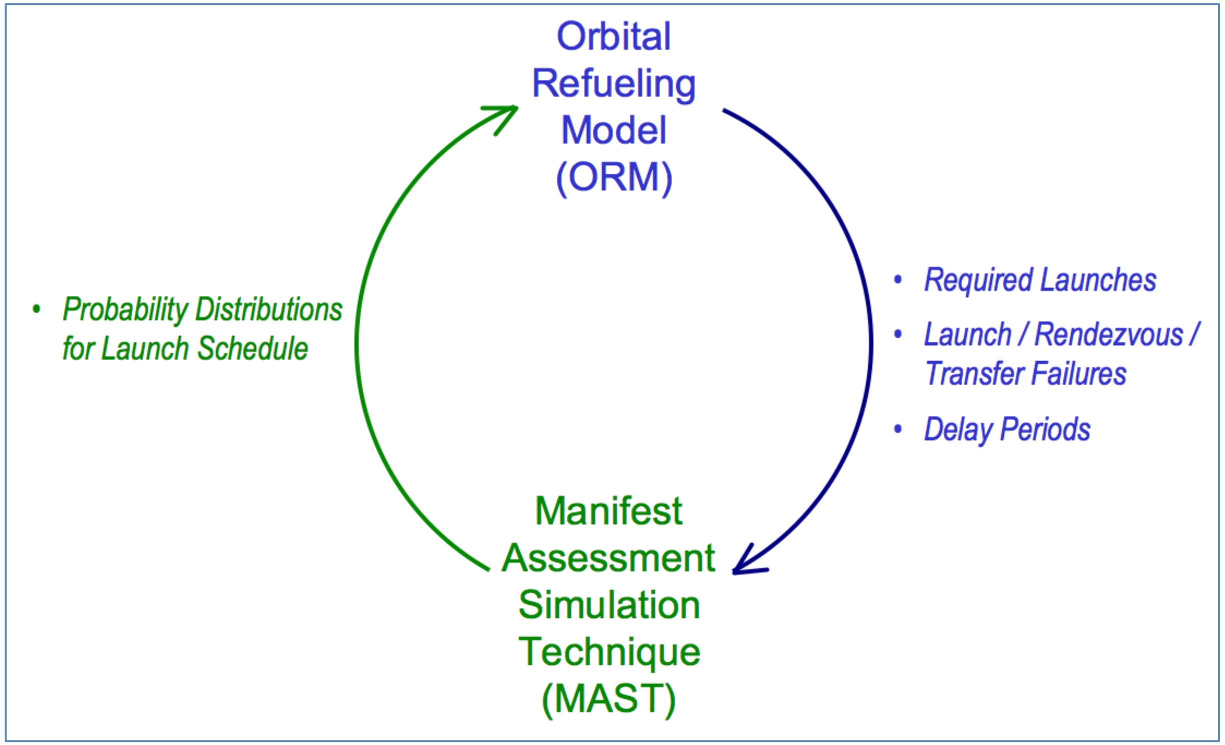


Figure 1. EDS Refueling Concept of Operations

Risk analysis of on-orbit spacecraft refueling concepts (2010)

Risks analyzed using iterative simulation

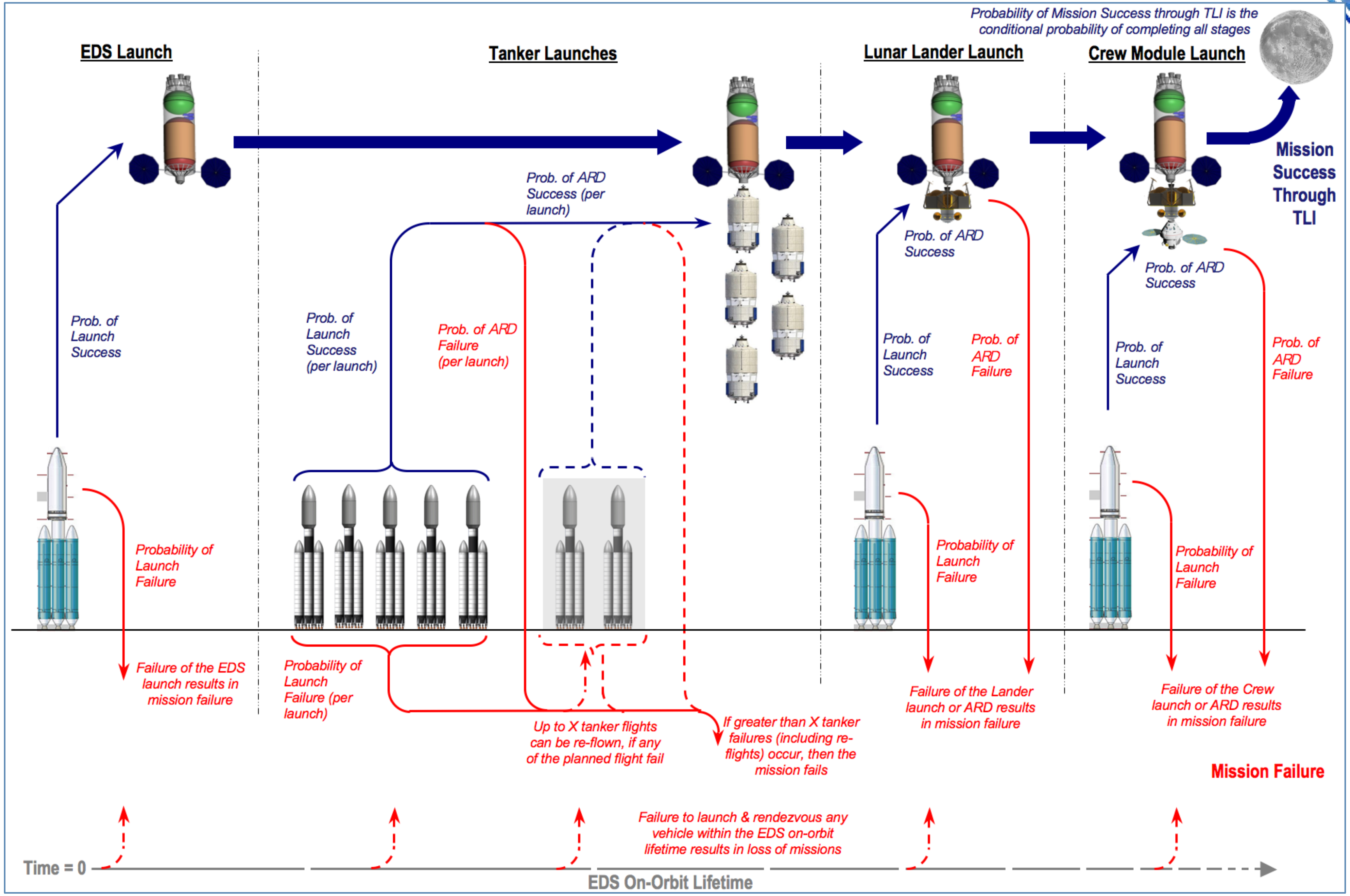
- Large number of opportunities for mission failure
  - *If 8 refueling flights are required, then*
    - 11 launches are required,
    - 10 rendezvous and docking events,
    - 8 propellant transfer events.
    - Each having potential to disrupt the mission.
  - *Although each individual event may be accomplished with high reliability, the total number of events could still result in low overall mission reliability.*
- EDS maximum time in LEO
  - *May be limited by design lifetime, propellant boil-off, and MMOD risk*
  - *Some maximum period of time in which all of the planned launches must take place.*
  - *Lifetime of the EDS can be extended to some extent; however, this adds mass, and cost.*



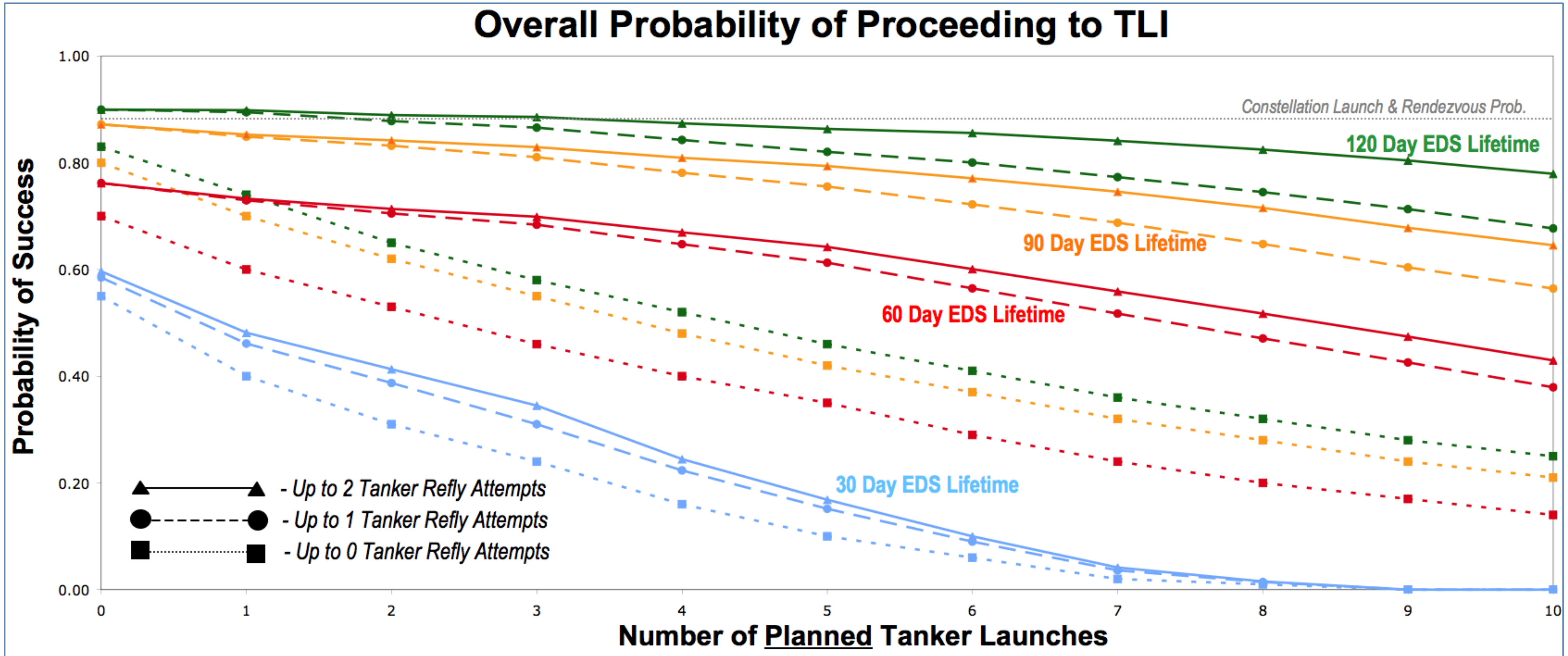
Risk analysis of on-orbit spacecraft refueling concepts (2010)

Simulation flow of on-orbit refueling and associated risks

- Model began with launch of the EDS and included all subsequent operations required to achieve Trans Lunar Injection (TLI).
- Risks that were modeled:
  - *Ascent failures*
  - *Launch delays*
  - *Automated Rendezvous and Dock (ARD) failures*
  - *Failure to complete TLI within the lifetime limit of the EDS*
- Main factors that were studied
  - *Number of propellant flights*
  - *EDS lifetime*
  - *Number of available spare propellant flights*

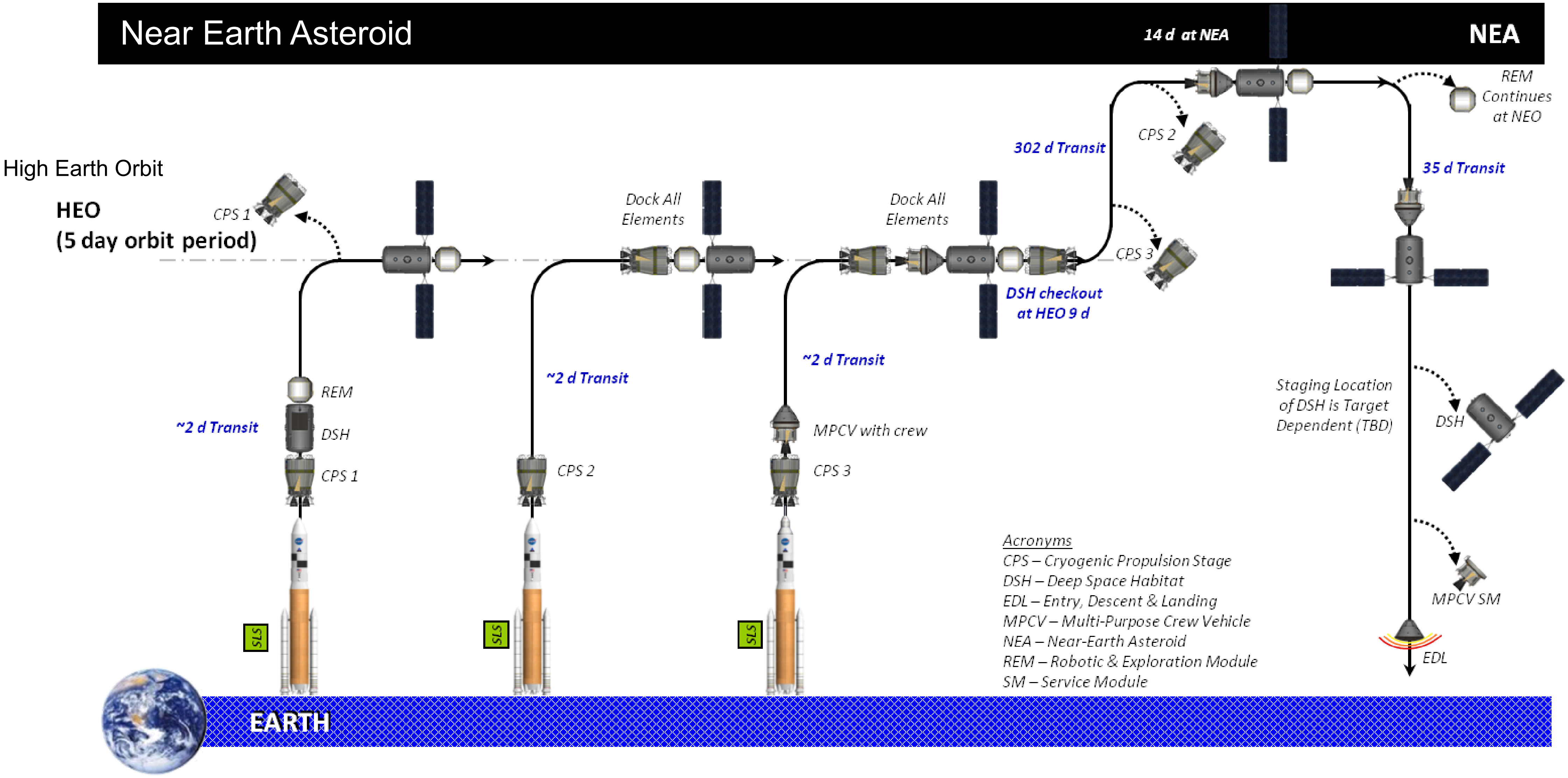


Risk analysis of on-orbit spacecraft refueling concepts (2010)



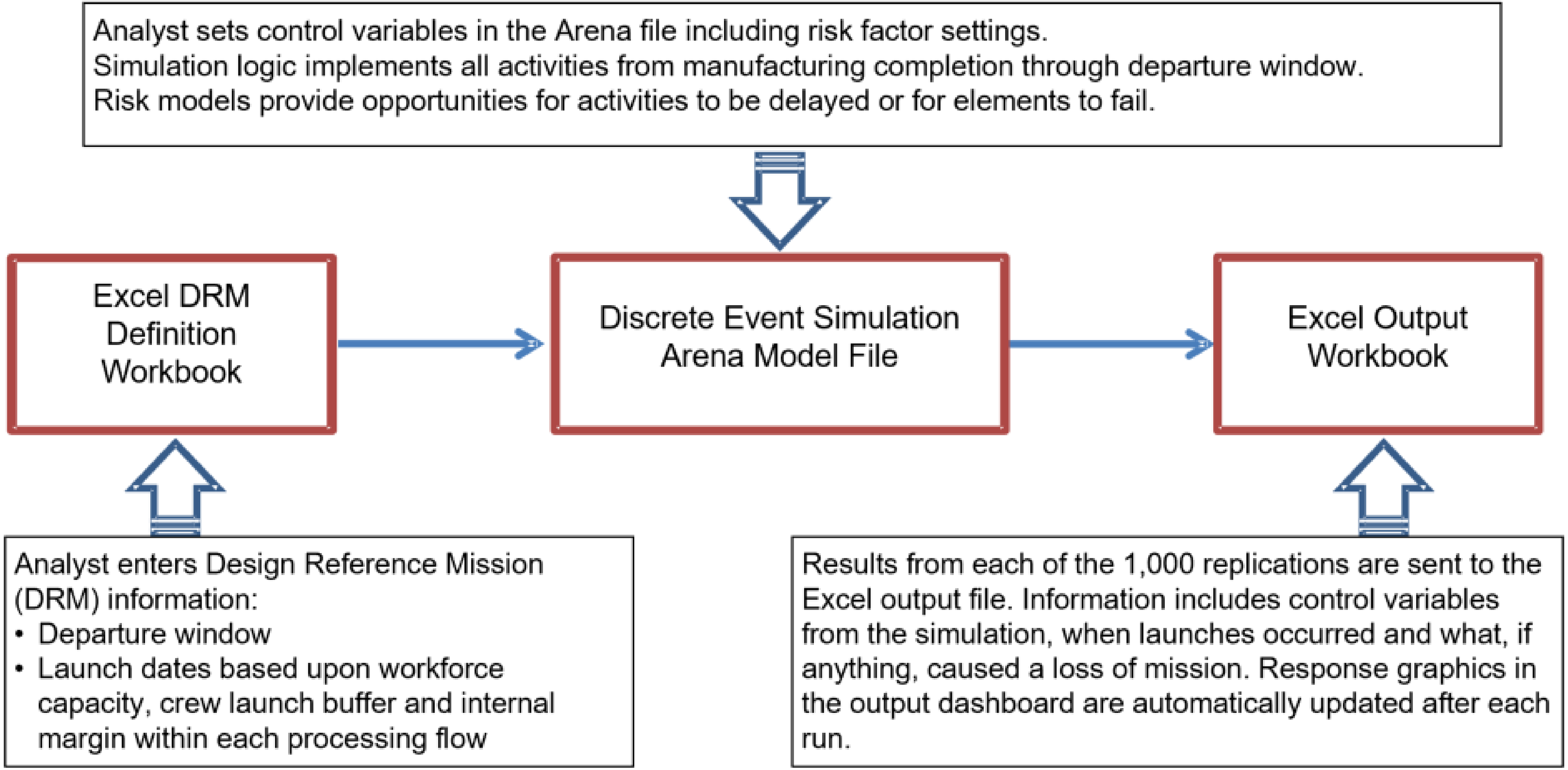
Number of Planned Tanker Launches	Up to 0 Tanker Refly Attempts – EDS Loiter Duration				Up to 1 Tanker Refly Attempts – EDS Loiter Duration				Up to 2 Tanker Refly Attempts – EDS Loiter Duration			
	30	60	90	120	30	60	90	120	30	60	90	120
0	0.55	0.70	0.80	0.83	0.58	0.76	0.87	0.90	0.60	0.76	0.87	0.90
1	0.40	0.60	0.70	0.74	0.46	0.73	0.85	0.89	0.48	0.73	0.85	0.90
2	0.31	0.53	0.62	0.65	0.39	0.71	0.83	0.88	0.41	0.71	0.84	0.89
3	0.24	0.46	0.55	0.58	0.31	0.68	0.81	0.87	0.35	0.70	0.83	0.89
4	0.16	0.40	0.48	0.52	0.22	0.65	0.78	0.84	0.24	0.67	0.81	0.87
5	0.10	0.35	0.42	0.46	0.15	0.61	0.76	0.82	0.17	0.64	0.79	0.86
6	0.06	0.29	0.37	0.41	0.09	0.56	0.72	0.80	0.10	0.60	0.77	0.86
7	0.02	0.24	0.32	0.36	0.04	0.52	0.69	0.77	0.04	0.56	0.75	0.84
8	0.01	0.20	0.28	0.32	0.01	0.47	0.65	0.74	0.02	0.52	0.72	0.82
9	0.00	0.17	0.24	0.28	0.00	0.43	0.60	0.71	0.00	0.47	0.68	0.80
10	0.00	0.14	0.21	0.25	0.00	0.38	0.56	0.68	0.00	0.43	0.65	0.78

Launch and Assembly Reliability Analysis for Human Space Exploration Missions (2012)



Launch and Assembly Reliability Analysis for Human Space Exploration Missions (2012)

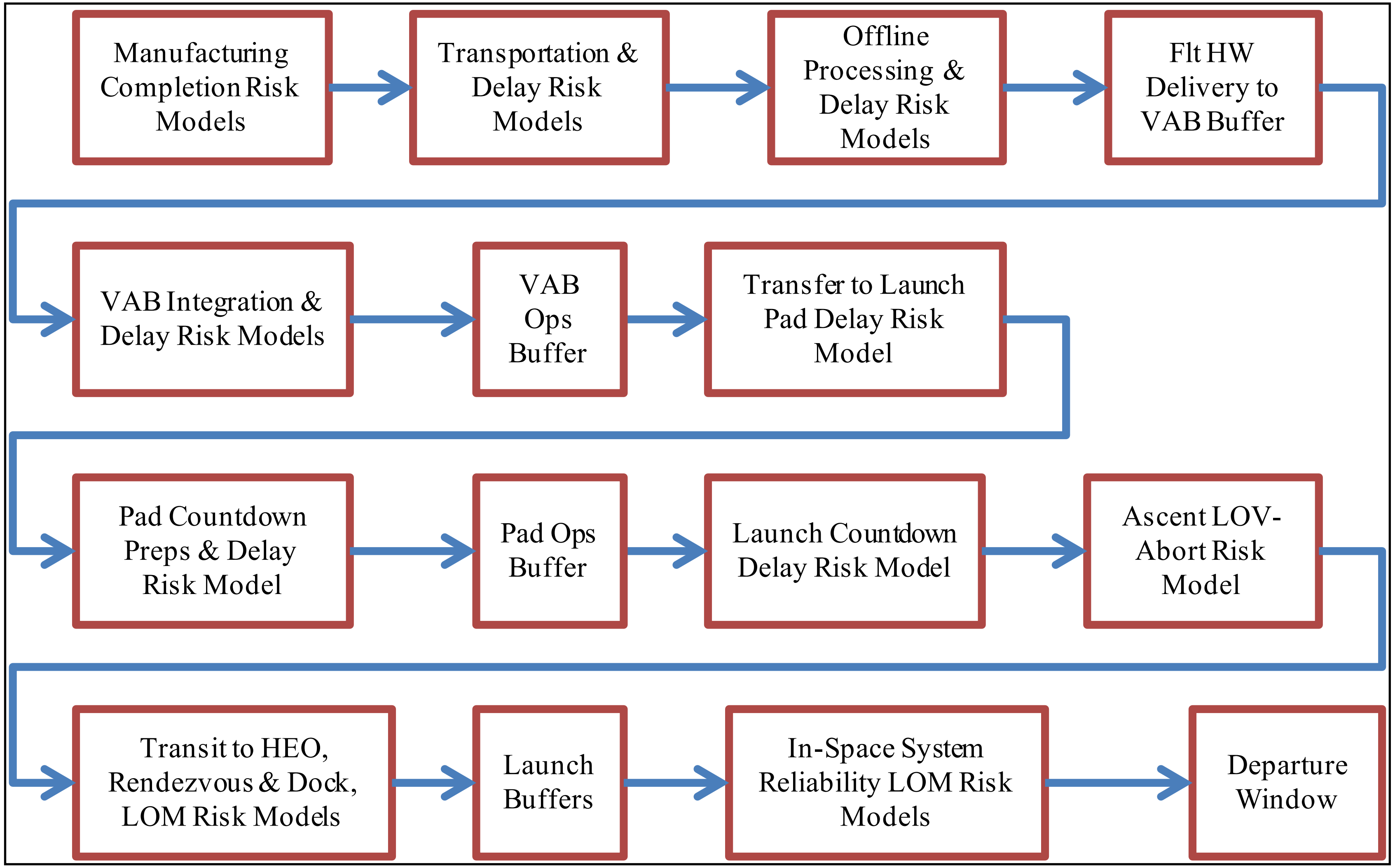
Model Overview



Same figure will be used again in 2013 and 2014 papers

Launch and Assembly Reliability Analysis for Human Space Exploration Missions (2012)

Flight Hardware Elements Entity Routing Within Model



Same figure used in 2014 paper

VAB = Vehicle Assembly Building; HEO = High Earth Orbit; LOV = Loss of Vehicle; LOM = Loss of Mission

Launch and Assembly Reliability Analysis for Human Space Exploration Missions (2012)

Processing Delay Probabilities

- Risk models account for potential delays during a launch campaign.
- Developed using historical data from the analogous Space Shuttle operations.
- Each delay probability has an associated delay distribution.

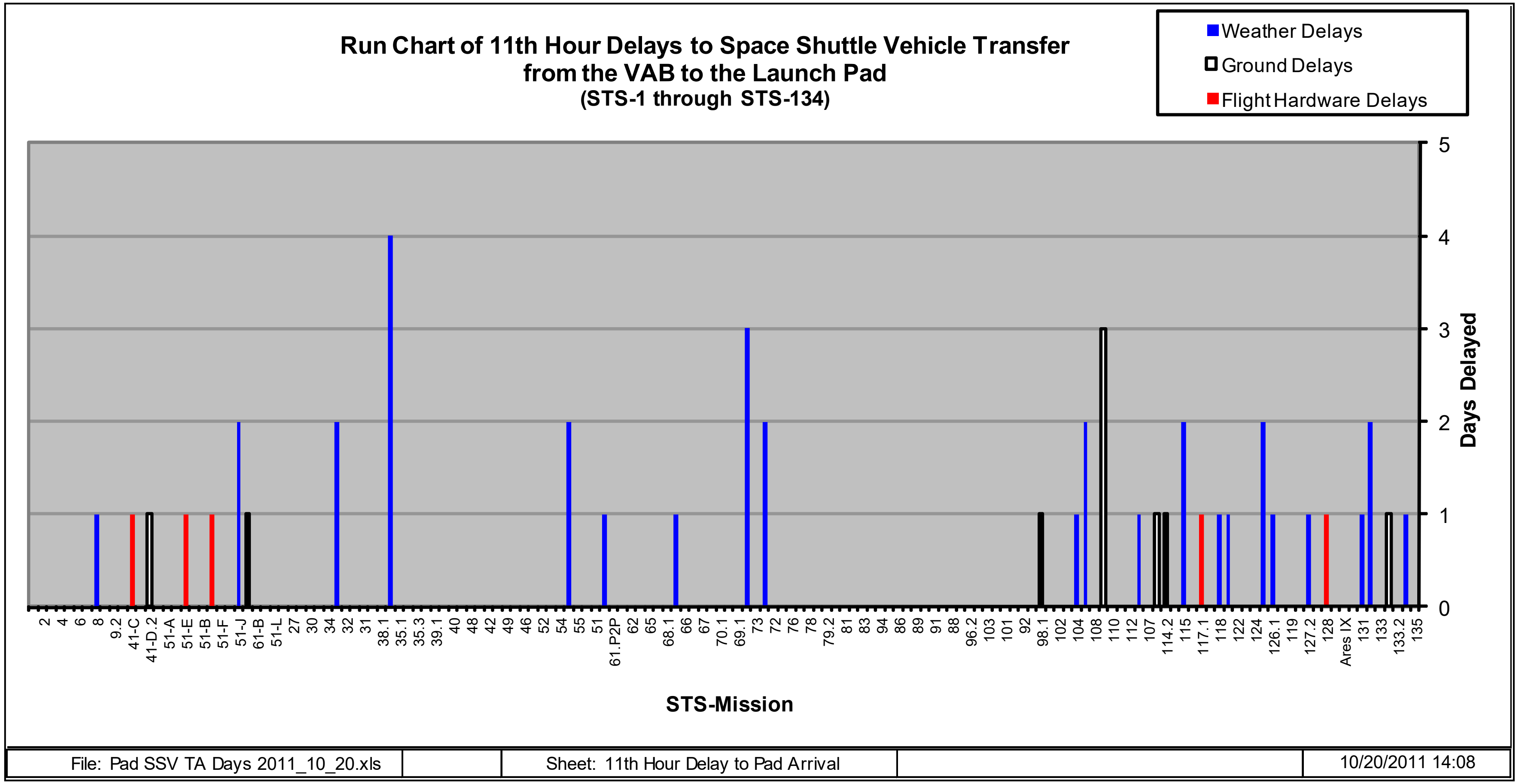
Delays to Start of SRB Stacking		Delays to Core Stage Mate / Upper Stage Mate		Delays to Payload to SLS Mate		Delays to SLS Readiness for Rollout		Delays to Countdown Readiness	
Subcategory	Delay Prob	Subcategory	Delay Prob	Subcategory	Delay Prob	Subcategory	Delay Prob	Subcategory	Delay Prob
MLP Post Launch Problems	0.1682	VAB (Crane Problems, MLP etc.)	0.1193	VAB Crane Problems	0.0190	Range Availability	0.0476	SRB Induced Delays to Launch Countdown Start	0.0571
VAB Problems (Crane, etc.)	0.1405	RSRM Segment Delivery Delays	0.0158	Orbiter Availability	0.6076	SRB/RSRM induced delays	0.0667	SSME-MPS induced Delays to Launch Countdown Start	0.1274
VAB Major Mods / Major Maintenance	0.0190	SRB-RSRM Stacking Problems	0.3274	Miscellaneous	0.0286	SSME induced delays	0.0381	Environment Induced delays to Launch Countdown Start	0.0416
MLP Stack Prep Delays	0.0667	Cold Weather	0.0381			Monoball induced delays	0.1000	Ground Systems	0.0429
Crawler Transporter	0.0095	Miscellaneous	0.0286			Flight Crew	0.0000	Flight Crew	0.0000
Aft Booster Delivery Delays	0.0190					Miscellaneous Flight Hardware	0.0467	Miscelleous Flight Hardware	0.0262
Miscellaneous	0.0286								
File:	**GOMES STS Based Risk Factors 2009_10_02 R1.xlsx**								
Sheet:	**SLS Risk Factor Table**								

SRB = Solid Rocket Booster;
MLP = Mobile Launch Platform;
VAB = Vehicle Assembly Building;
RSRM = Reusable Solid Rocket Motors;
SSME = Space Shuttle Main Engine;
MPS = Main Propulsion System;
SLS = Space Launch System

"11th hour" delays to transferring launch vehicle from VAB to the Launch Pad

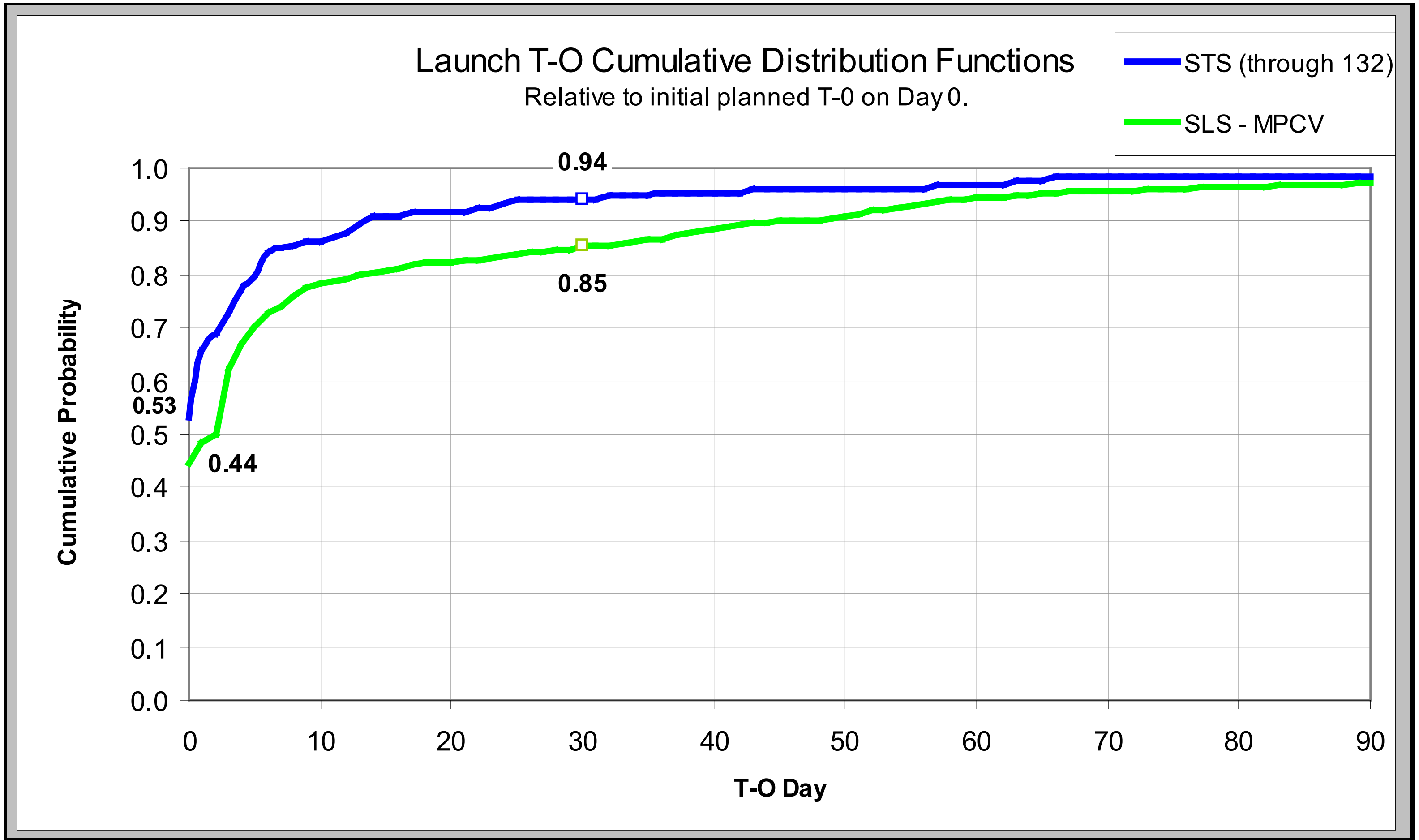
- Risk model to account for delays for the VAB to pad transfer operation stemming from adverse weather delays, ground equipment failures, and flight hardware problems, known as 11th hour delays.

- Based upon the Space Shuttle history of vehicle transfers between the VAB and the launch pads



Launch and Assembly Reliability Analysis for Human Space Exploration Missions (2012)

Launch Countdown Delay Risk: Estimated SLS – MPCV (Orion)

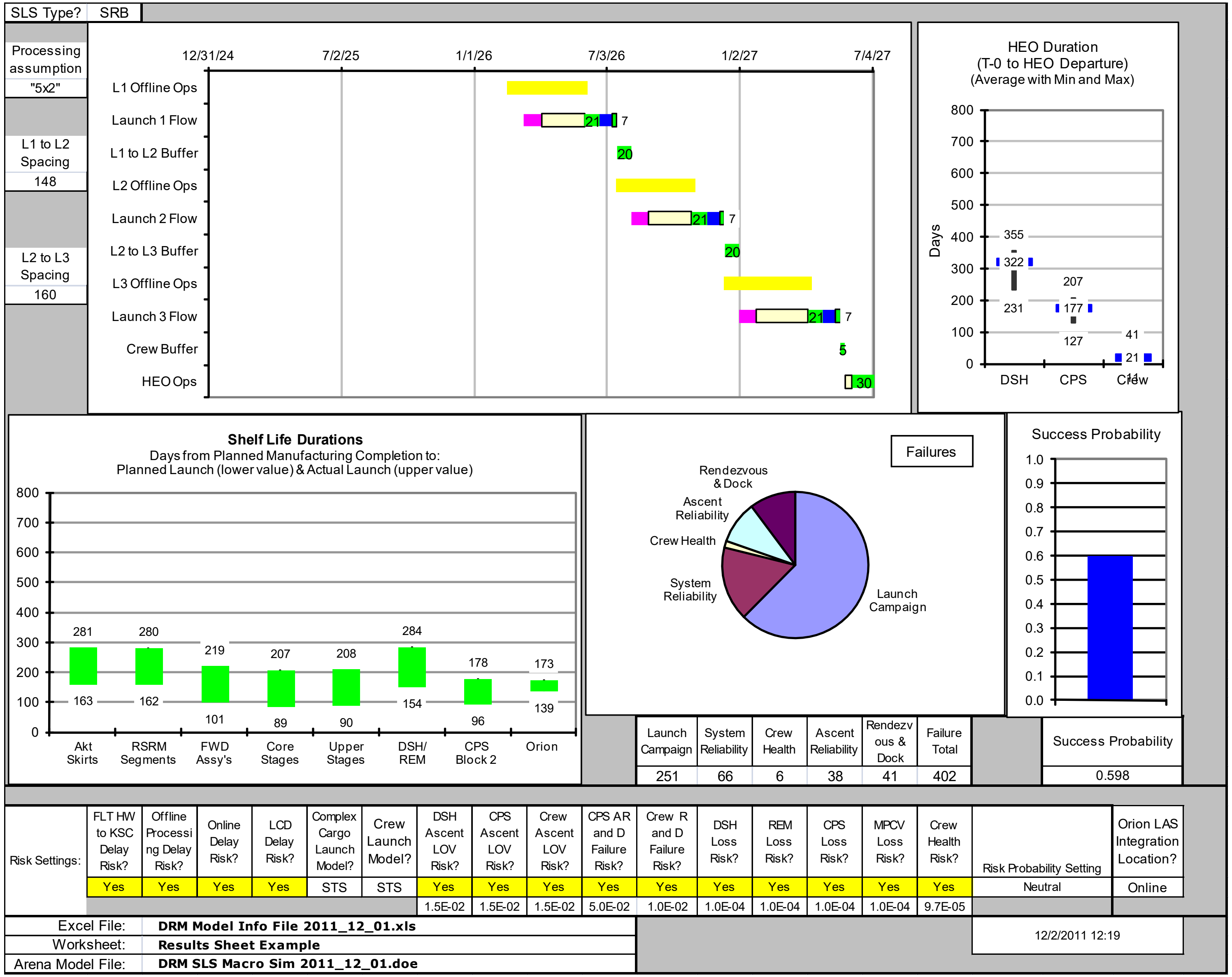


C-RAST Results 2010_10_22R1.xls	*CDF for SLS-MPCV and STS*

Launch and Assembly Reliability Analysis for Human Space Exploration Missions (2012)

Model Dashboard

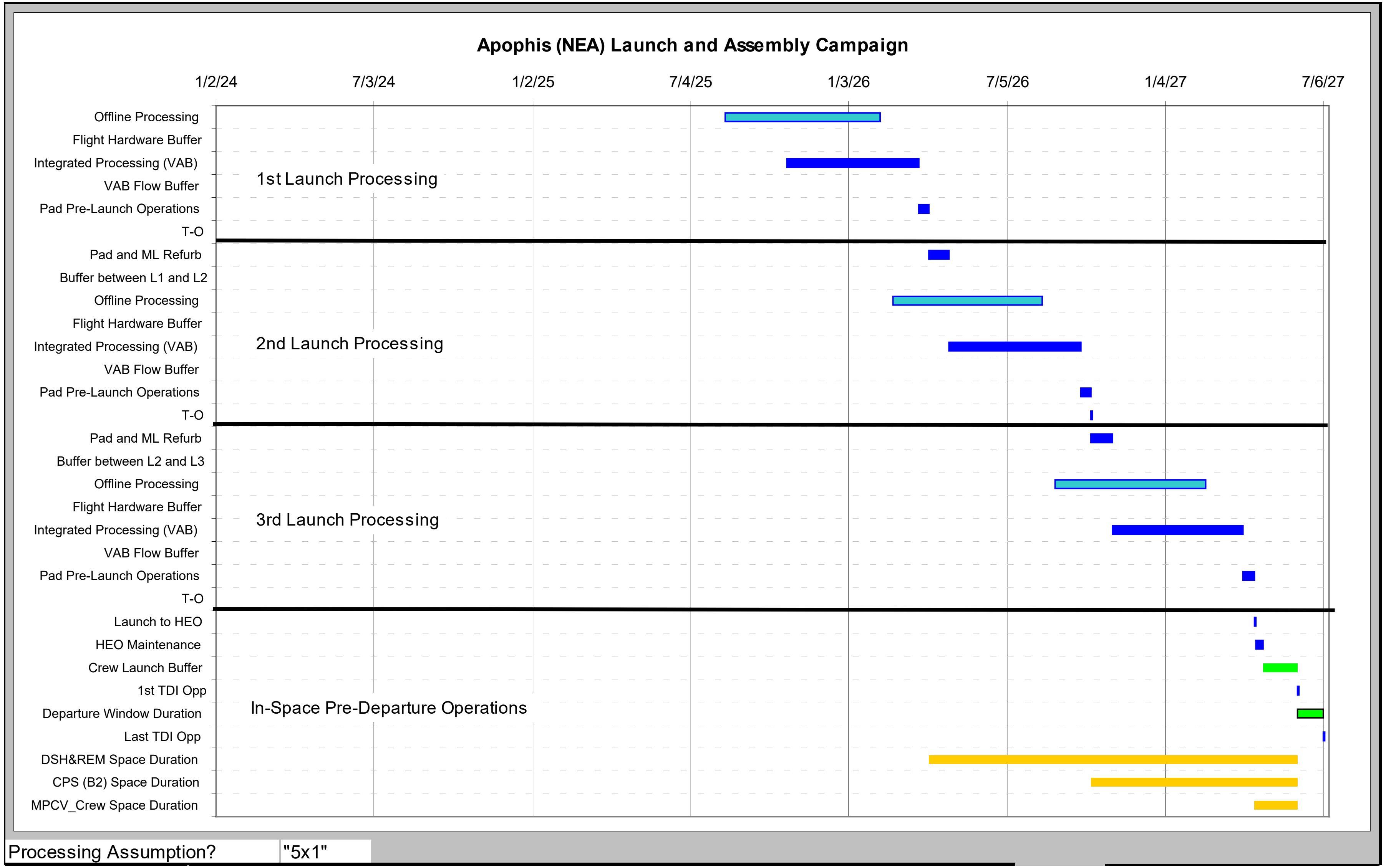
- Inputs
  - *Launch Campaign Plan*
  - *Processing Assumptions*
  - *Shelf-Life Durations*
  - *Risk Factors Active*
  - *Risk Probabilities*
- Outputs
  - *HEO Durations*
  - *Failures*
  - *Success Probability*



5x2 = Five days per week, two shifts per day; FLT HW = Flight Hardware; KSC = Kennedy Space Center; LCD = Launch Countdown; DSH = Deep Space Habitat; CPS = Cryogenic Propulsion Stage; MPCV = Multi-Purpose Crew Vehicle (Orion); LAS = Launch Abort System; HEO = High Earth Orbit; REM = Robotic & Exploration Module; FWD = Forward

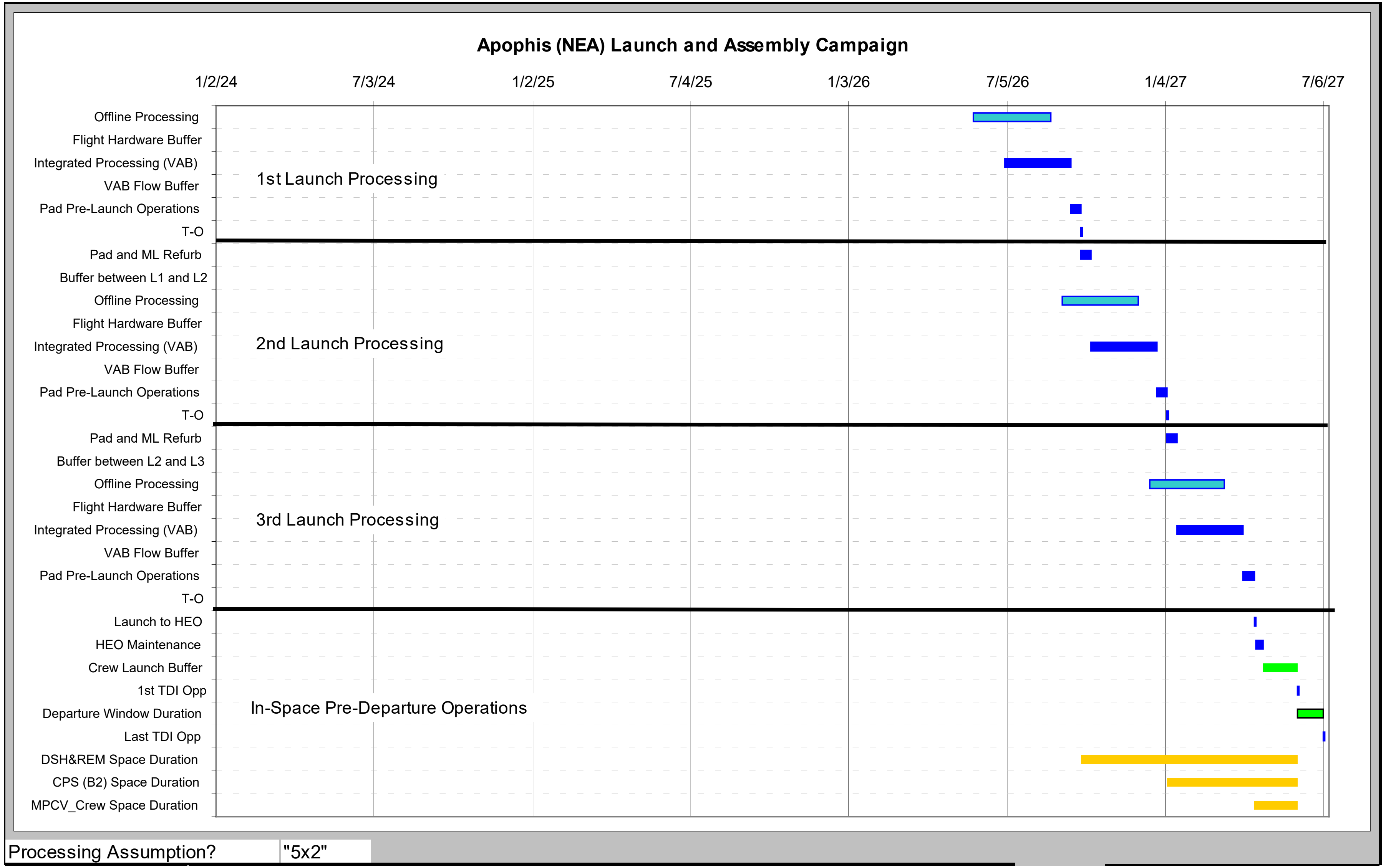
Launch and Assembly Reliability Analysis for Human Space Exploration Missions (2012)

Five Days Per Week x One Shift Per Day Processing (5x1)



Launch and Assembly Reliability Analysis for Human Space Exploration Missions (2012)

2-shift Processing (5x2)



Launch and Assembly Reliability Analysis for Human Space Exploration Missions (2012)

Risk Factor Settings for Optimistic, Neutral, and Conservative Cases

- Paper provides the basis of estimate for each of the risk factor settings
- Ascent Failure Probability Estimate Example
  - *Optimistic estimate based upon SLS goal 1 in 250 failure rate, which equates to a 0.4% chance of an ascent failure.*
  - *Neutral estimate set at 1.5%, consistent with the Delta II launch vehicle's demonstrated reliability through 149 launches and the Space Shuttle's demonstrated reliability over 135 missions.*
  - *Conservative estimate of 3% value was consistent with the Soyuz launch vehicle history (over 700 flights).*
- Crew Health Example
  - *An entity representing each crew member is created for the crew health risk model where there is a daily probability that a significant medical event will develop prompting need to abort the mission and return the crew to earth.*
  - *Inputs for the crew health risk were based upon work performed by NASA's Integrated Medical Model (IMM) project team.*

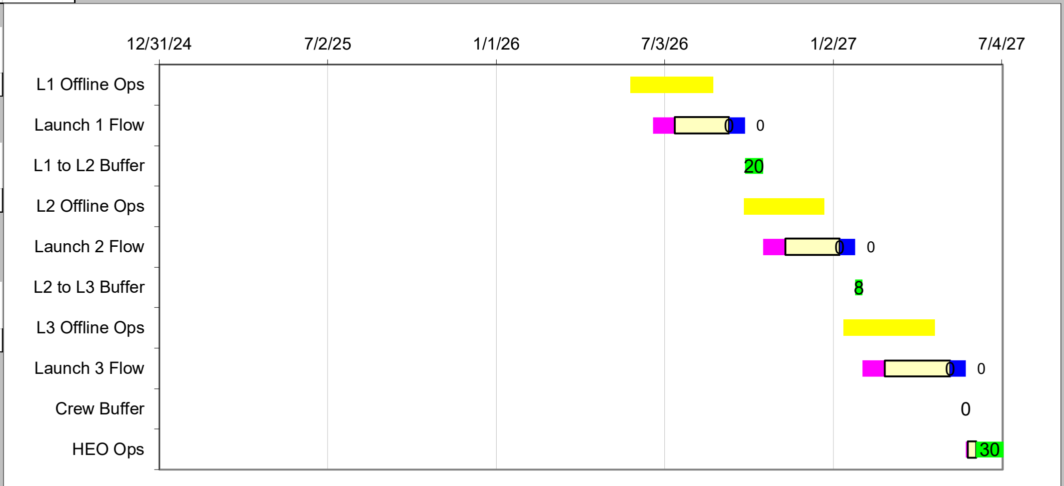
Risk Factors	Optimistic	Neutral	Conservative
Ascent LOV-LOM Probability (Cargo Launches	4.00E-03	1.50E-02	3.00E-02
Ascent Abort (Crew Launch)	4.00E-03	1.50E-02	3.00E-02
CPS to DSH / REM Automated Rendezvous & Dock Failure	1.50E-02	5.00E-02	1.00E-01
MPCV to DSH Rendezvous & Dock Failure (Crew assisted)	5.00E-03	1.00E-02	5.00E-02
DSH Daily Loss Probability	1.00E-05	1.00E-04	5.00E-04
REM Daily Loss Probability	1.00E-05	1.00E-04	5.00E-04
CPS Block 2 Daily Loss Probability	1.00E-05	1.00E-04	5.00E-04
MPCV Daily Loss Probability	1.00E-05	1.00E-04	5.00E-04
Crew Health LOM (Daily risk per crew member)	7.19E-05	9.72E-05	2.05E-04

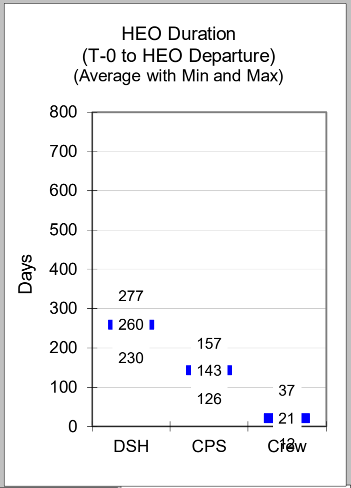
Launch and Assembly Reliability Analysis for Human Space Exploration Missions (2012)

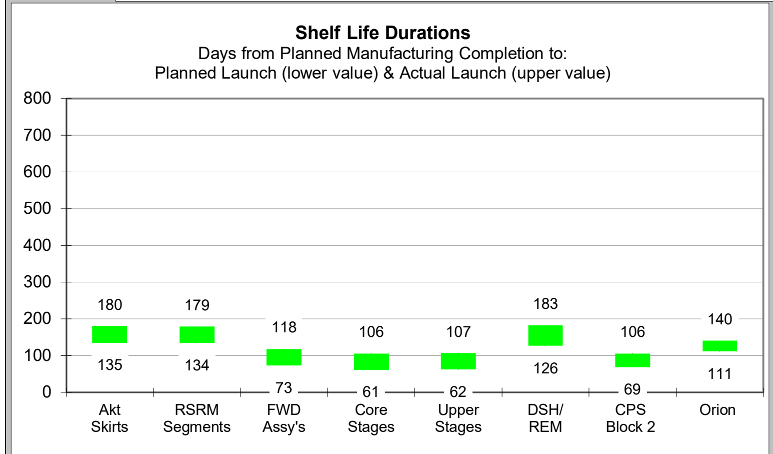
Five Days Per Week x Two Shifts Per Day Processing (5x2); Optimistic Settings

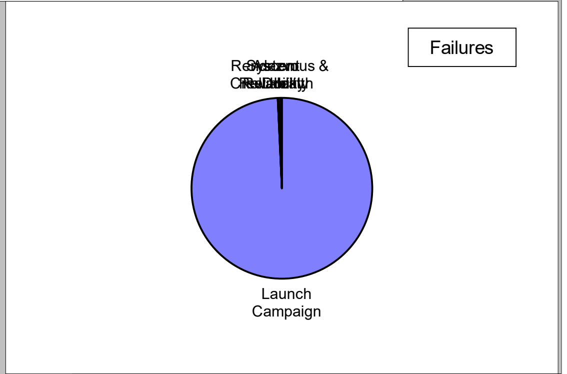
- Overall success probability is low
- Failure to launch all the assets in a timely fashion is the main risk.

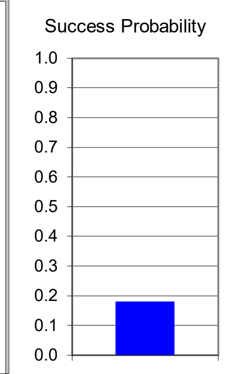
SLS Type?	SRB
Processing assumption	"5x2"
L1 to L2 Spacing	120
L2 to L3 Spacing	120











Launch Campaign	System Reliability	Crew Health	Ascent Reliability	Rendezvous & Dock	Failure Total
814	0	1	3	2	820

Success Probability
0.180

Risk Settings:	FLT HW to KSC Delay Risk?	Offline Processing Delay Risk?	Online Delay Risk?	LCD Delay Risk?	Complex Cargo Launch Model?	Crew Launch Model?	DSH Ascent LOV Risk?	CPS Ascent LOV Risk?	Crew Ascent LOV Risk?	CPS AR and D Failure Risk?	Crew R and D Failure Risk?	DSH Loss Risk?	REM Loss Risk?	CPS Loss Risk?	MPCV Loss Risk?	Crew Health Risk?	Risk Probability Setting	Orion LAS Integration Location?
	Yes	Yes	Yes	Yes	STS	STS	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Optimistic	Online
							4.0E-03	4.0E-03	4.0E-03	1.5E-02	5.0E-03	1.0E-05	1.0E-05	1.0E-05	1.0E-05	7.2E-05		

Excel File:	**DRM Model Info File 2011_12_01_Figures12_13 plus.xlsx**
Worksheet:	**5x2 120-Day Spacing Optimistic**
Arena Model File:	**DRM SLS Macro Sim 2011_12_01.doe**

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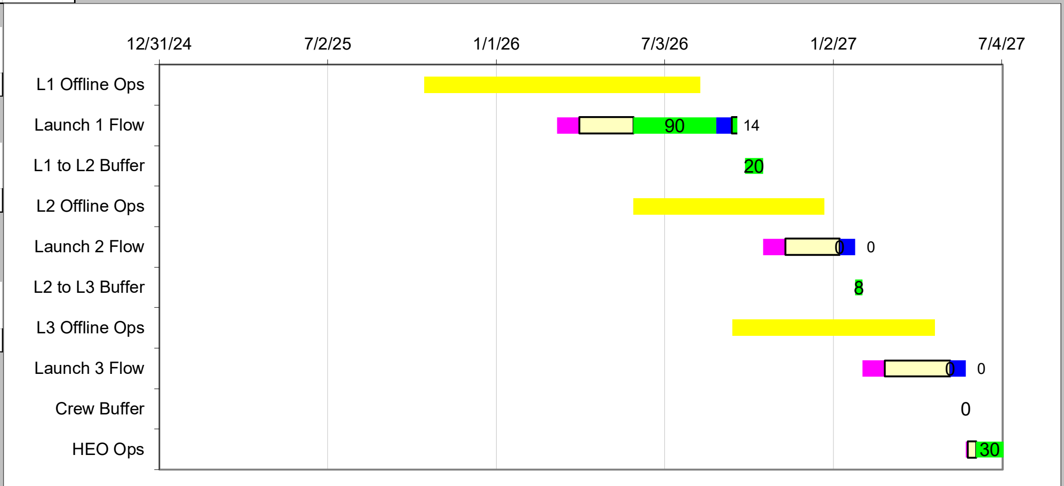
FLT HW = Flight Hardware; KSC = Kennedy Space Center; LCD = Launch Countdown; DSH = Deep Space Habitat; CPS = Cryogenic Propulsion Stage; MPCV = Multi-Purpose Crew Vehicle (Orion); LAS = Launch Abort System; HEO = High Earth Orbit; REM = Robotic & Exploration Module; FWD = Forward

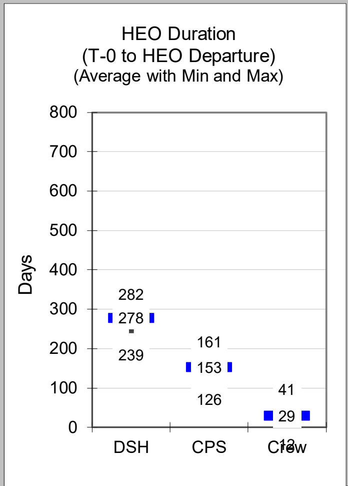
Launch and Assembly Reliability Analysis for Human Space Exploration Missions (2012)

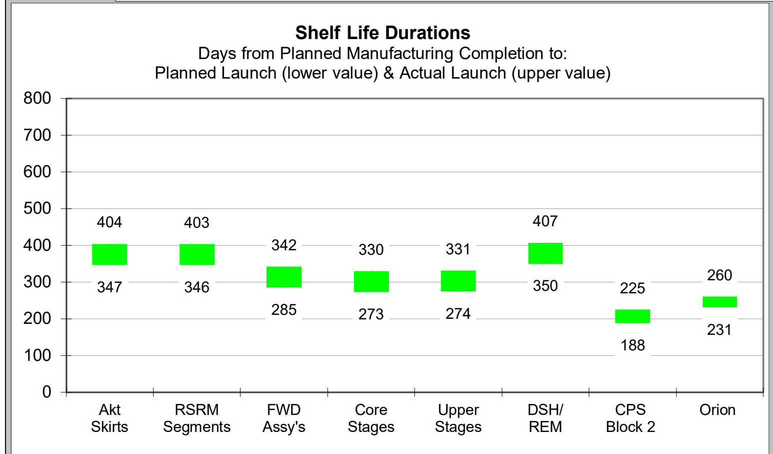
2-shift Processing; Optimistic Settings; Added Margin to 1st Launch Flow

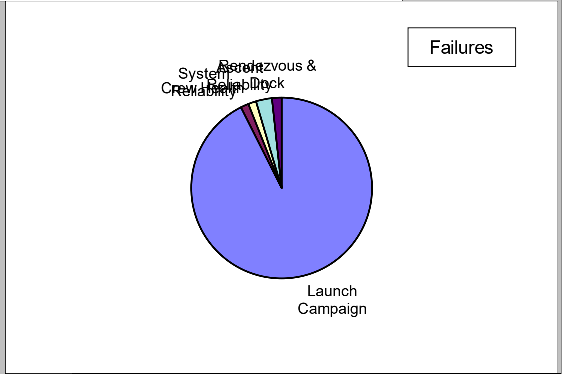
- Success probability substantially improved.
- Added campaign margin and required delivery of flight hardware earlier.
- Increased shelf-life durations required.
- Failure to launch all the assets in a timely fashion remains the main risk driver.

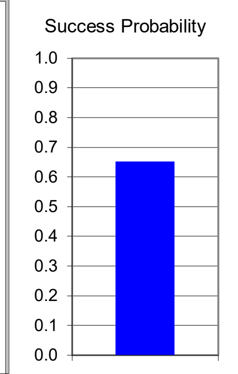
SLS Type?	SRB
Processing assumption	"5x2"
L1 to L2 Spacing	120
L2 to L3 Spacing	120











Launch Campaign	System Reliability	Crew Health	Ascent Reliability	Rendezvous & Dock	Failure Total	Success Probability
324	5	5	10	6	350	0.650

Risk Settings:	FLT HW to KSC Delay Risk?	Offline Processing Delay Risk?	Online Delay Risk?	LCD Delay Risk?	Complex Cargo Launch Model?	Crew Launch Model?	DSH Ascent LOV Risk?	CPS Ascent LOV Risk?	Crew Ascent LOV Risk?	CPS AR and D Failure Risk?	Crew R and D Failure Risk?	DSH Loss Risk?	REM Loss Risk?	CPS Loss Risk?	MPCV Loss Risk?	Crew Health Risk?	Risk Probability Setting	Orion LAS Integration Location?
	Yes	Yes	Yes	Yes	STS	STS	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Optimistic	Online
							4.0E-03	4.0E-03	4.0E-03	1.5E-02	5.0E-03	1.0E-05	1.0E-05	1.0E-05	1.0E-05	7.2E-05		

Excel File:	**DRM Model Info File 2011_12_01_Figures12_13 plus.xlsx**
Worksheet:	**5x2 120-Day M1_90_14 Optimistic**
Arena Model File:	**DRM SLS Macro Sim 2011_12_01.doe**

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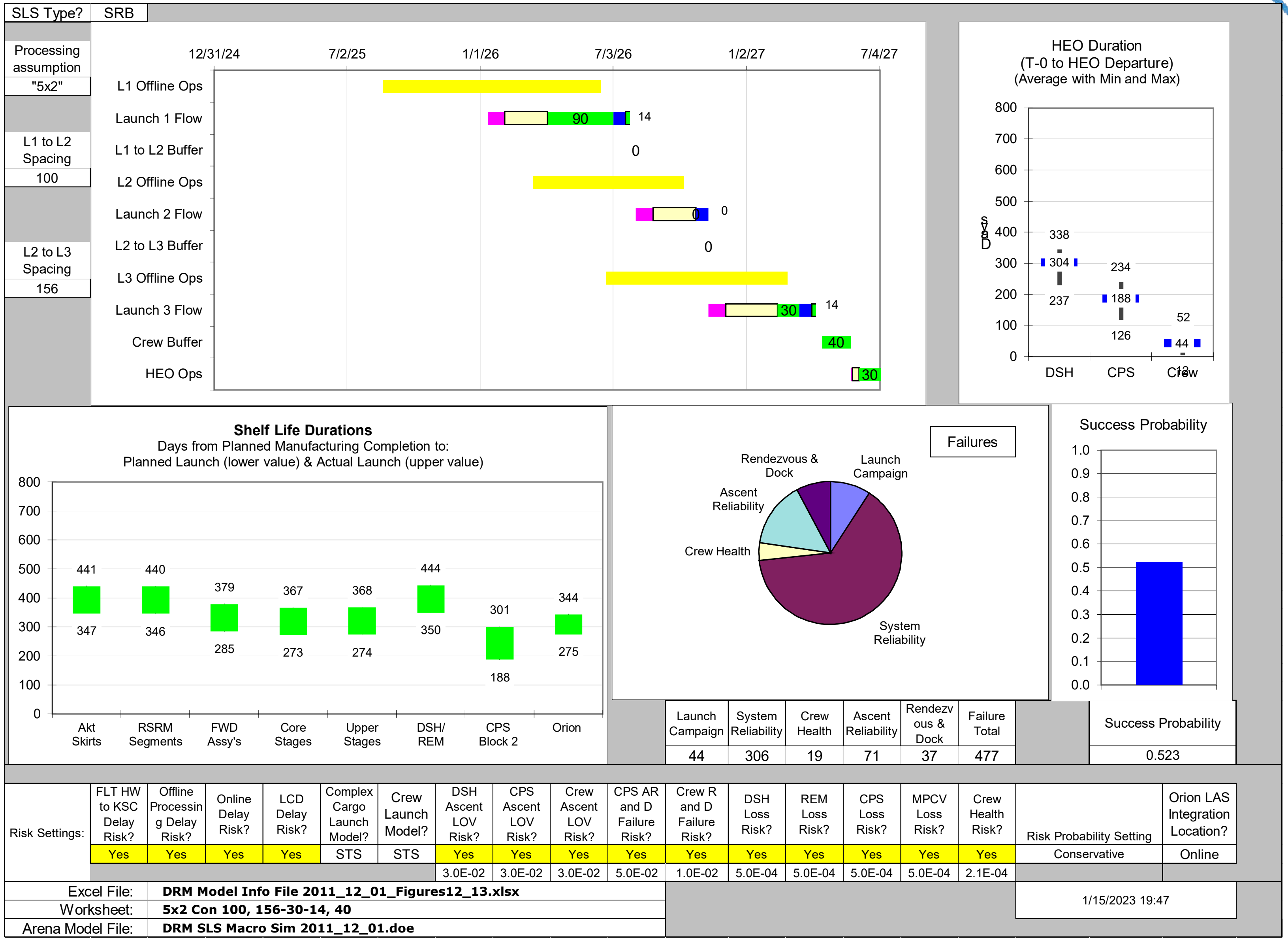
FLT HW = Flight Hardware; KSC = Kennedy Space Center; LCD = Launch Countdown; DSH = Deep Space Habitat; CPS = Cryogenic Propulsion Stage; MPCV = Multi-Purpose Crew Vehicle (Orion); LAS = Launch Abort System; HEO = High Earth Orbit; REM = Robotic & Exploration Module; FWD = Forward

Launch and Assembly Reliability Analysis for Human Space Exploration Missions (2012)

2-shift Processing; Conservative Risk Factors; Added Margin in 3rd Launch; Added 40-day Crew Buffer

- Success probability is 50-50
- Changed to Conservative Risk Factors, which substantially increase loss of mission risk.
- Added Margin in 3rd Launch Flow and a Crew Buffer
  - *Increases crew time in earth orbit, but substantially reduces launch campaign risk*
- System reliability is the largest contributor to loss of mission risk, but others are also significant



FLT HW = Flight Hardware; KSC = Kennedy Space Center; LCD = Launch Countdown; DSH = Deep Space Habitat; CPS = Cryogenic Propulsion Stage; MPCV = Multi-Purpose Crew Vehicle (Orion); LAS = Launch Abort System; HEO = High Earth Orbit; REM = Robotic & Exploration Module; FWD = Forward

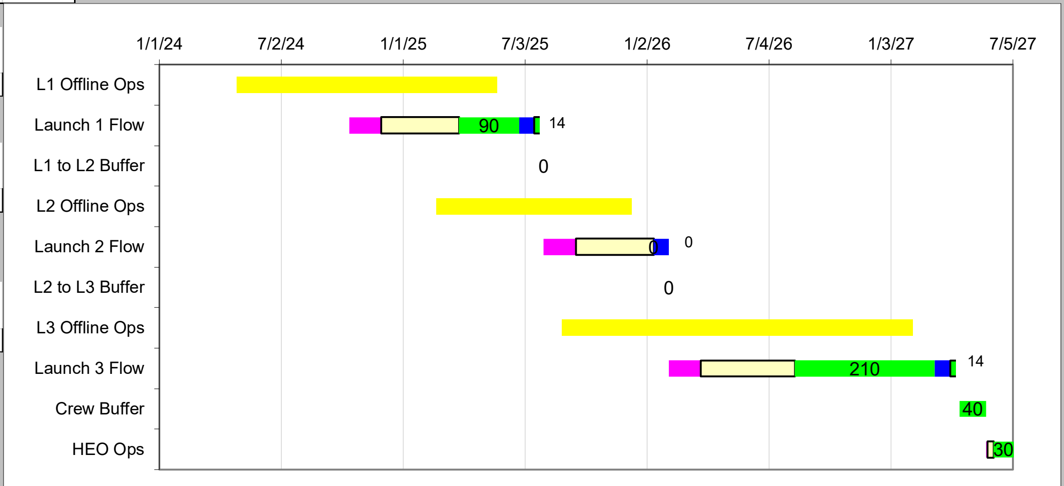
Launch and Assembly Reliability Analysis for Human Space Exploration Missions (2012)

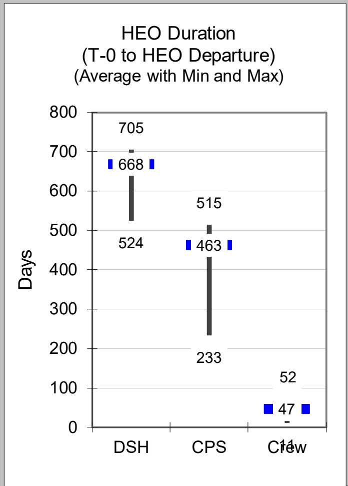
1-shift Processing; Optimistic Risk Factor Setting; Added Additional Campaign Margin; Crew Buffer

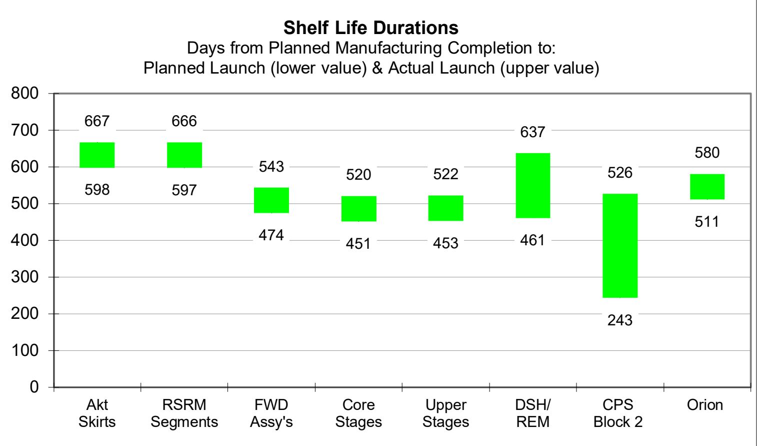
- Success probability is greater than 0.9.
- Added large amount of margin to the third launch campaign.
- Greatly increased shelf-life capability requirement.
- No dominant risk. Essentially an equal mix of:
  - *Launch campaign*
  - *System Reliability*
  - *Crew Health*
  - *Ascent Reliability*
  - *Rendezvous & Dock*

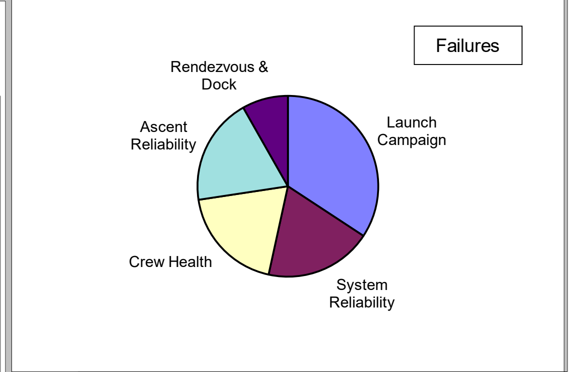
FLT HW = Flight Hardware; KSC = Kennedy Space Center; LCD = Launch Countdown; DSH = Deep Space Habitat; CPS = Cryogenic Propulsion Stage; MPCV = Multi-Purpose Crew Vehicle (Orion); LAS = Launch Abort System; HEO = High Earth Orbit; REM = Robotic & Exploration Module; FWD = Forward

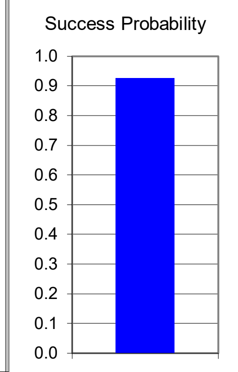
SLS Type?	SRB
Processing assumption	"5x1"
L1 to L2 Spacing	188
L2 to L3 Spacing	436











Launch Campaign	System Reliability	Crew Health	Ascent Reliability	Rendezvous & Dock	Failure Total
25	14	14	14	6	73

Success Probability
0.927

Risk Settings:	FLT HW to KSC Delay Risk?	Offline Processing Delay Risk?	Online Delay Risk?	LCD Delay Risk?	Complex Cargo Launch Model?	Crew Launch Model?	DSH Ascent LOV Risk?	CPS Ascent LOV Risk?	Crew Ascent LOV Risk?	CPS AR and D Failure Risk?	Crew R and D Failure Risk?	DSH Loss Risk?	REM Loss Risk?	CPS Loss Risk?	MPCV Loss Risk?	Crew Health Risk?	Risk Probability Setting	Orion LAS Integration Location?
	Yes	Yes	Yes	Yes	STS	STS	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Optimistic	Online
							4.0E-03	4.0E-03	4.0E-03	1.5E-02	5.0E-03	1.0E-05	1.0E-05	1.0E-05	1.0E-05	7.2E-05		

Excel File:	**DRM Model Info File 2011_12_01_Figure12.xlsx**
Worksheet:	**5x1 Opt 188, 436-210-14, 40**
Arena Model File:	**DRM SLS Macro Sim 2011_12_01.doe**

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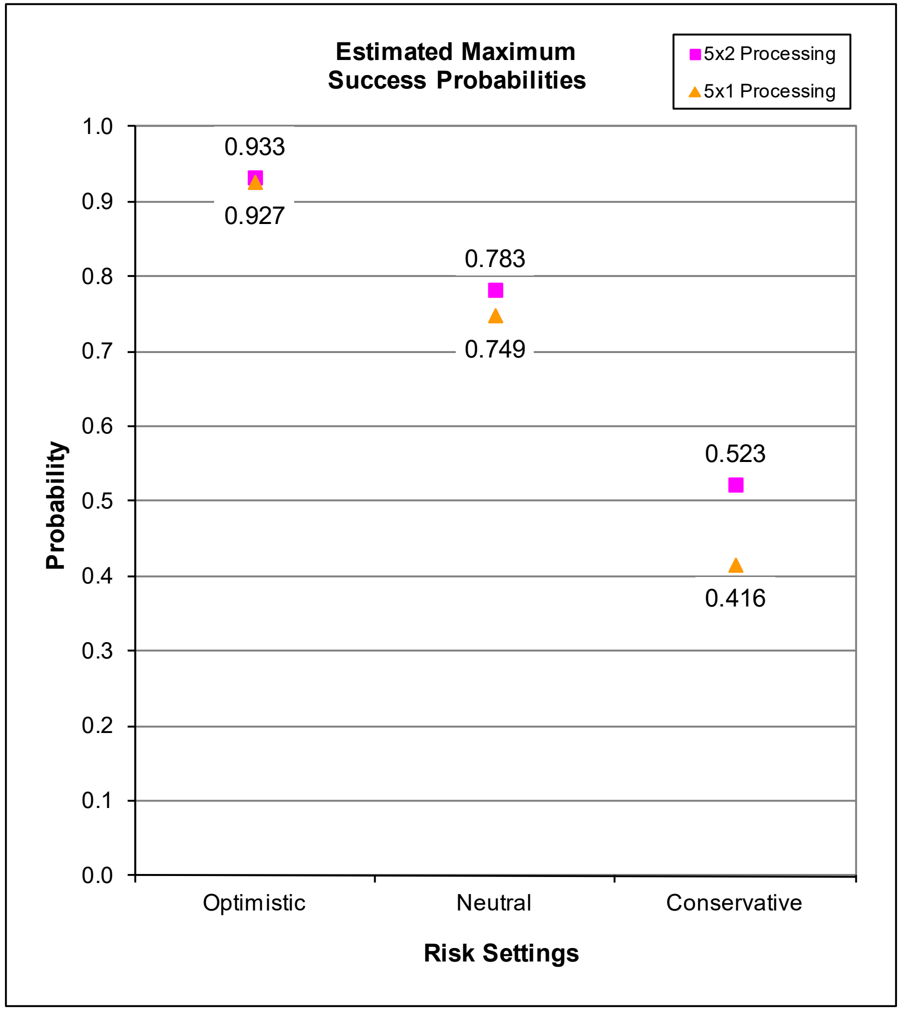
Launch and Assembly Reliability Analysis for Human Space Exploration Missions (2012)

Estimated Maximum Success Probabilities for Achieving the Trans-NEA-Injection

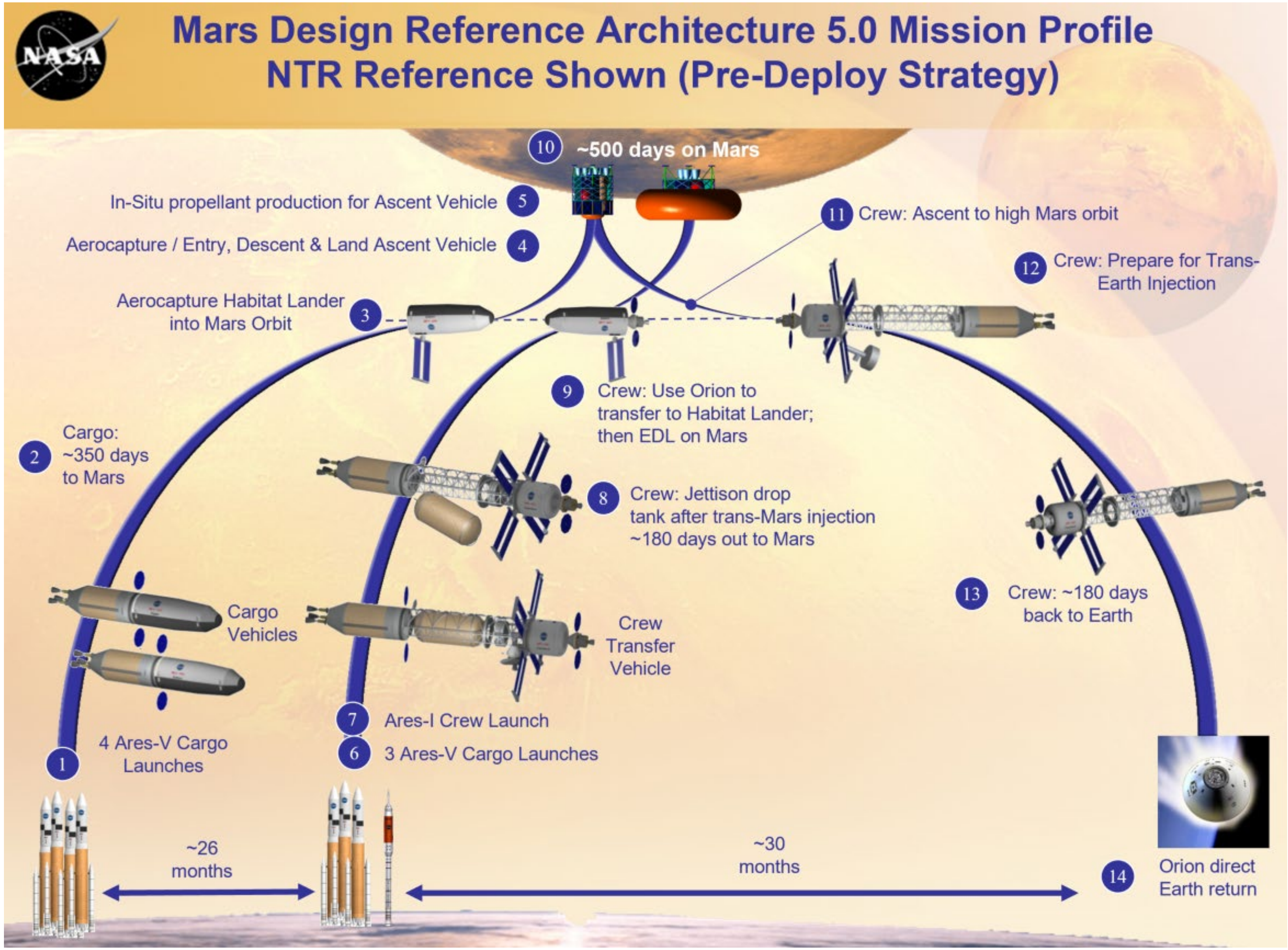
- Risk settings have a significant influence on the results
  - *Optimistic*
  - *Neutral*
  - *Conservative*
- The launch campaign processing assumption is more influential with the conservative risk settings



Launch and assembly reliability analysis for Mars human space exploration missions (2013)

- Multiple launches and assembly of multiple Mars Transfer Vehicles
- Constrained departure windows of approximately 60 days that repeat on a 26-month cycle
- Fundamental tension between adding margin to the launch schedule and the amount of in-space risk exposure
- Several factors are interconnected in how they influence Launch and Assembly Reliability for missions that require multiple launches and have a constrained departure window
  - *Launch availability, launch spacing, mission hardware (element) time limits, crew health, in-space system reliability, departure window constraints, and availability of spares*
- Challenge – Structure total launch and assembly reliability to result in an acceptable probability of mission success

Launch and assembly reliability analysis for Mars human space exploration missions (2013)



Launch and assembly reliability analysis for Mars human space exploration missions (2013)

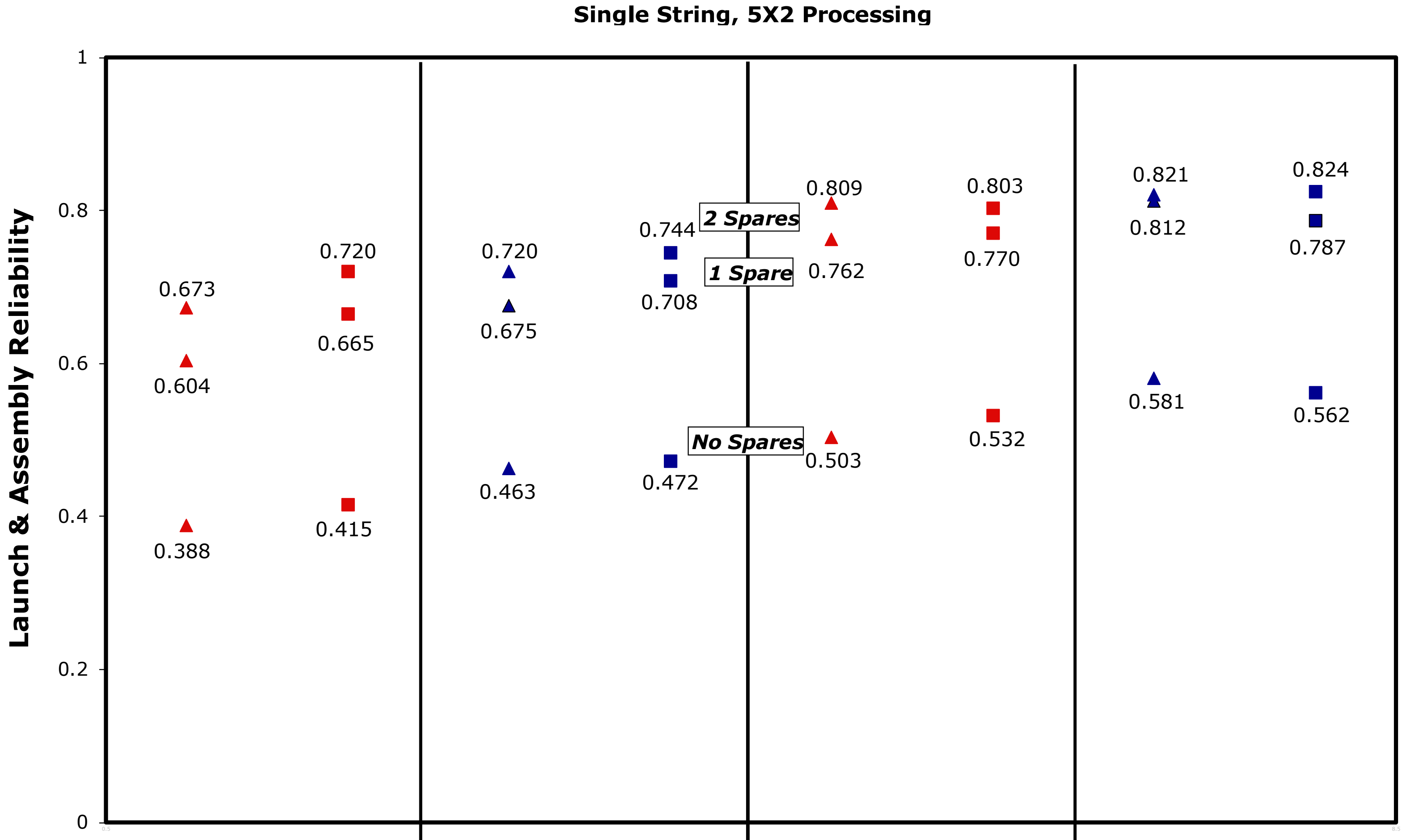
Scenarios that were studied

- Mars Transfer Vehicle (MTV) Propulsion Type
  - *Nuclear Thermal (NTR)*
  - *Chemical (Chem)*
- Deployment Strategies for MTVs
  - *Pre-Deploy*
  - *All-Up*
- SLS Lift Capacity
  - *105 t*
  - *130 t*
- Ground Processing Architecture
  - *Single String – 5x2 Processing*
  - *Dual String – 5x3 processing*
- Spares
  - *0, 1, or 2*

Case #	MTV Prop. Type	MTV Deploy Strategy	Number of Launches	Cargo SLS Version	Ground Architecture		Spares
1	Chem	All Up	13	105 t	Single String	5x2	0, 1, 2
2			12	130 t			
3	NTR	All Up	11	105 t			
4			10	130 t			
5	Chem	Pre-Deploy	8 and 5	105 t	Dual String	5x3	
6			6 and 5	130 t			
7	NTR	Pre-Deploy	6 and 4	105 t			
8			5 and 4	130 t			

Launch and assembly reliability analysis for Mars human space exploration missions (2013)

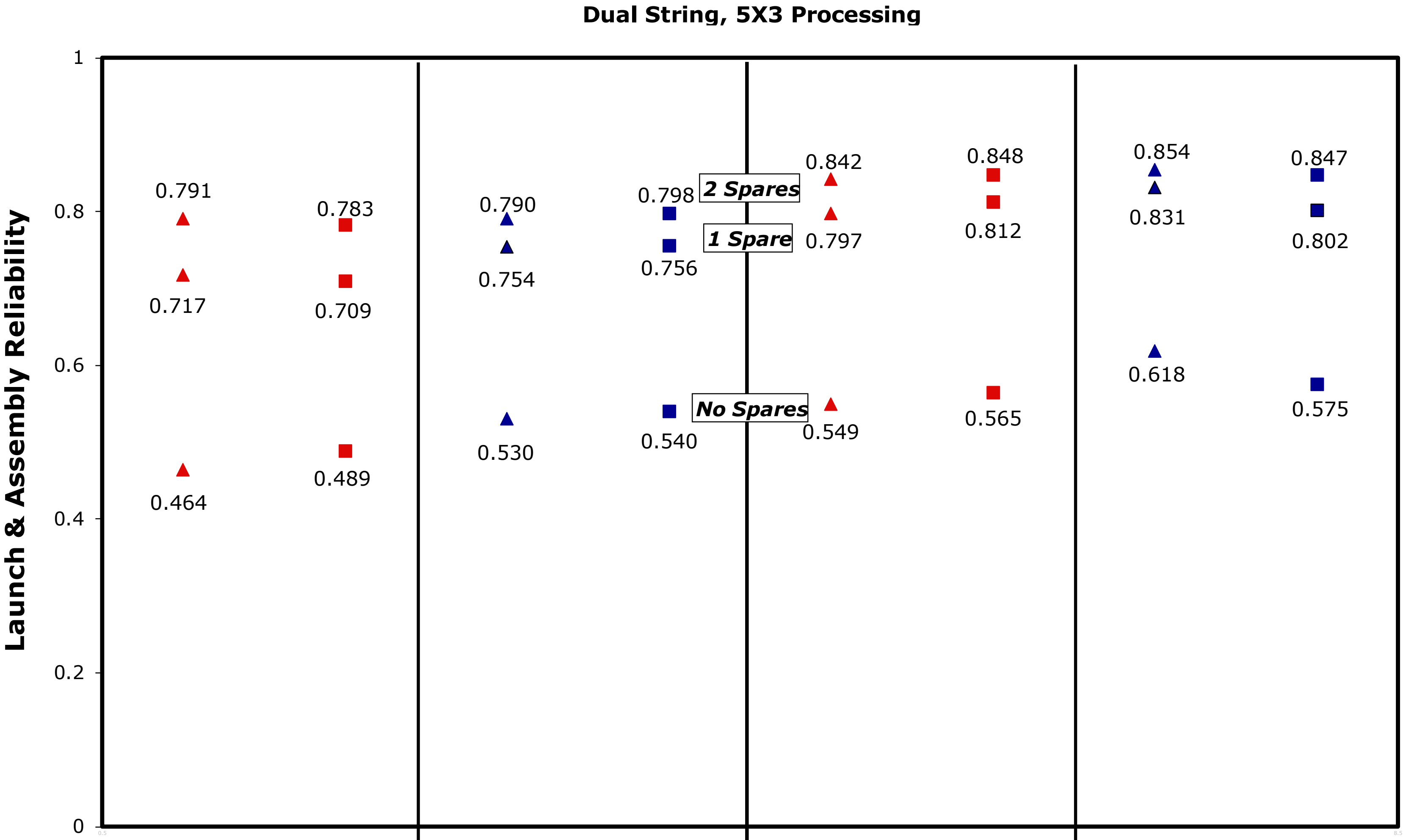
Summary Results – Single String Ground Processing Architecture – 5x2 Processing



Case	1	2	3	4	5	6	7	8
Deployment	All-Up				Pre-Deploy			
Propulsion	Chemical		NTR		Chemical		NTR	
Launch Vehicle	105 t	130 t	105 t	130 t	105 t	130 t	105 t	130 t

Launch and assembly reliability analysis for Mars human space exploration missions (2013)

Summary Results - Dual String Ground Processing Architecture – 5x3 Processing



Case	1	2	3	4	5	6	7	8
Deployment	All-Up				Pre-Deploy			
Propulsion	Chemical		NTR		Chemical		NTR	
Launch Vehicle	105 t	130 t	105 t	130 t	105 t	130 t	105 t	130 t

International Human Mission to Mars (2014)

Analyzing a Conceptual Launch and Assembly Campaign

In July of 2013, U.S. Congressman Kennedy of Massachusetts successfully offered an amendment to H.R. 2687, the National Aeronautics and Space Administration Authorization Act of 2013.

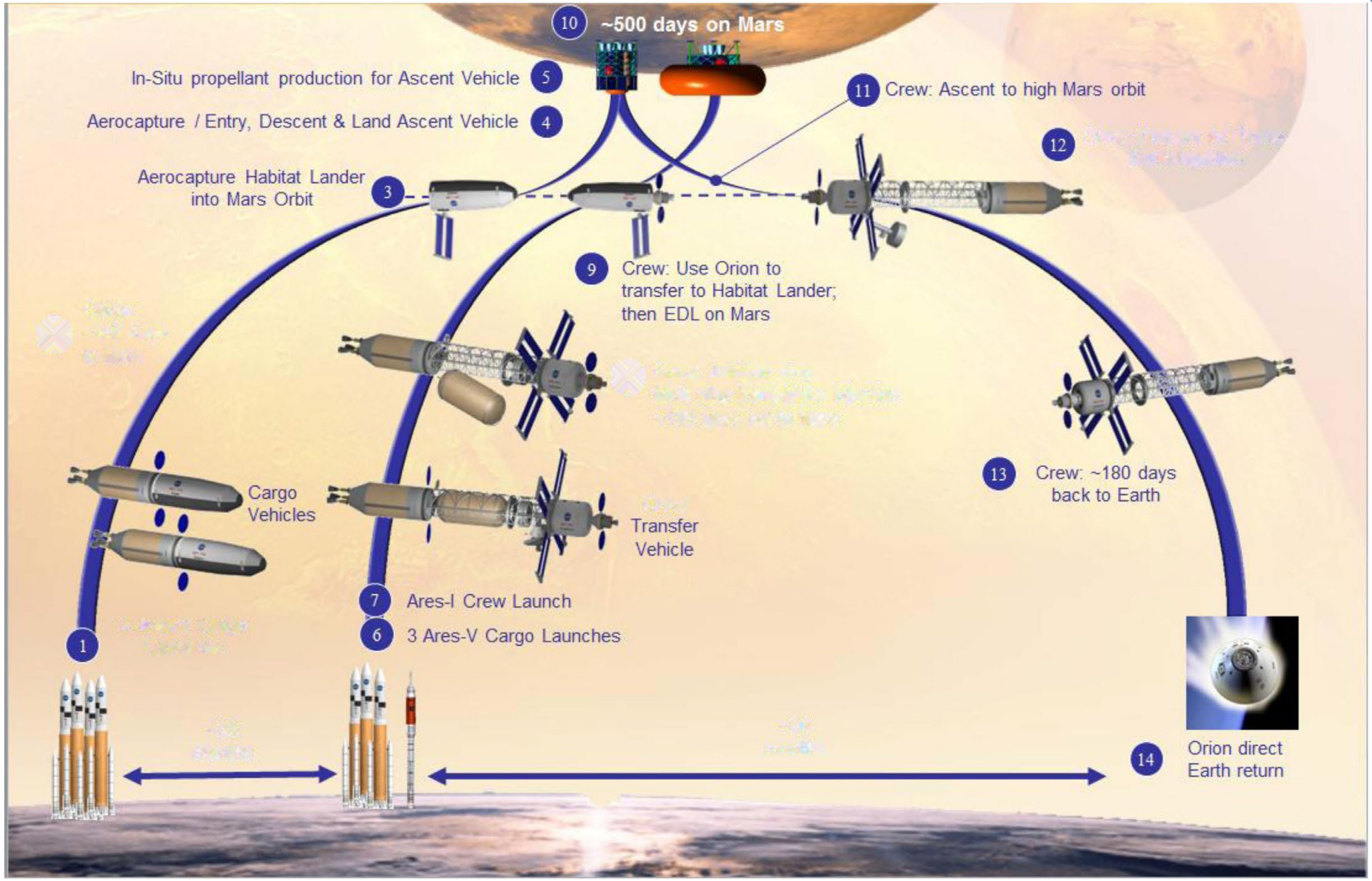
International Participation – The President should invite the United States partners in the International Space Station program and other nations, as appropriate, to participate in an international initiative under the leadership of the United States to achieve the goal of successfully conducting a crewed mission to the surface of Mars.

- NASA's "Human Exploration of Mars: Design Reference Architecture 5.0" (DRA 5.0) was our point of departure.
- DRA 5.0 assumed use of NASA launch vehicles.
- Developed concepts utilizing a mixed fleet of NASA Space Launch System (SLS), U.S. commercial and international launch vehicles.
  - *Potential to reduce the campaign duration.*
  - *Added complexity.*
  - *The reliability of the launch and assembly campaign utilizing SLS launches augmented with commercial and international launch vehicles was analyzed and compared using discrete event simulation.*

International Human Mission to Mars (2014)

Analyzing a Conceptual Launch and Assembly Campaign

- Three Mars Transfer Vehicles (MTVs) sent to Mars. Each MTV to propel one of the three major payload elements required at Mars to conduct the mission.
  - ***Mars surface habitat (SHAB)*** *that the crew uses to descend to the Mars surface and where they live in and work from during their stay on Mars*
  - ***Mars descent / ascent vehicle (MDAV)*** *that is used to descend exploration gear to the Mars surface and then at the conclusion of the Mars surface mission to ascend the crew back to Mars orbit;*
  - ***Deep space transit habitat (HAB)*** *that the crew would live in during their transit from Earth orbit to Mars orbit and back.*
- The MTVs were to be assembled in earth orbit and each would require multiple launches of the SLS



International Human Mission to Mars (2014)

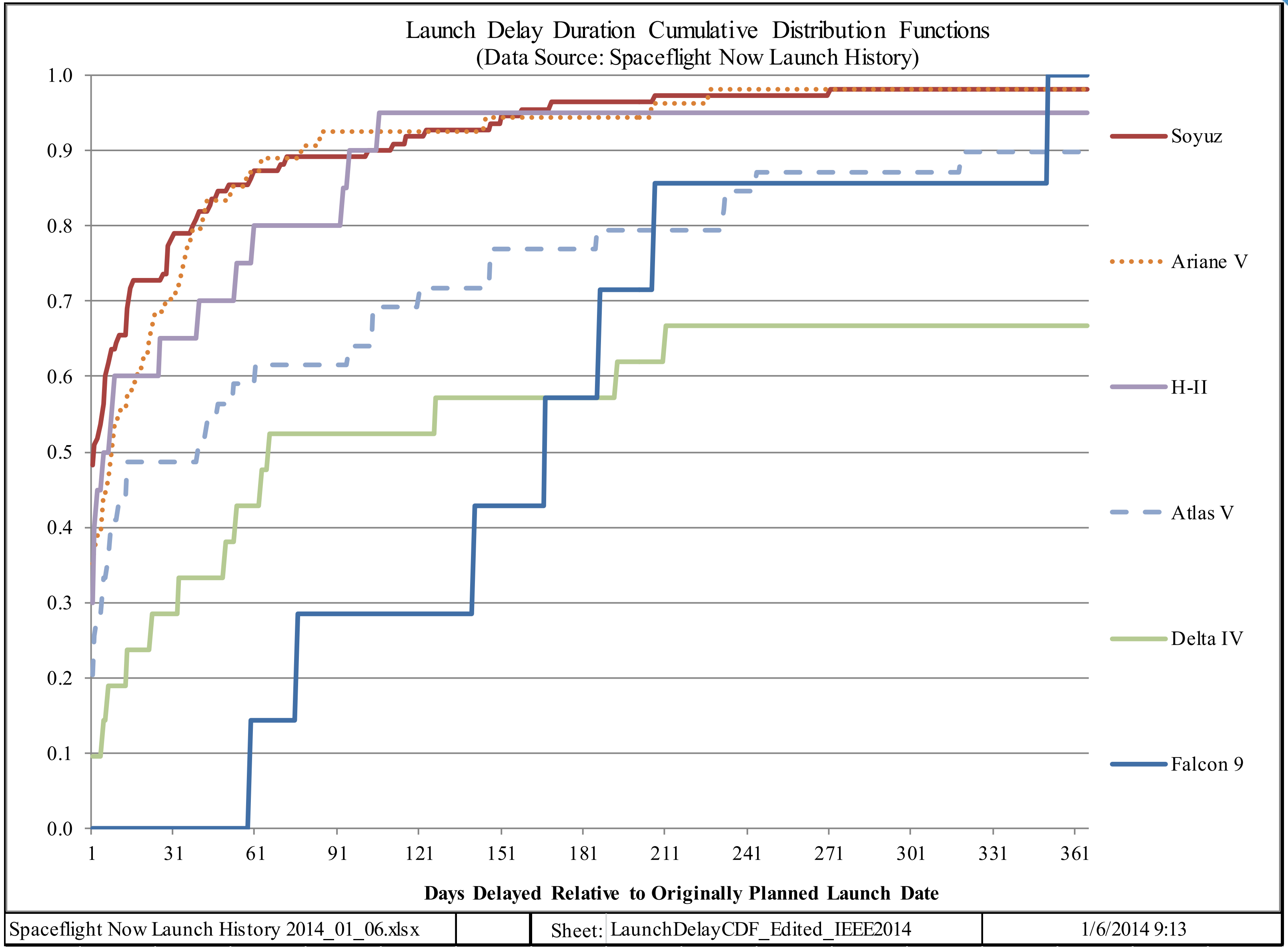
- Three campaigns were developed with all using a commercial crew vehicle
  - *4 SLS – 1 Spare SLS*
  - *3 SLS + 6 Commercial – International Partner Launchers*
  - *3 SLS + 11 Commercial – International Partner Launchers*
- The size of the buffers and the launch spacing were adjusted to maximize the reliability of the campaign.

Days Relative to Opening of TMI Window	4 SLS + 1 Spare SLS + Commercial Crew	3 SLS + 6 CIP + 1 Spare Each + Commercial Crew	2 SLS + 11 CIP + 1 Spare Each + Commercial Crew
60			
0			
	28-day crew launch buffer	28-day crew launch buffer	28-day crew launch buffer
-30	Commercial Crew	Commercial Crew	Commercial Crew
	~270 days of MTV launch & assembly campaign buffer	~270 days of MTV launch & assembly campaign buffer	~210 days of MTV launch & assembly campaign buffer
-240			**SLS: Spare (as-needed)**
-300	**SLS: Spare (as-needed)**	**SLS: Spare (as-needed)**	Delta IV H: Orion & SM
-315			Ariane V: Contingency Food
-330	~105-Day Launch-to-Launch Turnaround	Delta IV H: Orion & SM	Falcon H: Inflatable Trans-Hab
-345		Ariane V: Contingency Food	**SLS: NTR Prop Module**
		Falcon H: Inflatable Trans-Hab	
-390			Atlas V: H2 Tank
-405	**SLS: NTR Prop Module**	**SLS: NTR Prop Module**	Delta IV H: H2 Tank
-420	~105-Day Launch-to-Launch Turnaround	~105-Day Launch-to-Launch Turnaround	Ariane V: H2 Tank
-435			Falcon H: H2 Tank
-450			**SLS: In-Line Tank**
-495			Falcon H: Saddle Truss
-510	**SLS: In-Line Tank**	**SLS: In-Line Tank**	Soyuz: Power System & ZBO Cryo-Coolers
-525	~105-Day Launch-to-Launch Turnaround	~105-Day Launch-to-Launch Turnaround	H2B: 2nd Docking Module; Fwd RCS Prop
-540			Atlas V: Short Saddle Truss
-615	**SLS: Saddle Truss / Drop Tank**	**SLS: Saddle Truss / Drop Tank**	
-660	~105-Day Launch-to-Launch Turnaround	Soyuz: Power System & ZBO Cryo-Coolers	
-685		H2B: 2nd Docking Module; Fwd RCS Prop	
-690		Atlas V: Short Saddle Truss	
-720	**SLS: Payload Elements**		

International Human Mission to Mars (2014)

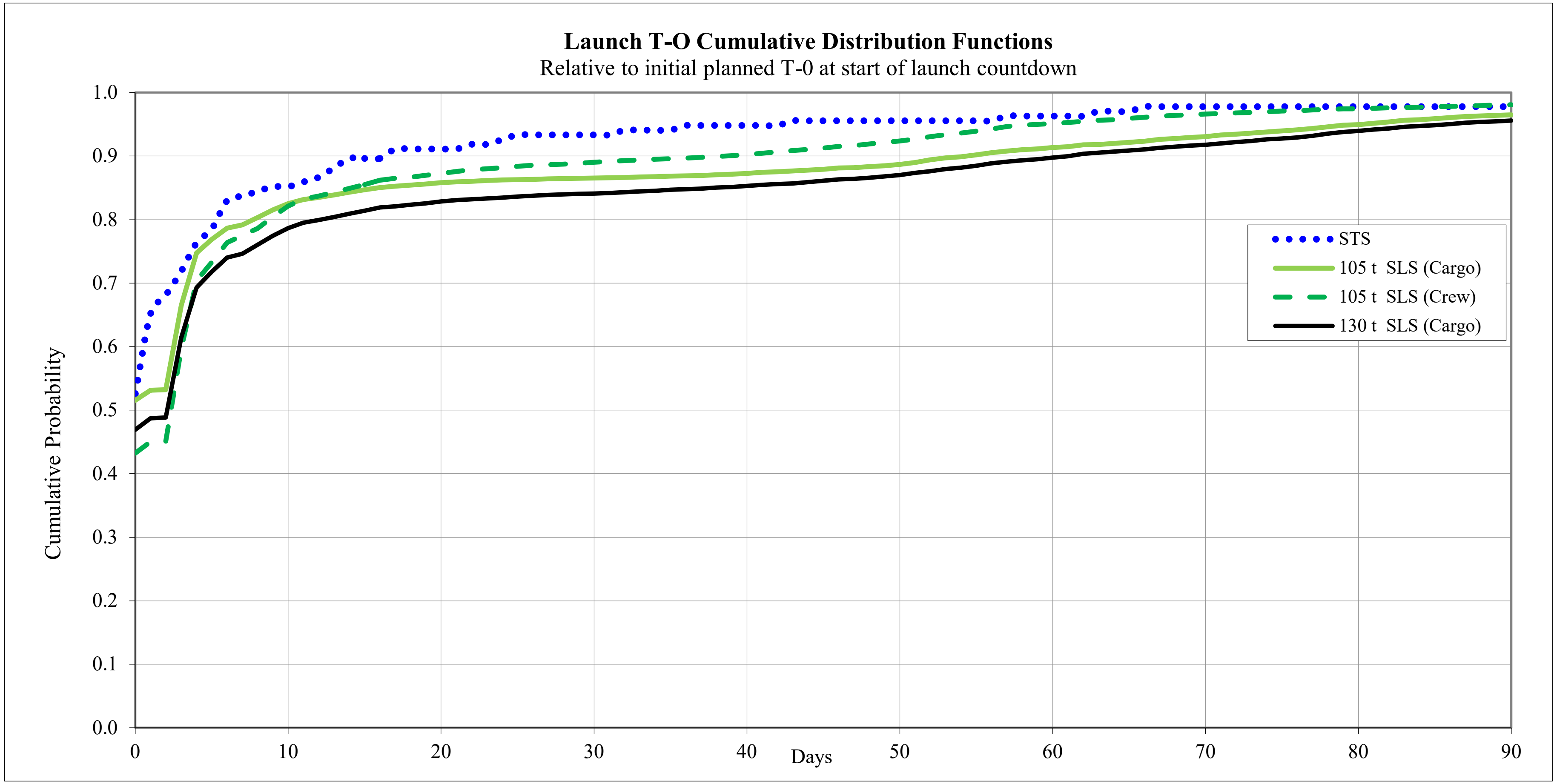
Launch Delay Risks for Various Launch Vehicles – Delay Relative to Original Planned Date

- SpaceflightNow.com's launch schedule has about a 6-month to one-year horizon, meaning that when a planned launch date is set on their schedule, the planned launch is 6 to 12 months away.
- The schedule is updated with any changes to the launch date.
- Once the launch has actually occurred, the history of delays is documented in their launch log.
- We compared the initial planned launch date to the actual launch date to create cumulative launch delay distribution functions.



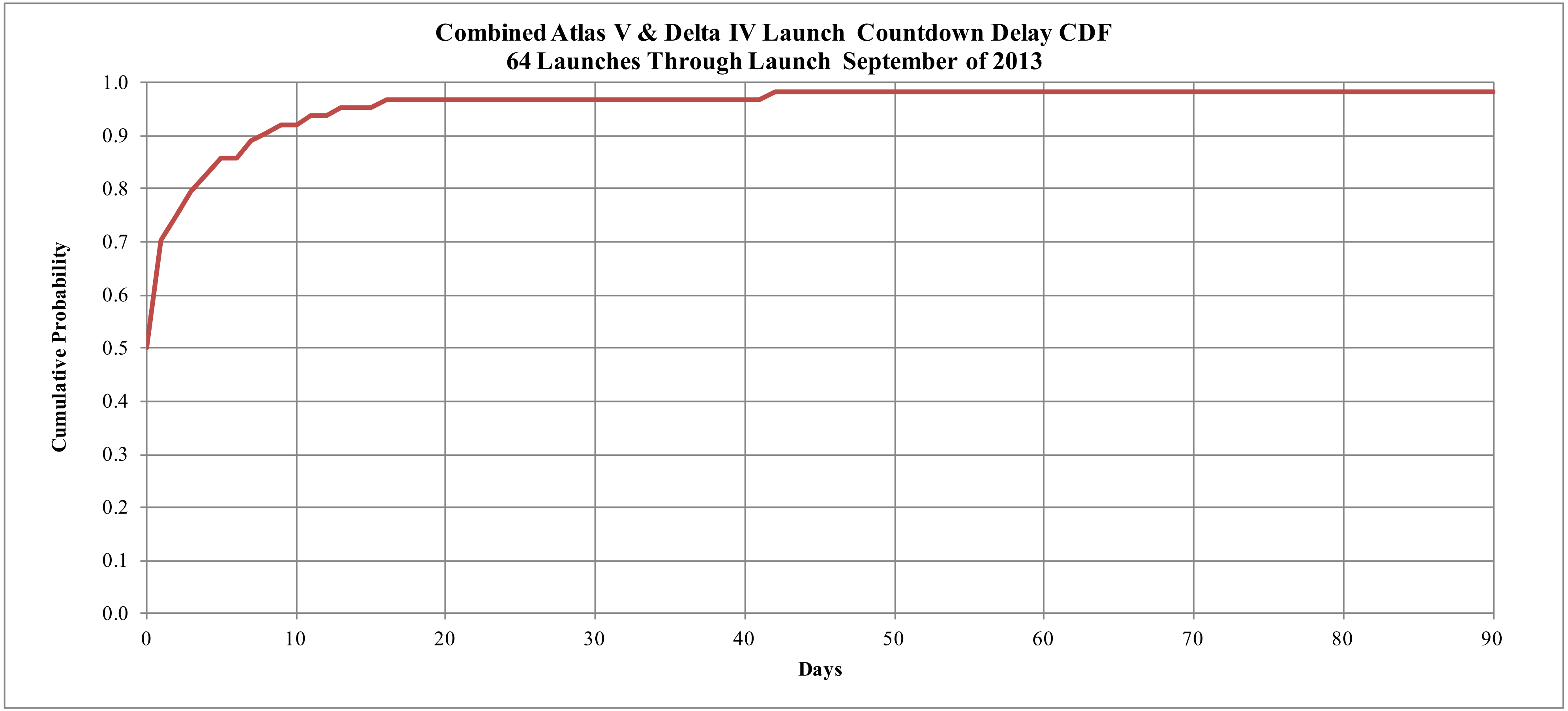
International Human Mission to Mars (2014)

Estimated launch countdown delay risk for SLS – Delay Relative to Initial Launch Attempt



International Human Mission to Mars (published in 2014)

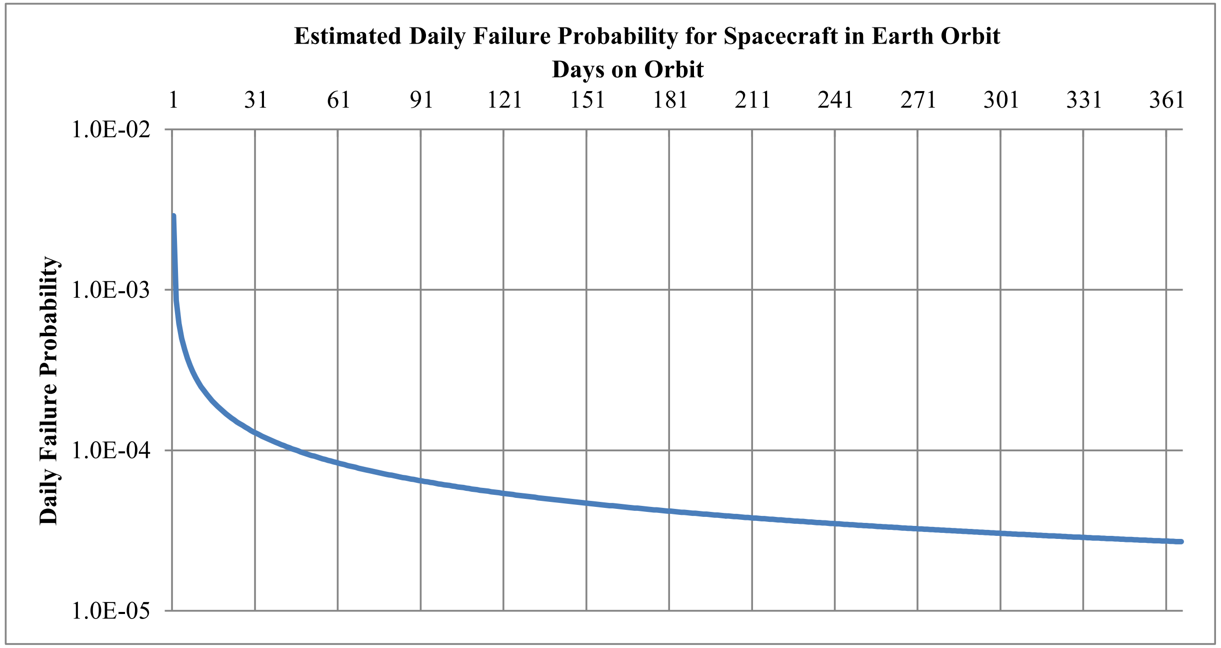
Launch countdown delay risk for Atlas V and Delta 4 – Delay relative to initial attempt



International Human Mission to Mars (2014)

Estimated daily failure probability for spacecraft in earth orbit

- As elements loiter in earth orbit, there is the potential that system failures will result in loss of mission.
- Difficult to develop accurate risk models of MTV elements that have not been designed/built yet.
- For risk modeling during the on-orbit assembly campaign, it was assumed that each of the 4 major MTV elements (NTR Prop, In-Line Tank, Drop Tank, and Payload Elements) were analogous to an Earth orbiting spacecraft.
- Used risk model developed by Saleh and Castet
  - *They analyzed a select portion of Ascend's [now Seradata] SpaceTrak database.*
    - 1,584 spacecraft launched between January 1990 and October 2008
  - *They developed a spacecraft reliability model as a function of time spent on orbit.*



Saleh, J.H. and Castet J-F., *Spacecraft Reliability and Multi-State Failures: A Statistical Approach*, Wiley, 2011

International Human Mission to Mars (2014)

Overview of Risk Models

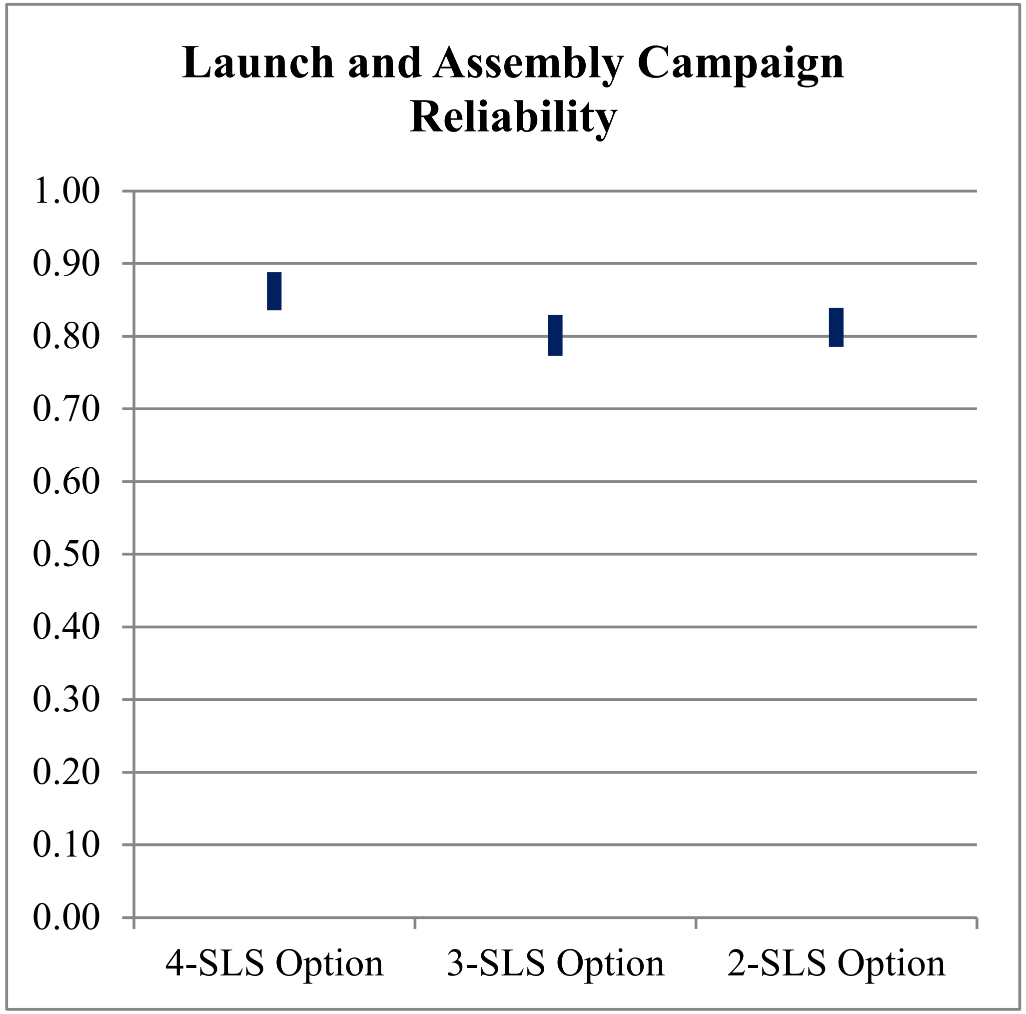
- Manufacturing, Processing & Launch Campaign Risks
- Ascent Loss of Mission Risk
- Automated Rendezvous & Docking Risk
- Element System Failure on Orbit
- MMOD Caused Failures on Orbit
- Crew Medical Risk

Risk Factors		P_{LOM}
Ascent	130 t SLS	3.317E-02
	Non-SLS launch vehicles	1.780E-02
Rendezvous, Proximity Operations & Docking/ Connection	Automated (between MTV Elements)	1.030E-02
	Crew Directed (Orion to MTV)	4.350E-03
MTV Element reliability (per Element per day on orbit)	1st day on orbit	2.892E-03
	Continue Saleh and Castet reliability model (Equation 1) for subsequent days on orbit	
MMOD (per Element per day on orbit)		1.000E-05
Health (per person per day on orbit)		9.720E-05
Earth orbit departure burn by NTR propulsion module		1.200E-02

International Human Mission to Mars (2014)

Analyzing a Conceptual Launch and Assembly Campaign

- Estimated reliability is below 0.90 for all options.
  - *Potential that one could lose a significant portion, and potentially all, of the investment made towards a human mission to Mars.*
  - *What level of predicted reliability will be required prior to committing to a multi-billion dollar launch and assembly campaign of international importance?*
- The 4-SLS option has the highest launch and assembly campaign reliability.
- The 3-SLS and 2-SLS have similar estimated reliability results.
  - *Interesting that the 2-SLS case appears to be slightly better.*
  - *The reduced duration of the 2-SLS case, and the corresponding reduced on-orbit system reliability risk, may account for the differential.*
- Options in which 1 or 2 of the SLS launches are replaced by commercial and international partner launch vehicles seem sufficiently reliable to warrant further study.



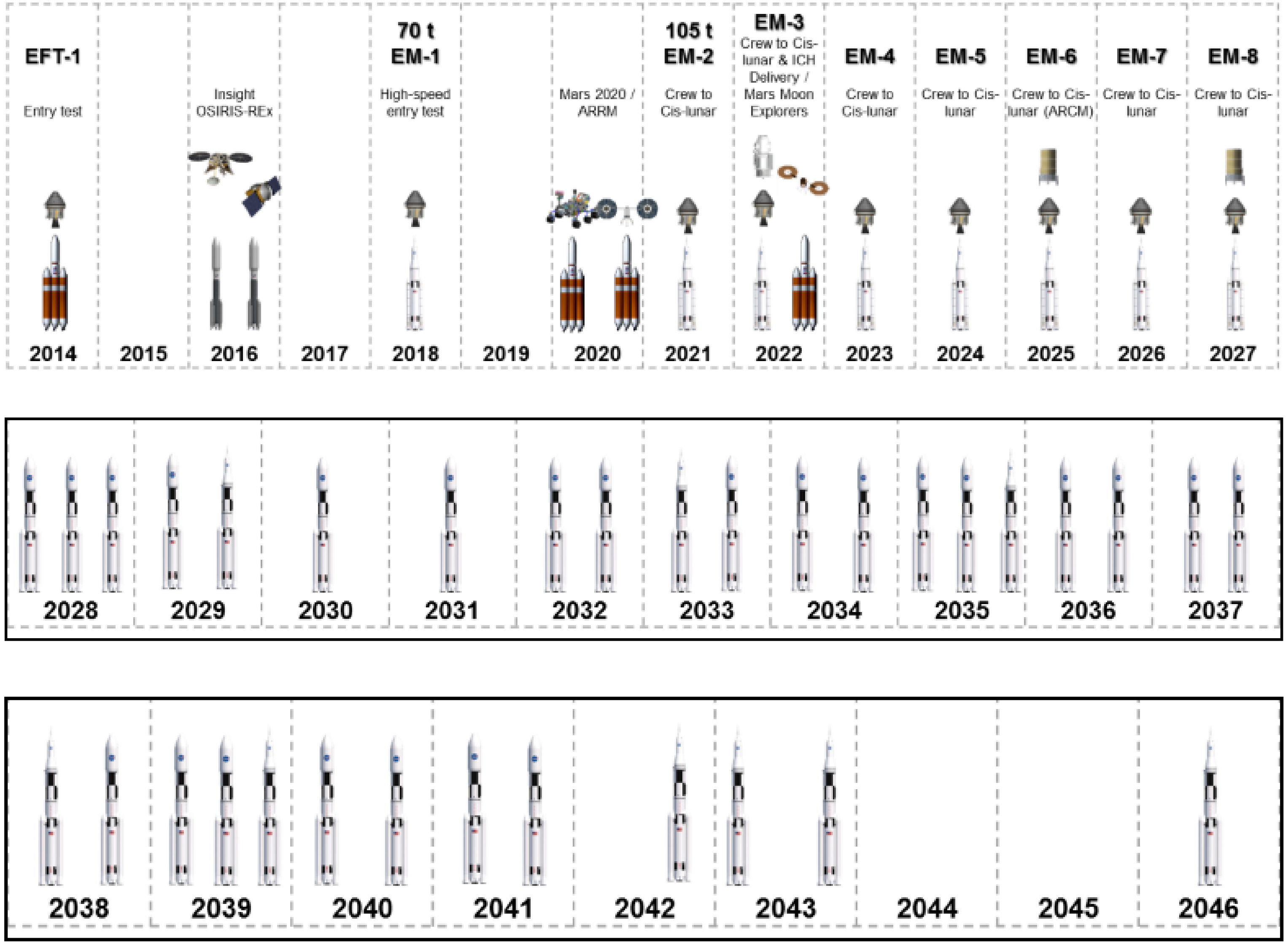
The Exploration of Mars Launch & Assembly Simulation (2016)

- The 'Exploration of Mars Launch & Assembly Simulation' was developed to model launch operations for the next several decades of human exploration of space.
- The model currently provides two capabilities.
  - *Analyze launch campaign success probability*
    - Assembly of Mars Transfer Vehicles that will be used to transport crews to Mars.
    - Discrete Trans-Mars-Injection windows that occur on an approximate 26-month cycle.
  - *An animation feature*
    - Allows users to visualize mission operations from the perspective of looking down upon the solar system
    - Compressed timescale (visualize 40 years in a few minutes)
    - Enhances the ability to comprehend the scale and complexity of the Mars campaign options under study

The Exploration of Mars Launch & Assembly Simulation (2016)

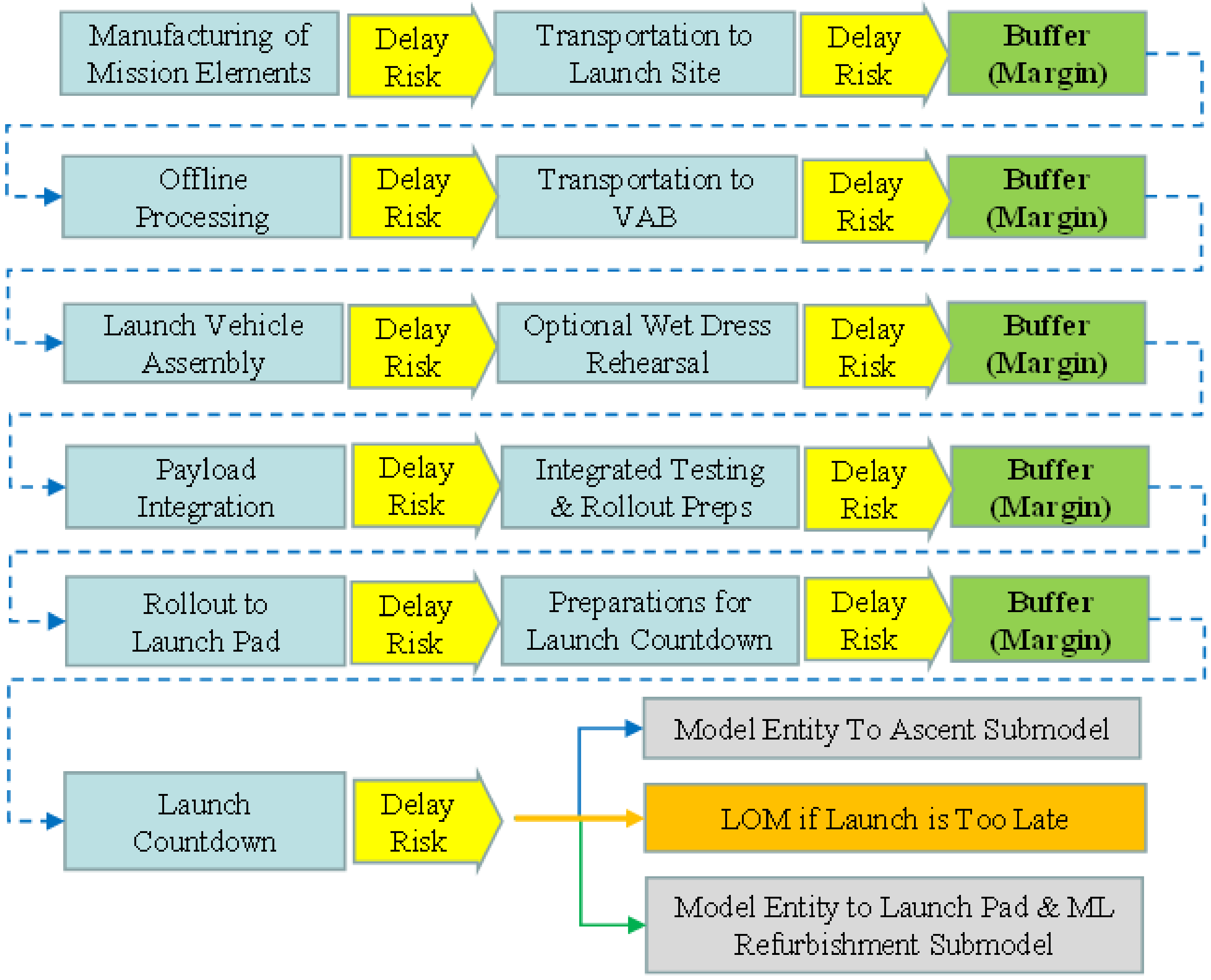
Notional Evolvable Mars Campaign Manifest

- The SLS launches depicted between 2028 and 2046 notionally support a crewed mission to Phobos in 2033, followed by crewed missions to Mars in 2039 and 2043.
- Subsequent missions to Mars could require additional launches during the 2042-2046 time-frame.



The Exploration of Mars Launch & Assembly Simulation (2016)

Flight Hardware Elements Entity Routing



LOM = Loss of Mision
ML = Mobile Launcher

The Exploration of Mars Launch & Assembly Simulation (2016)

Gantt Chart for the Mars 2039 Opportunity

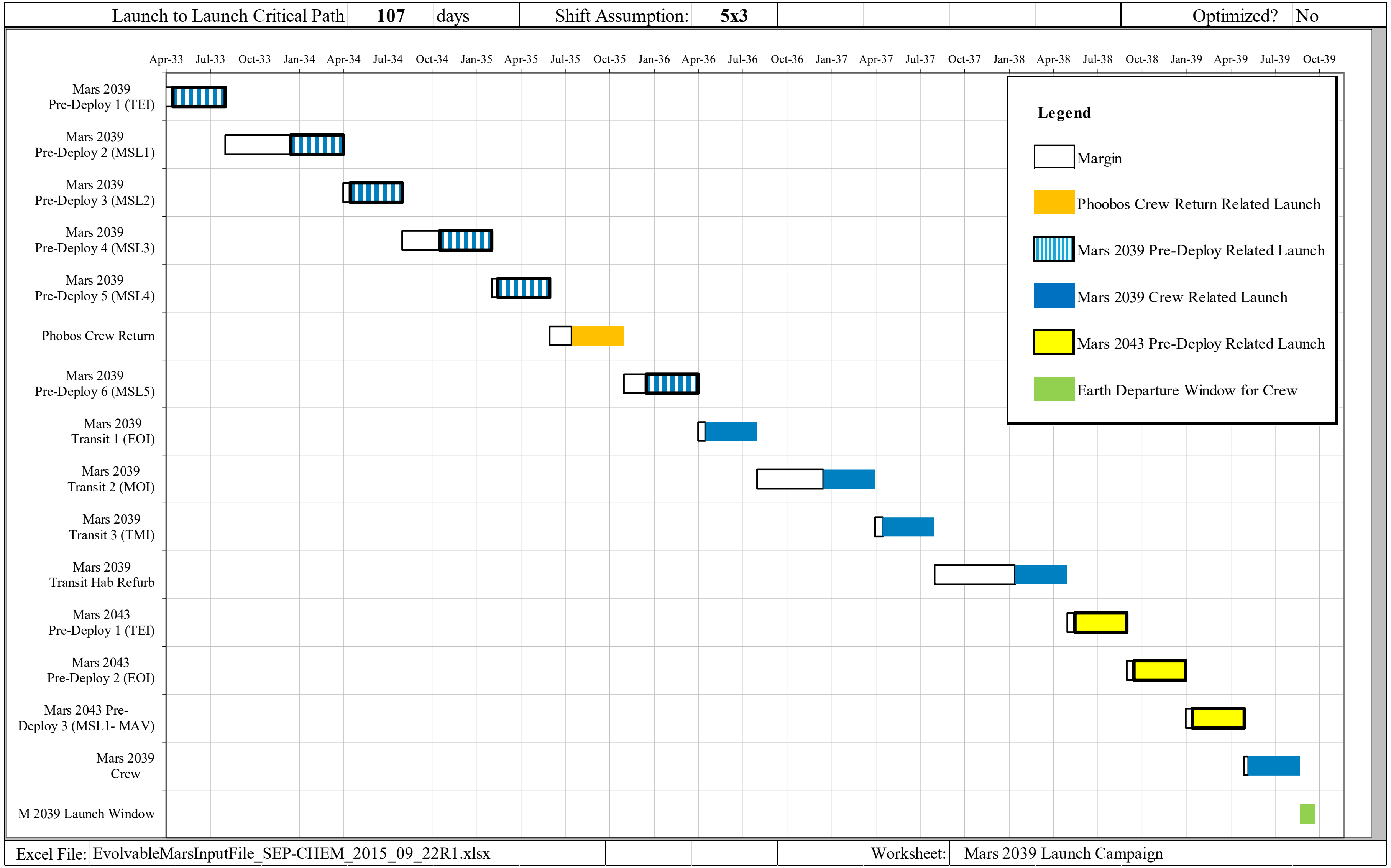
TEI = Trans Earth Injection Propulsion Module

MSL = Mars Surface Logistics

EOI = Earth Orbit Insertion Propulsion Module

TMI = Trans Mars Injection Propulsion Module

MAV = Mars Ascent Vehicle



The Exploration of Mars Launch & Assembly Simulation (2016)

"Optimized" Mars 2039 Gantt Chart

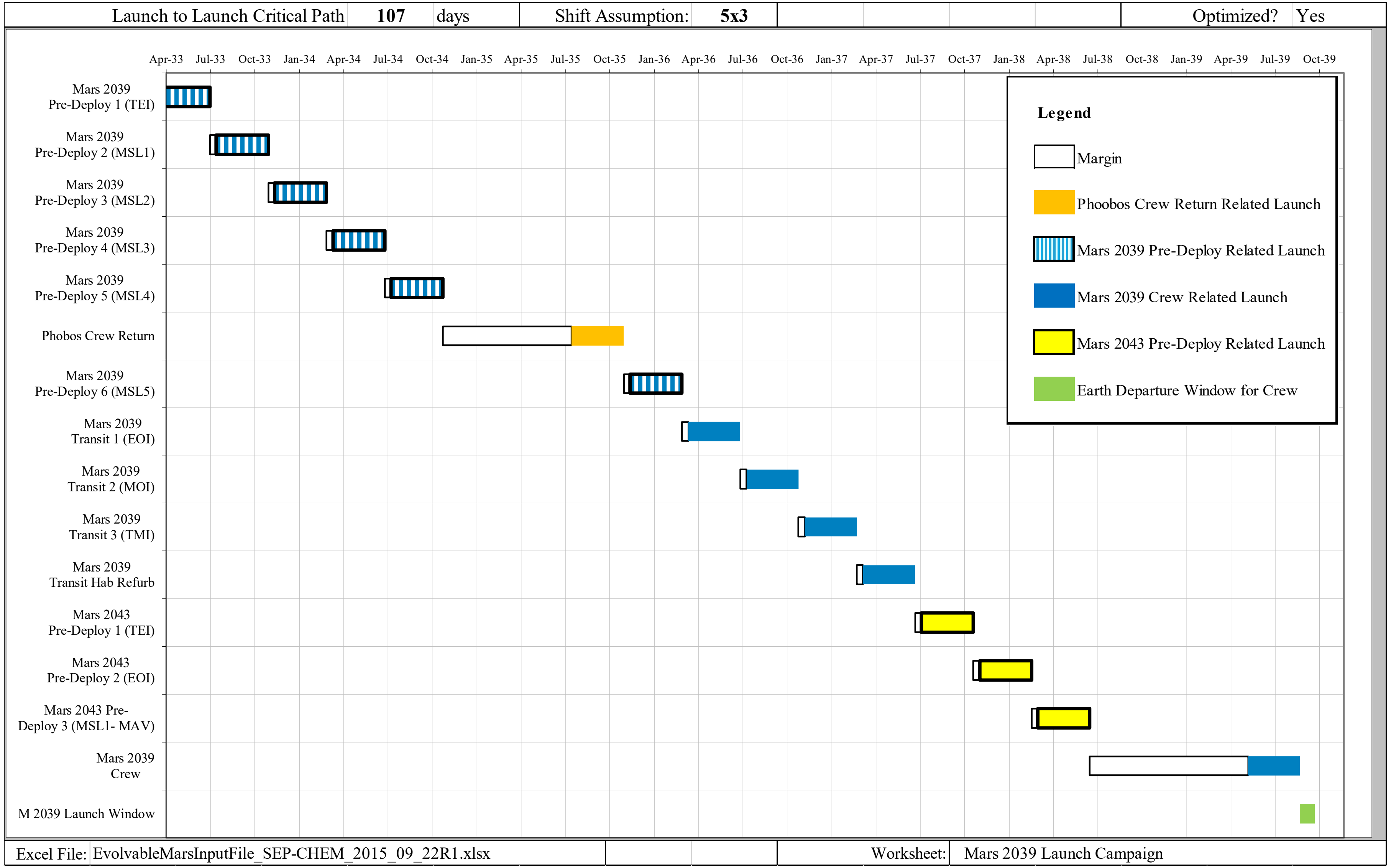
TEI = Trans Earth Injection Propulsion Module

MSL = Mars Surface Logistics

EOI = Earth Orbit Insertion Propulsion Module

TMI = Trans Mars Injection Propulsion Module

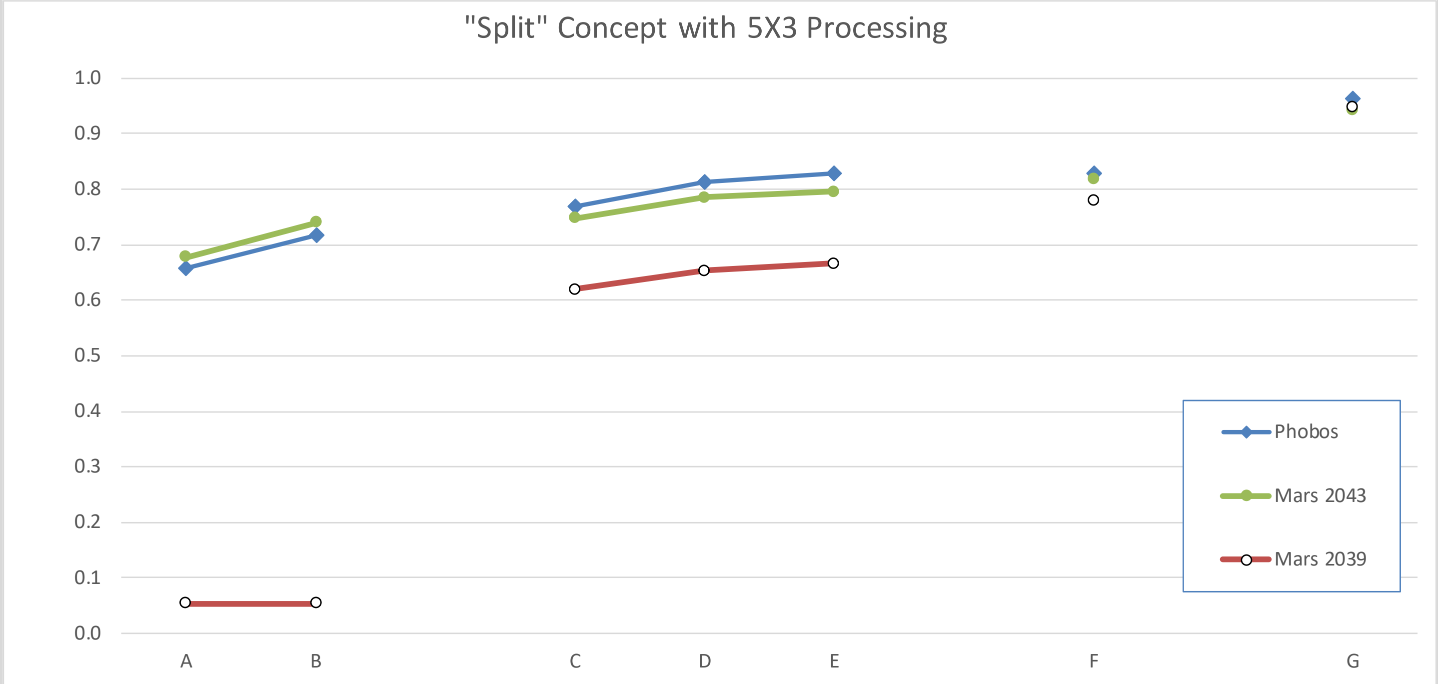
MAV = Mars Ascent Vehicle



The Exploration of Mars Launch & Assembly Simulation (2016)

"Optimized" Gantt Chart

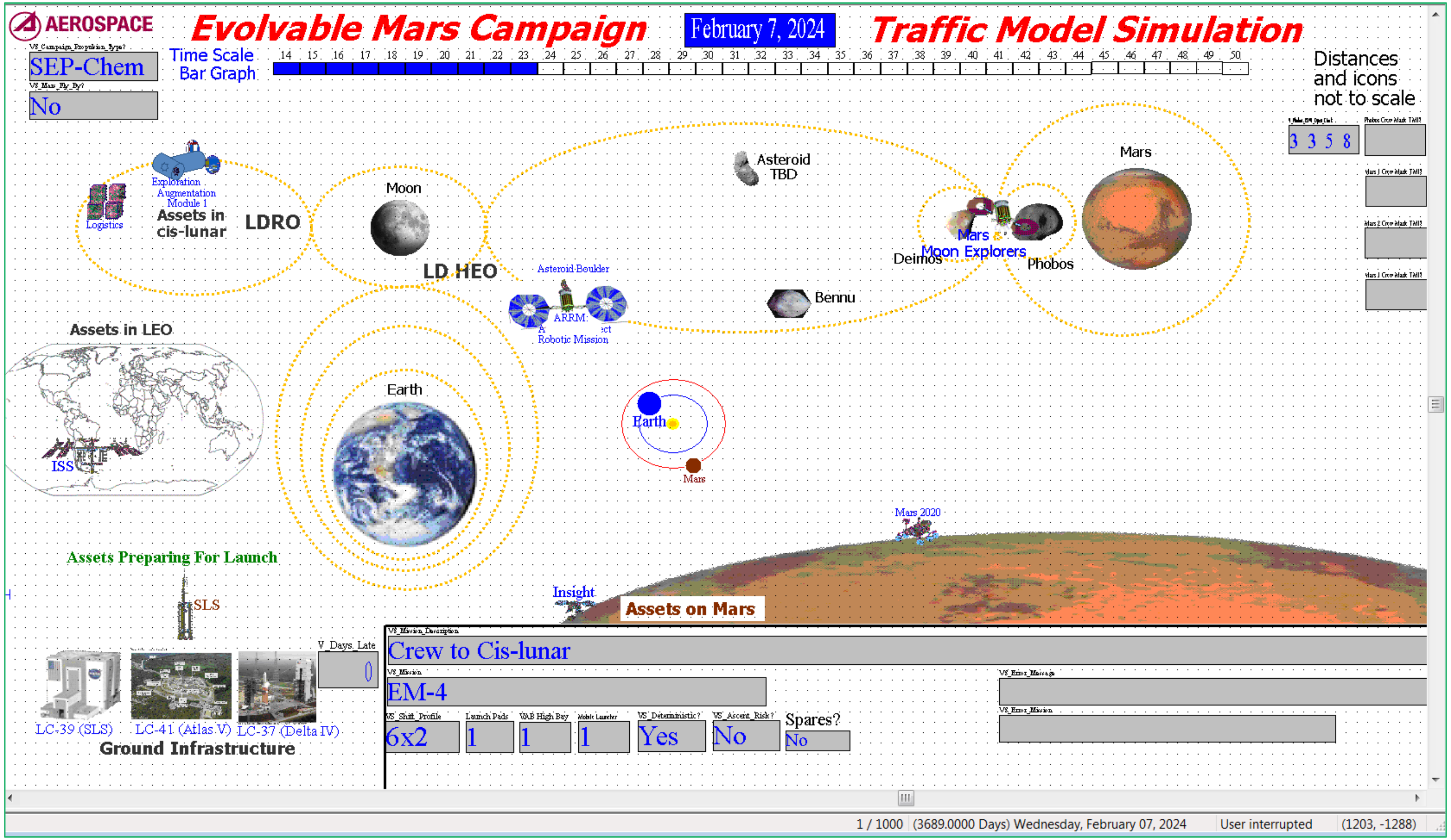
- The starting point Scenario A showed the Mars 2039 mission having a low probability of launching all elements to meet the departure window.
- Scenario B increased duration of the crew launch opportunity to 60 days.
- For Scenarios C - G, the available margin was increased by shifting planned launch dates earlier, adding more margin across the campaign, including the final launch.
- Scenarios D and E progressively increased the crew launch window by another 30 days in each case.
- Scenario F, added a mobile launcher and an integration high bay.
- Scenario G added the capability to launch a replacement mission with the added optimistic assumption that the grounding duration after an accident would be minimal.



Scenario	A	B		C	D	E		F		G
Optimized	No	No		Yes	Yes	Yes		Yes		Yes
Spares	No	No		No	No	No		No		Yes
ML	1	1		1	1	1		2		2
HB	1	1		1	1	1		2		2
Crew Launch Window	30	60		60	90	120		120		120
Excel File:	**EvolvableMarsInputFile_SEP-CHEM_2015_09_22.xlsx**						Worksheet	**Split Concept Summary Results**		

ML = Mobile Launcher
HB = High Bay

Evolvable Mars Campaign Simulation Animation



Multiple decades of future exploration can be viewed in a few minutes. Alternative to PowerPoint slides for communicating within NASA and externally to stakeholders.

The Exploration of Mars Launch & Assembly Simulation (2016)

Conclusions and Forward Work

- Capability to perform launch and assembly campaign reliability risk analysis and visualization
  - *evolving to meet the demands.*
  - *new features have been added to enhance the value of the tools.*
  - *latest findings are consistent with previous analyses*
- Launch and assembly campaign reliability remains a top overall risk.
- Keys to providing high reliability include:
  - *timely availability of launch vehicles and spacecraft,*
  - *adequate ground processing margin,*
  - *availability of ground processing infrastructure,*
  - *ability to launch the crew early relative to the closing of the TMI window,*
  - *wherewithal to return to flight quickly after failures.*

Forward work

- Modeling additional risk factors that are in play relative to achieving Trans-Mars-Injection (TMI) windows.
- Modeling post TMI risks.
- Reduce time and effort required to produce the animation feature.
- Develop additional animation features that drill down into key areas
  - *launch processing*
  - *critical flight operations*

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