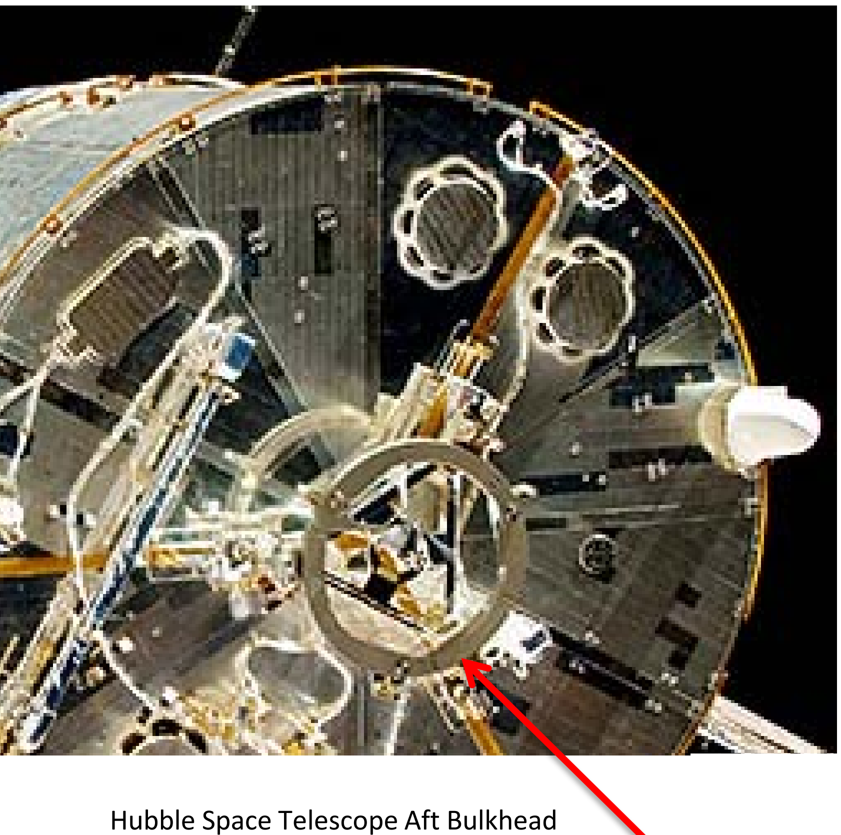
440-PRES-0028

HST Disposal Study Update

Results of the Architecture Design Lab (ADL) and Recommendations for Design Reference Mission



Hubble Space Telescope Aft Bulkhead with Soft Capture Mechanism (SCM) installed during SM4

Cosmic Origins Program Office Brief to HQ

June 7, 2012

Agenda and Objectives

- Background
- Architecture Study (ADL and Aerospace Task)
  - Introduction and Architecture Options
  - HST Orbit Altitude Decay Profile
  - Architecture Options by Altitude
  - Reliability, Debris Casualty and Cost
  - Cost – Mass – P_s – Casualty Summary Table
  - Total Mission Reliability
  - Probability of Injury (P_i)
  - Probability of Injury vs. Cost
- Autonomous Rendezvous and Docking (AR&D) Capabilities
- Potential Partners
- DRM Recommendation
- Conclusion

Ideally, at the end of this meeting we'll have:

- Provided information required for a decision about which mission approach to develop into a HST Disposal Design Reference Mission (DRM)
- A plan to reach the decision before July 1, 2012

Background

- Natural orbit decay of the HST will result in uncontrolled reentry NET ~2025
  - Modeled using 3-sigma predictions of solar cycle and atmospheric effects
- Debris-Casualty Assessment (DCA)
  - Most recent (prior to SM4) analysis predicts a 1/240 chance of harm from uncontrolled reentry
- Probability of Mission Success (Ps) is factored into DCA, so disposal mission approach must balance mission cost and mission risk
- HST Disposal Study FY11/12 activities will culminate in a design reference mission with vetted cost and schedule to be used in long-term planning. Elements included:
  - ✓ High-level trades of risk vs. cost for multiple mission architectures
    - ✓ Aerospace task (cost and development risk)
    - ✓ Architecture Design Lab (ADL) (cost and mission risk)
  - Select an architecture and develop into a design reference mission in the Mission Design Lab (MDL)
  - Identify potential partnership options to offset or leverage SMD cost for this mission
  - ✓ Survey AR&D capabilities and vendors to monitor until project formulation

Architecture Study: Introduction

- Created trade tree of 5 mission elements: HST functional state, disposal location, capture method, disposal method, main prop system
  - 27 architectures considered and dispositioned with a rationale (see Trade Tree in backup charts)
    - Cat 1: Confirmed realistic/feasible
    - Cat 2: Potentially feasible, requires further analysis
    - Cat 3: Unattainable/unfeasible/absurd
  - After mapping trade tree, 9 Cat 1 architectures + uncontrolled re-entry were developed and assessed for risk and cost

- ADL derived assumptions for Architecture Options (AO)
  - HST's natural orbit degradation will cause its uncontrolled reentry NET ~2025
    - Action required as HST reaches altitude of 500 km. The models diverge and options close
    - Uncontrolled reentry predicted 3 to 5 years later
  - Uncontrolled HST attitude rates modeled for HRSDM: 0.22 deg/sec/axis
  - Baseline Docking hardware: HST Soft Capture Mechanism (SCM)
    - Based on the ISS Low Impact Docking System (LIDS) for all architectures
    - Active side never designed; requires customized, flight design/development/hardware for HST-LIDS
  - Assumed autonomous rendezvous and docking package proposed for RESTORE mission
  - Considered architectures for HST disposal via
    a) Controlled reentry into Pacific Ocean
    b) Boost to 1200 km disposal orbit (off-nominal orbit; see Debris Density backup chart)
    c) Boost 2000 km disposal orbit (in accordance with international agreement)
  - All architecture options require at least one waiver to orbital debris mitigation standards NASA-STD 8719.14A (see Waivers backup chart)

Architecture Study:
Options in the ADL

Assessed 9 Architecture Options (AO) and uncontrolled re-entry:

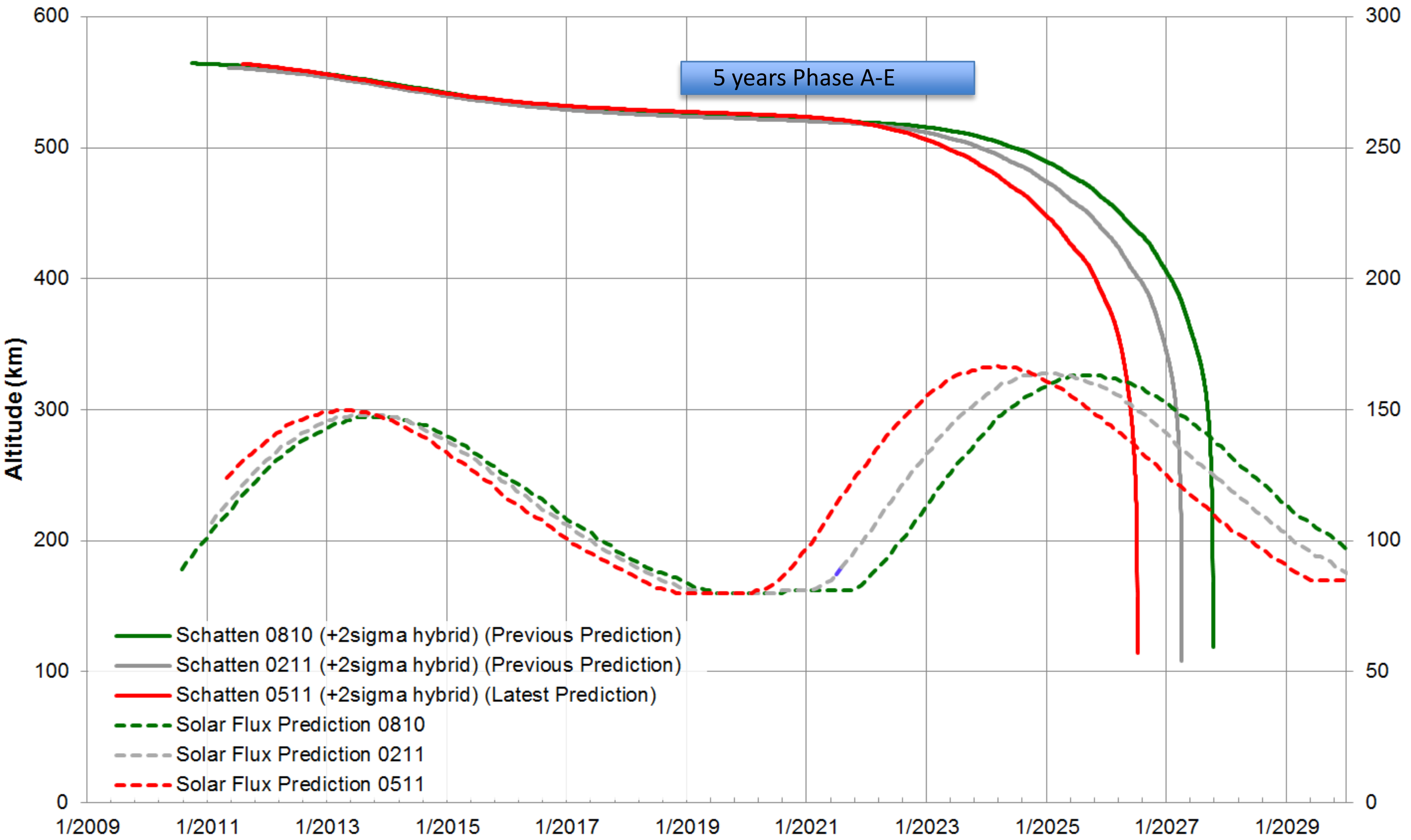
- Considered 3 HST states
  1. Non-functional (dead bird)
  2. Active attitude control, no science
  3. Operational, active science (working)

- Considered 3 disposal approaches (location/prop system**)**
  A. Deorbit into Pacific (Bi-prop)
  B. 1200 km storage orbit (Bi-prop)
  C. 2000 km storage orbit using solar electric propulsion (SEP)
     - C.5 is Option C with second set of SEP thrusters, reduced mission duration and higher reliability
     - Other alternative propulsion system (e.g., electrodynamic tether) could be used based on partnerships or TRLs at project formulation

ADL Architecture Options (AO)

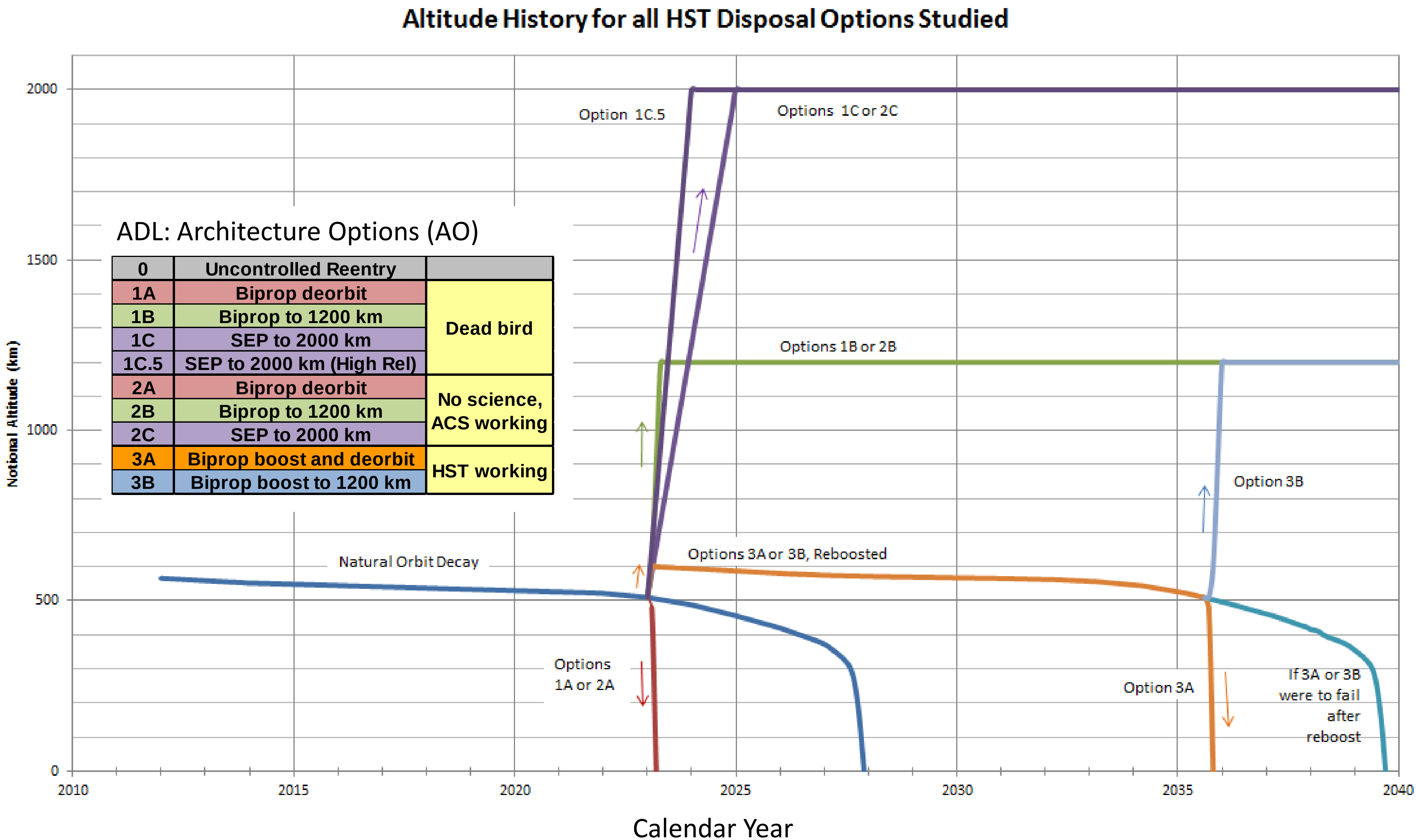
0	**Uncontrolled Reentry**	
1A	**Biprop deorbit**	**Dead bird**
1B	**Biprop to 1200 km**	
1C	**SEP to 2000 km**	
1C.5	**SEP to 2000 km (High Rel)**	
2A	**Biprop deorbit**	**No science, ACS working**
2B	**Biprop to 1200 km**	
2C	**SEP to 2000 km**	
3A	**Biprop boost and deorbit**	**HST working**
3B	**Biprop boost to 1200 km**	

HST Orbit Altitude Decay Profile



Calendar Year

Architecture Options: Mission Concept of Operations by Altitude



0	Uncontrolled Reentry	
1A	Biprop deorbit	Dead bird
1B	Biprop to 1200 km	
1C	SEP to 2000 km	
1C.5	SEP to 2000 km (High Rel)	
2A	Biprop deorbit	No science, ACS working
2B	Biprop to 1200 km	
2C	SEP to 2000 km	
3A	Biprop boost and deorbit	HST working
3B	Biprop boost to 1200 km	

Architecture Study Summary: Reliability, Debris Casualty and Cost

- **Mission Reliability is dominated by Docking Reliability**
  - Total Mission Reliability takes into account all mission phases (launch, docking and disposal) and hardware reliability throughout mission life
  - As the docking reliabilities degrade for a specific option, the Total Mission Reliability degrades (see Docking Phase Reliability in backups)
    - Analyzed options by parametric assessment of docking reliability
      - Assumed docking reliability values: 1.0, 0.95, 0.90, 0.85
      - Assumed residual dependency of multiple docking attempts: 0.0, 0.05, 0.10, 0.15
    - Total Mission Reliability degradation is similar for all architecture options
  - Uncontrolled HST (dead bird) presents the most challenging docking scenario
    - 0.22 deg/sec/axis (per HRSDM analysis)
    - A mission designed to handle AO-1 cases can easily accomplish AO-2 cases. The reverse is not true.

- **Probability of Injury**
  - Low probability of injury for architecture options 1A, 1B, 2A, and 2B
    - Odds of an Injury (1 in "n") for 1A/B; 2A/B: → 1:9,152 (~1:9200)
    - NASA-STD 8719.14A Requirement (1 in "n"): →1:10,000
  - All other options have higher probability of injury

- **Estimated Life Cycle Cost ($FY12, incl. LV and reserves)**
  - At or below $500M: Options: 1A, 1B, 2A, 2B
  - Greater than $500M: Options: 1C, 1C.5, 2C, 3A, 3B

ADL Architecture Options (AO)

0	Uncontrolled Reentry	
1A	Biprop deorbit	Dead bird
1B	Biprop to 1200 km	
1C	SEP to 2000 km	
1C.5	SEP to 2000 km (High Rel)	
2A	Biprop deorbit	No science, ACS working
2B	Biprop to 1200 km	
2C	SEP to 2000 km	
3A	Biprop boost and deorbit	HST working
3B	Biprop boost to 1200 km	

ADL Summary Table
Cost – Mass – P_s – Casualty

- For each architecture option, a mission was sketched out to the degree needed to estimate mass, cost, mission reliability and resulting DCA
- Summary table of values for each option
  - Each value is only precise to roughly 2 significant figures. Additional digits provided to allow comparison between options.

ADL Architecture Options (AO)

0	Uncontrolled Reentry	
1A	Biprop deorbit	Dead bird
1B	Biprop to 1200 km	
1C	SEP to 2000 km	
1C.5	SEP to 2000 km (High Rel)	
2A	Biprop deorbit	No science, ACS working
2B	Biprop to 1200 km	
2C	SEP to 2000 km	
3A	Biprop boost and deorbit	HST working
3B	Biprop boost to 1200 km	

Architecture Options:	AO-0	AO-1A	AO-1B	AO-1C	AO-1C.5	AO-2A	AO-2B	AO-2C	AO-3A	AO-3B
Life Cycle Cost ($FY12, incl. LV and reserves)	0	$440M	$515M	$622M	$625M	$415M	$482M	$579M	$1,090M	$,1264M
Total Wet Launch Mass [kg]	0	2549	4494	2046	2398	2496	4417	2026	3183	5052
Mission Reliability (Pdock =.9 per try, no residual dependence)	1.0000	0.9749	0.9749	0.7458	0.9174	0.9749	0.9749	0.7458	0.9481	0.9481
End-to-End Probability of Casualty	0.00424	0.00011	0.00011	0.00115	0.00037	0.00011	0.00011	0.00115	0.00102	0.00102
Odds of an Injury: 1 in "n"	236	9152	9152	868	2704	9152	9152	868	981	981

P_{dock} = 0.90 per attempt, 4 attempts budgeted, no residual dependence for subsequent attempts

ADL: Total End-to-End Mission Reliability

$P_{S/AO\text{-}1A}$ shown parameterized as $f(P_{docking})$

ADL: Architecture Options (AO)

0	Uncontrolled Reentry	
1A	Biprop deorbit	Dead bird
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1C	SEP to 2000 km	
1C.5	SEP to 2000 km (High Rel)	
2A	Biprop deorbit	No science, ACS working
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2C	SEP to 2000 km	
3A	Biprop boost and deorbit	HST working
3B	Biprop boost to 1200 km	

➤ ***Docking Reliability Dominates Total Mission Reliability.***

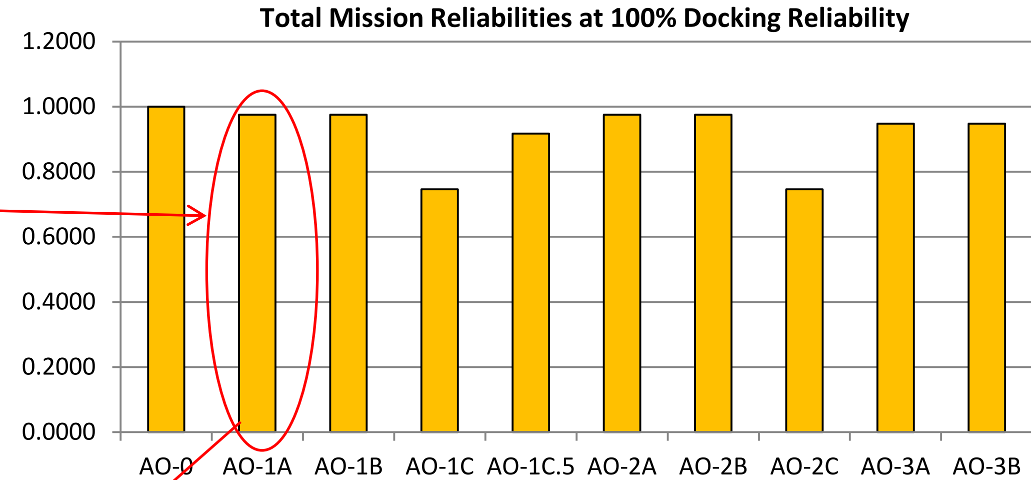
99.99% LIDS Docking Reliability	Options							
	1A, 2A	1B, 2B	1C, 2C	1C.5, 2C.5	3A Var 1	3B Var 1	3A Var 2	3B Var 2
Spacecraft Reliability	0.995	0.995	0.761	0.936	0.823	0.823	0.968	0.968
Docking Reliability	1	1	1	1	1	1	1	1
Launch Reliability	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98
Total Mission Reliability	**0.975**	**0.975**	**0.746**	**0.917**	**0.806**	**0.806**	**0.948**	**0.948**

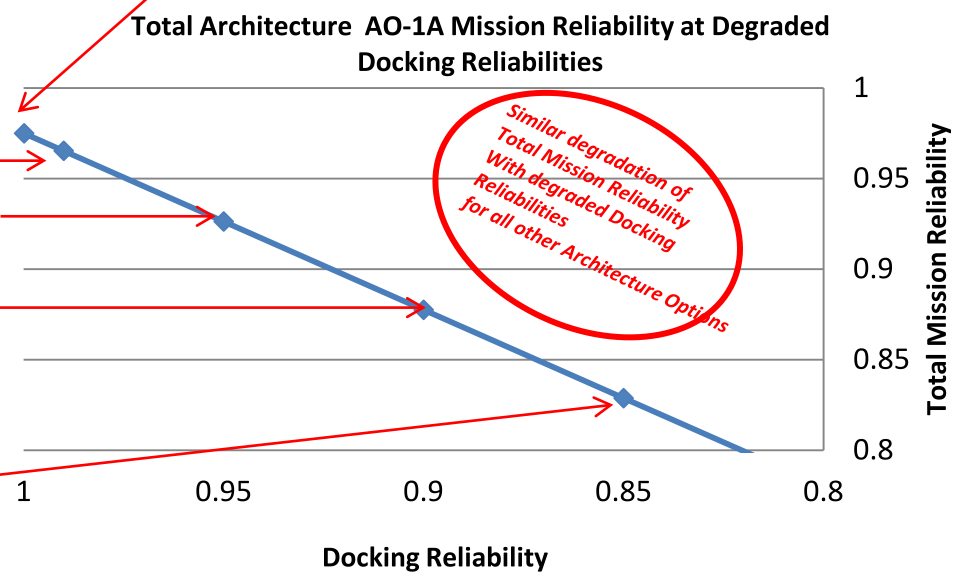
99 % LIDS Docking Reliability	Options							
	1A, 2A	1B, 2B	1C, 2C	1C.5, 2C.5	3A Var 1	3B Var 1	3A Var 2	3B Var 2
Spacecraft Reliability	0.995	0.995	0.761	0.936	0.823	0.823	0.968	0.968
Docking Reliability	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99
Launch Reliability	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98
Total Mission Reliability	**0.965**	**0.965**	**0.738**	**0.908**	**0.798**	**0.798**	**0.939**	**0.939**

95 % LIDS Docking Reliability	Options							
	1A, 2A	1B, 2B	1C, 2C	1C.5, 2C.5	3A Var 1	3B Var 1	3A Var 2	3B Var 2
Spacecraft Reliability	0.995	0.995	0.761	0.936	0.823	0.823	0.968	0.968
Docking Reliability	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95
Launch Reliability	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98
Total Mission Reliability	**0.926**	**0.926**	**0.709**	**0.872**	**0.766**	**0.766**	**0.901**	**0.901**

90 % LIDS Docking Reliability	Options							
	1A, 2A	1B, 2B	1C, 2C	1C.5, 2C.5	3A Var 1	3B Var 1	3A Var 2	3B Var 2
Spacecraft Reliability	0.995	0.995	0.761	0.936	0.823	0.823	0.968	0.968
Docking Reliability	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
Launch Reliability	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98
Total Mission Reliability	**0.878**	**0.878**	**0.671**	**0.826**	**0.725**	**0.725**	**0.853**	**0.853**

85 % LIDS Docking Reliability	Options							
	1A, 2A	1B, 2B	1C, 2C	1C.5, 2C.5	3A Var 1	3B Var 1	3A Var 2	3B Var 2
Spacecraft Reliability	0.995	0.995	0.761	0.936	0.823	0.823	0.968	0.968
Docking Reliability	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85
Launch Reliability	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98
Total Mission Reliability	**0.829**	**0.829**	**0.634**	**0.78**	**0.685**	**0.685**	**0.806**	**0.806**





ADL: Probability of Injury (P_i)

(at $P_{docking}$ = 0.90 per attempt)

0	Uncontrolled Reentry	
1A	Biprop deorbit	Dead bird
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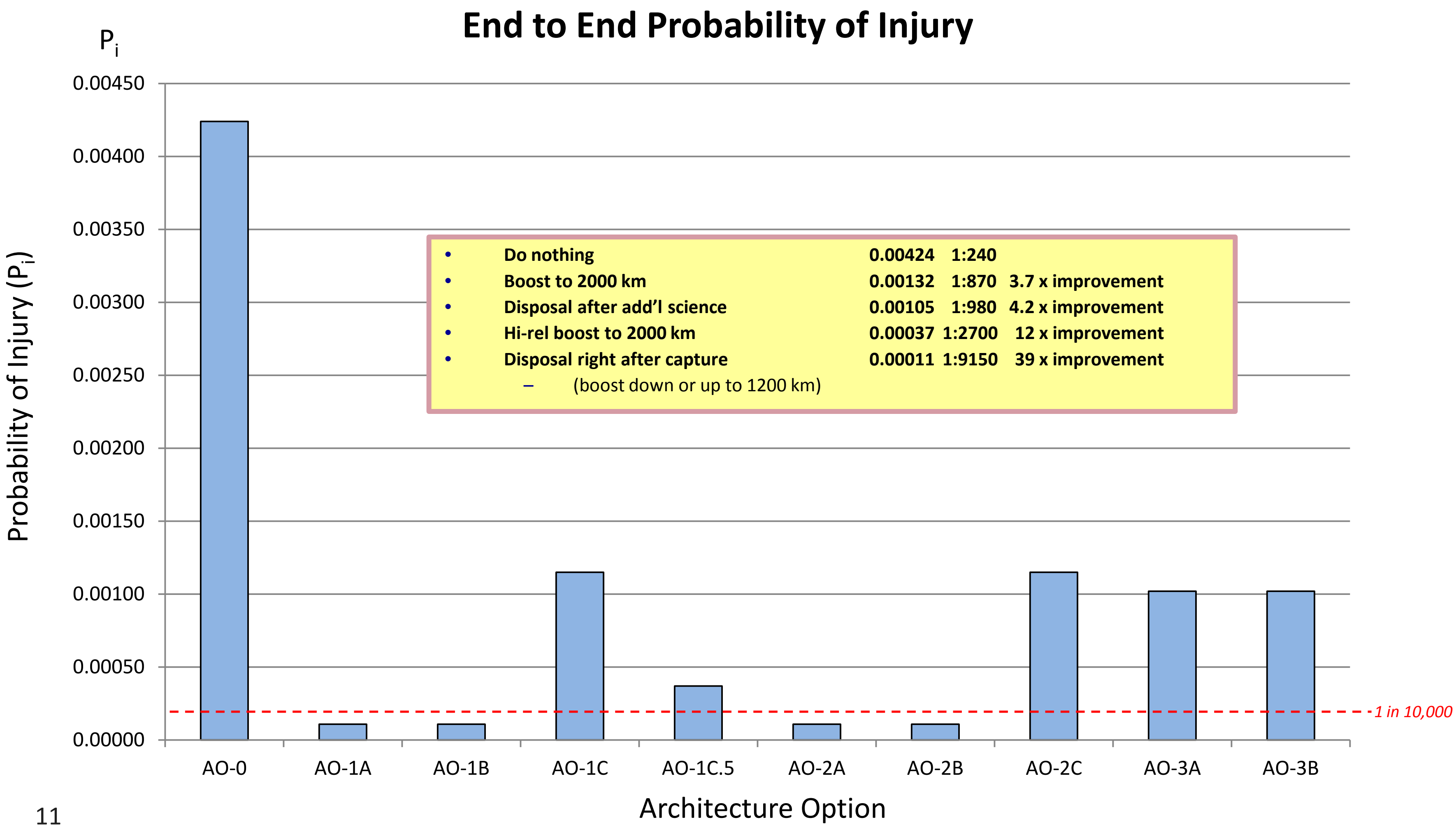

ADL in a Single Chart: Probability of Injury vs. Total Cost

0	Uncontrolled Reentry	
1A	Biprop deorbit	Dead bird
1B	Biprop to 1200 km	
1C	SEP to 2000 km	
1C.5	SEP to 2000 km (High Rel)	
2A	Biprop deorbit	No science, ACS working
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3A	Biprop boost and deorbit	HST working
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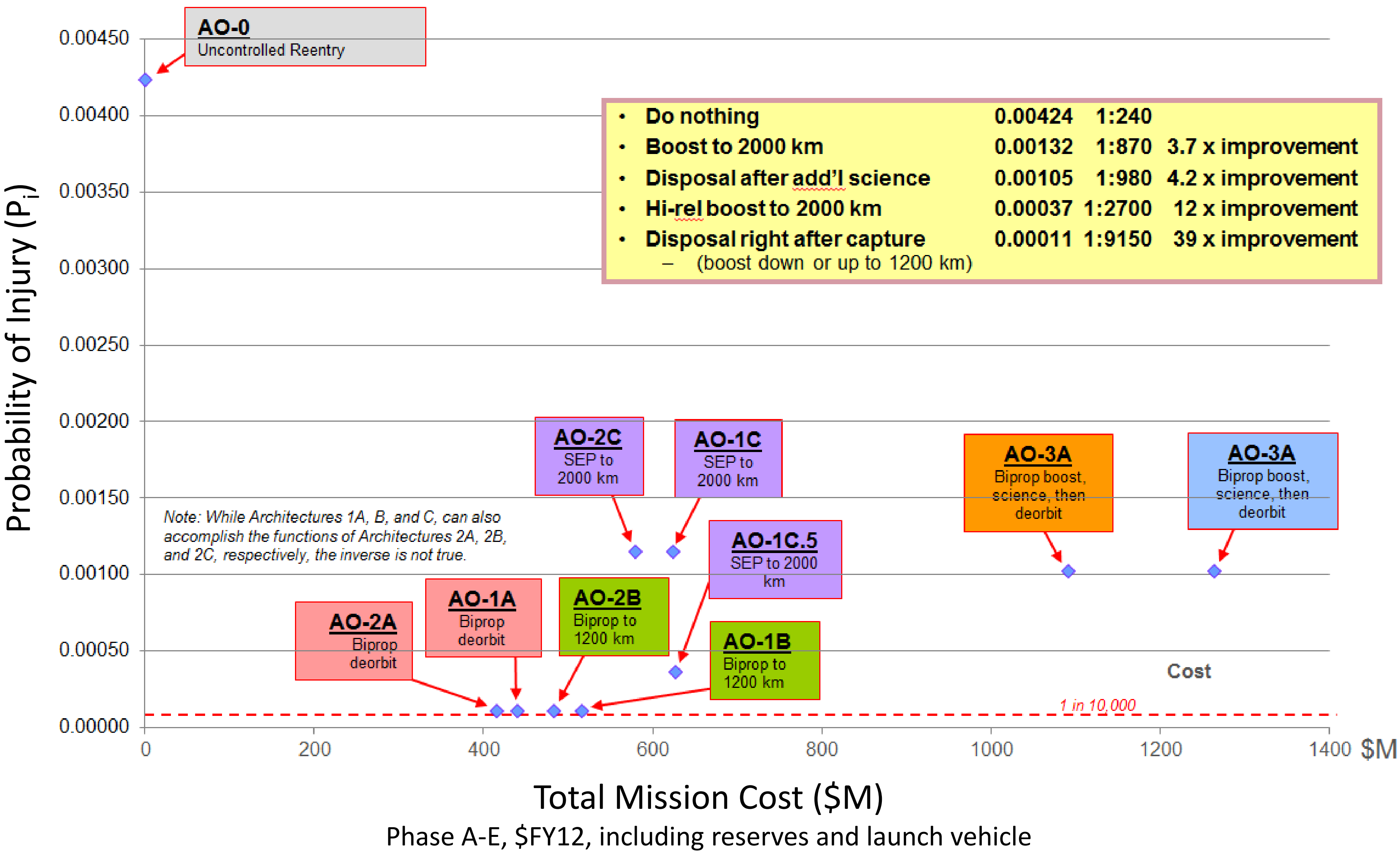


Autonomous Rendezvous and Docking (AR&D) Survey Status

- **Background**
  - AR&D is a mission phase that requires specialized hardware and software that works in concert with the spacecraft systems and actuators
    - Because AR&D is a critical capability for well-funded human flight and defense applications, the HST Disposal mission budget currently assumes AR&D reaches TRL 6 prior to Phase A without SMD funding, which is a risk.
    - This risk can be mitigated
      - Identifying key enabling capabilities, monitoring progress made by technology providers, and working closely with other AR&D stakeholders
      - Minimize unique elements in HST Disposal AR&D design
  - FY12 Study deliverable: a survey of current AR&D capabilities and suppliers

- **AR&D Survey delivered by MSFC team members in March 2012**
  - Snapshot of AR&D integrators and vendors with sensors, electronics, algorithms that could be useful for HST Disposal mission
    - Provides a reference for MDL in August 2012
  - Excerpt from a larger AR&D database tool developed and maintained by NASA's AR&D community of practice
  - Snapshot vendors and entire database will be monitored and updated routinely until project formulation
  - MSFC prepared to present AR&D Survey results to HQ when schedules permit

Potential Partnerships

- **Objective: identify HST disposal implementations that could attract partners**
  - Focus on partners that could provide some element of the mission that would reduce or leverage SMD's cost for the mission
  - Note: purchasing the mission (e.g., commercial cargo) is not considered in this partnership survey, but should be considered in the acquisition strategy discussions
- **Developed & began populating draft Partnering Possibilities spreadsheet that will be delivered to HQ in July 2012**
  - Organized information for each idea to make it useful for:
    - Monitoring the technologies and potential partners
    - Assessing risk to the disposal mission, increasing the cost of the mission,
    - Determining political/education/outreach benefit, science benefit, technology demonstration, standalone payload
- **Partners could be interested in any mission phase:**
  - Pre-rendezvous (on the way up)
    - Ride-sharing (deploy other payload, e.g., HST replacement)
    - Technology demonstrations (e.g., propellants, propulsion, guidance, communications)
    - Science or environmental data collection
    - Operations testbed
  - While attached to HST in LEO or in transit to disposal (AO-3 options)
  - After disposal
    - Re-boost HDV after HST disposal and use HDV as a platform for other objectives (e.g. – science, tech demo, orbital debris disposal, commercial)

Recommendation

Develop DRM based on Option 1B: non-functional HST is boosted to 1200 km disposal orbit using bi-prop system

- Technical considerations:
  - Option 1B is in the set that nearly meets DCA requirements
  - Bounds the worst-case HST attitudes for AR&D phase
  - Since the AR&D phase of all missions require bi-prop, the spacecraft bus designed for this option could apply to any option – even those with alternate prop system for disposal
  - If disposal fails after partial re-boost, the uncontrolled re-entry is delayed by many years
- Programmatic considerations:
  - Cost ROM bounds the set that nearly meets DCA
  - Preserves many partnering options, but doesn't require them for affordability
  - DRM could easily be modified (and costed) to account for different types of partnering
  - Requires interesting waiver to orbital debris standards
- Available FY12 funding sufficient for "customer" team and MDL costs (see study cost actuals in backup)
  - Funding available for a full MDL for the DRM and a short MDL later to probe costs for other bounding cases if interested
  - Study team (including MSFC) will develop MDL intake packages over the next couple of months

0	Uncontrolled Reentry	
1A	Biprop deorbit	Dead bird
1B	Biprop to 1200 km	
1C	SEP to 2000 km	
1C.5	SEP to 2000 km (High Rel)	
2A	Biprop deorbit	No science, ACS working
2B	Biprop to 1200 km	
2C	SEP to 2000 km	
3A	Biprop boost and deorbit	HST working
3B	Biprop boost to 1200 km	

Conclusion

- **High-level tradespace of mission risk and mission cost is understood, and many connections are well defined**
- **AR&D Survey is complete**
- **Partnership assessment is underway; delivery on schedule for July 2012**
- **The next step is to develop a mission concept of sufficient detail to provide a vetted cost and schedule for long term planning**
  - Optimal solution will strike the right balance to maximize probability of mission success and minimize cost to SMD (low total cost or valuable partnerships)
  - Recommend DRM based on Option 1B: boost non-functional HST up to 1200 km

Backup Material

HST Disposal Study Plan

- **Stage 1: Develop Preliminary Mission Concept** (28 months)
  - Define concept architecture, enabling technologies, and potential partners
  - Develop Baseline Design Reference Mission (DRM)
  - Draft Technology Development Plan (e.g. - Gap Assessment & Roadmap)
- **Hold: Monitor Technology / Potential Partners** (Baseline: ~36 months)
- **Stage 2: Pre-Formulation Study Phase** (9 months)
  - Assess and revise DRM (architecture/tech/partners/schedule/cost)
  - Obtain an Independent Cost Estimate (ICE)
  - Assess and revise Technology Development Plan
- **Stage 3: Project Office Formulation** (12 months)
  - Study Elements (pre-handover; managed by PO, staffed by expected project personnel):
    - Release RFI for Potential Partners
    - Develop/ Release Study RFP for Industry Studies
  - Obtain an Independent Cost Estimate

ADL Backup Material

Trade Tree Snapshot 1

	HST Operational State	When to Dispose HST	Capture Method	Disposal Method	Main Prop System		Comments / Rationale
HST Disposal Architectures	**Disposal Option 3:** Attach HDV and continue HST Science Ops for years	Dispose HST only after science ops have been officially declared terminated. After capture HST returns to science ops. HDV remains in dormant state attached to HST until activation for disposal.	LIDS	Boost to 2000 km storage orbit	Electrical Propulsion, augmented by small Chemical Prop, used for Capture and Avoidance	CATEGORY 3: Excessive complexity for a s/c attached to HST still doing science. Complications with requirement to be operational after possibly long dormant state.	S/C must have redundancy commensurate w/ this requirement.
				Boost to 1200 km storage orbit Architecture 3A	Chemical Propulsion	CATEGORY 1	Needs a waiver In-space lifetime of disposed HST at 1200 km is >> 1600 years.
				Controlled Deorbit Architecture 3B	Chemical Propulsion	CATEGORY 1	
		Dispose HST a Immediately after capture	X CATEGORY 3: Immediate disposal would preclude continued HST science ops.				

Trade Tree Snapshot 2

Disposal Option 2:

HST Science Ops over HST is cooperating target (ADCS or HST Safemode ADCS still working)

This option, worth considering, is in fact probably the most likely to occur, as the HST has massive resilience against Safe-mode ADCS failure, see Appendix 3.

- Dispose HST immediately after capture
  - LIDS
    - Boost to 1200 km storage orbit — Architecture 2B
      - Electrical Propulsion, augmented by small Chemical Prop, used for Capture and Avoidance — X CATEGORY 2: See Appendix 4. Boosting to 2000 km needs essentially the same DM just with more Xenon propellant
        - Boosting to 1200 km only needs a Waiver. In light of the fact that the difference between boosting to 2000 km vs. to 1200 km is only the amount of Xenon propellant (on the order of 100 kg) in otherwise substantially identical s/c; applying for a waiver is not justified, and probably would be rejected anyway.
      - Chemical Propulsion — CATEGORY 1
        - Needs a waiver. In-space lifetime of disposed HST at 1200 km is >> 1600 years.
    - Boost to 2000 km storage orbit — Architecture 2C
      - Electrical Propulsion — CATEGORY 1
        - 722 m/s low thrust augmented by small Chemical Prop. used for Capture and Avoidance. Actual cruise time is 705 calendar days (390 days of "theoretical" full sun thrust time)
      - Chemical Propulsion — X CATEGORY 2: Too much propellant required
        - Delta-v is 680 m/s. Requires excesssive amounts of propellant: 2.8 mT biprop or 4.2 mT of hydrazine; unfavorably impacting DM design and LV selection.
    - Controlled Deorbit — Architecture 2A
      - Electrical Propulsion — X CATEGORY 3: Doesn't have required authority, not truly controlled (may miss the ocean)
        - Very slow gradual altitude decrease due to mN level thrust forces: may miss the Ocean.
      - Chemical Propulsion — CATEGORY 1
        - Results of Biprop vs. Monoprop Trade is reflected in sizing of AO 1A Biprop and Monoprop versions.

Trade Tree Snapshot 3

Disposal Option 1:

HST dead
HST is non-cooperating target
Max. attitude rate is .22 deg/s/axis

Dispose HST immediately after capture	LIDS (Note 1)	Boost to 1200 km storage orbit	Electrical Propulsion, augmented by small Chemical Prop, used for Capture and Avoidance (X)	CATEGORY 2: See Appendix 4. Boosting to 2000 km needs essentially the same DM just with more Xenon propellant	Boosting to 1200 km needs a Waiver. In light of the fact that the difference between boosting to 2000 km vs. to 1200 km is the amount of Xenon propellant (on the order of 100 kg) and the time to complete the transfer in otherwise substantially identical s/c applying for a waiver is not justified, and probably would be rejected anyway.
		Boost to 1200 km storage orbit – Architecture 1B	Chemical Propulsion	CATEGORY 1	Needs a waiver. In-space lifetime of disposed HST at 1200 km is >> 1600 years.
		Boost to 2000 km storage orbit – Architecture 1C	Electrical Propulsion	CATEGORY 1	722 m/s low thrust augmented by small Chemical Prop. used for Capture and Avoidance. Actual cruise time is 705 calendar days (390 days of 'theoretical" full sun thrust time)
		Boost to 2000 km storage orbit	Chemical Propulsion (X)	CATEGORY 2: Too much propellant required	Delta-v is 680 m/s. Requires excesssive amounts of propellant: 2.8 mT biprop or 4.2 mT of hydrazine; unfavorably impacting DM design and LV selection.
		Controlled Deorbit	Electrical Propulsion (X)	CATEGORY 3: Doesn't have required authority, not truly controlled (may miss the ocean)	Very slow gradual altitude decrease due to mN level thrust forces: may miss the Ocean.
		Controlled Deorbit – Alternate Architecture 1A – may be viable depending on LV selection	Monoprop	CATEGORY 1	Biprop vs. Monoprop Trade (see Appendix 1) applies across the board for all Chemical Prop options. Significant differences in propellandt masses favor Biprop, yet no specific conclusions can be drawn without looking at LV selection in each specific case. (Monoprop used for all ACS thrusters.)
		Controlled Deorbit – Architecture 1A	Biprop	CATEGORY 1	Even In Biprop systems, Monoprop is used for ACS thrusters.

Trade Tree Snapshot 4

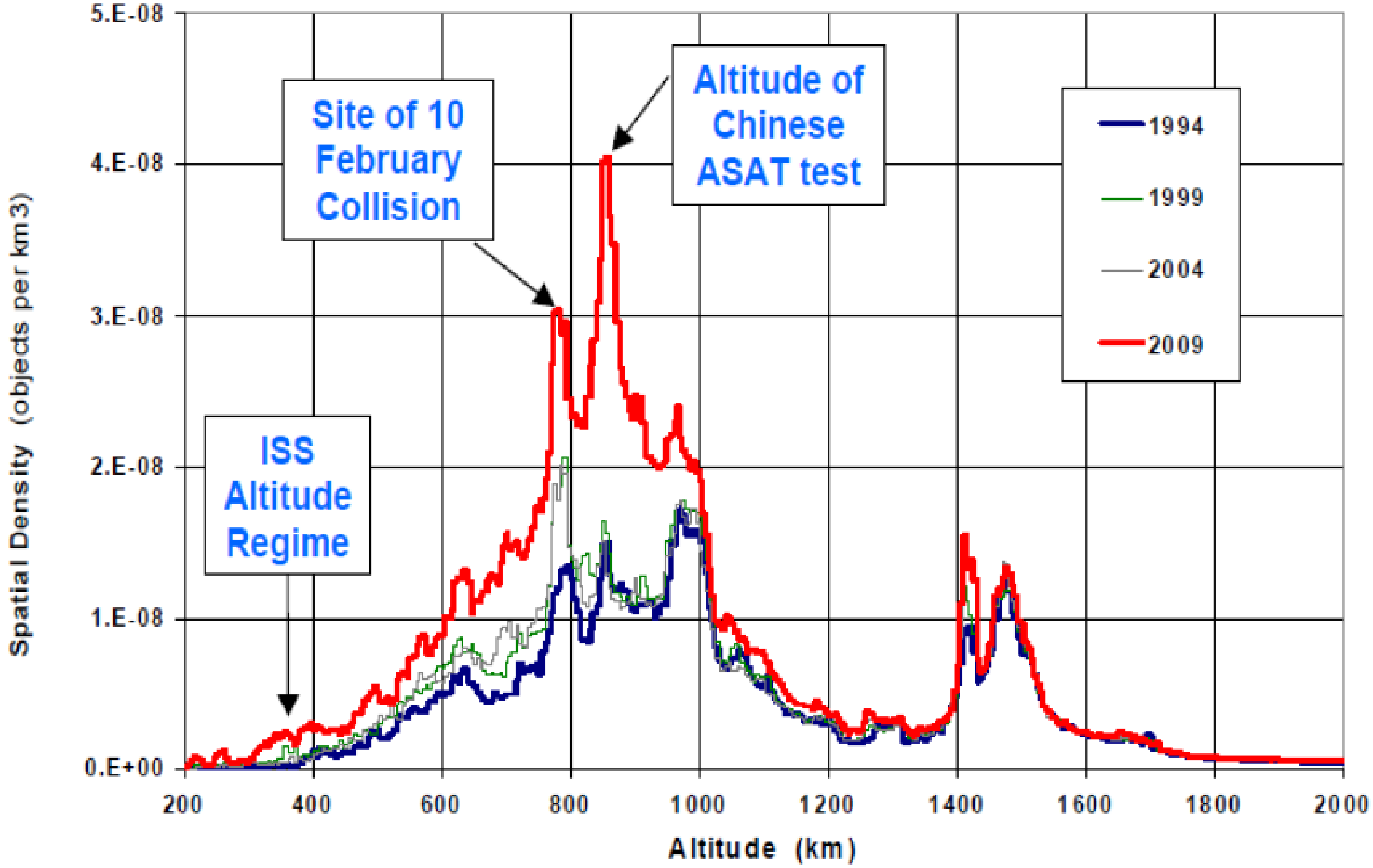
Option		Rationale
Robot Arm Grapple (all variations)	X	CATEGORY 2: Docking with LIDS is routine operations. (Also see rationale for using LIDS under noncooperative HST.)
Net	X	CATEGORY 3: Low TRL, impractical. Also, still need AR&D, docking, etc.
Harpoon	X	CATEGORY 3: Low TRL for HW and tether dynamics. Also, still need AR&D, docking, etc.
Unicorn	X	CATEGORY 3: Low TRL, not any easier then LIDS. Shroud may not be strong enough
Cut up to chunks safe for uncontrolled deorbit	X	CATEGORY 2: See Appendix 2: must cut to >> 20,000 pieces. Also: 1. Low TRL; 2. Have to grapple first anyway.
Move to Disposal Orbit using Solar Sail	X	CATEGORY 2: Impractical, numerous issues, such as low level of thrust, steering, drag; see Appendix 11
Ballute and other drag enhancers, then chemical deorbit burn	X	CATEGORY 2: Initiating deorbit burn from low altitudes is not OK; need steep flight path angle, otherwise s/c will have long and uncertain reentry footprint, and reentry site is undeterministic. Also: 1. Low TRL; 2. Would still need prop system on s/c for controlled deorbit just with less propellant.
Shoot down with missile	X	CATEGORY 2: See Appendix 2: must end up with >> 20,000 pieces.
Electrodynamic tether to boost up to 2000 km storage orbit	X	CATEGORY 2: Presently low TRL. See separate "HST Disposal Study 3b - El Dyn Tether.pptx" file.
Dispose HST a considerable time (days, months or years) after capture	X	CATEGORY 3: No circumstance identified that would require a delay in disposal. The "Ps" of disposal deteriorates with passing time. Delayed disposal doesn't make sense.

Docking with LIDS is routine operations for cooperating targets, can be baselined as is for free drifting HST capture if HDV (not LIDS) provides 100% of rate nulling (as is baselined here).

All variations of Robot Arm grappling of free drifting HST are significantly lower TRL. Also, HST must mate w/ LIDS to rigidize assestack for thrust; or else must use novel "Rigidization Mechanism" (TRL < 3).

If only use drag enhancers to lower orbit altitude "some", then the added complexity doesn't make sense.

Debris Density vs. Altitude



Source: ODPO

0	Uncontrolled Reentry	
1A	Biprop deorbit	Dead bird
1B	Biprop to 1200 km	
1C	SEP to 2000 km	
1C.5	SEP to 2000 km (High Rel)	
2A	Biprop deorbit	No science, ACS working
2B	Biprop to 1200 km	
2C	SEP to 2000 km	
3A	Biprop boost and deorbit	HST working
3B	Biprop boost and 1200 km	

Waivers Required per Option

Every architecture option requires at least one waiver to NASA orbital debris standard (NPR NASA-STD 8719.14A)

Scenario	Req. 4.6-1 Orbital Lifetime	Req. 4.6-1 Disposal Location	Req. 4.6-4 Disposal Reliability	Req. 4.7-1 Reentry Risk
0 Do Nothing	Waiver	√	√	Waiver
1A Cont. Reentry, Dead HST	Waiver	√	√	Waiver
1B Up to 1200 km, Dead HST	√	Waiver	Waiver	Waiver
1C Up to 2000 km, Dead HST	√	√	Waiver	Waiver
1C.5 Hi-rel up to 2000 km, Dead	√	√	√	Waiver
2A Cont. Reentry, Live ACS	Waiver	√	√	Waiver
2B Up to 1200 km, Live ACS	√	Waiver	√	Waiver
2C Up to 2000 km, Live ACS	√	√	Waiver	Waiver
3A Cont. Reentry, HST Science	Waiver	√	Waiver	Waiver
3B Up to 1200 km, HST Science	√	Waiver	Waiver	Waiver

Docking Phase Reliability

Unreliable capture not launch worthy (applies to the 0.7 columns)

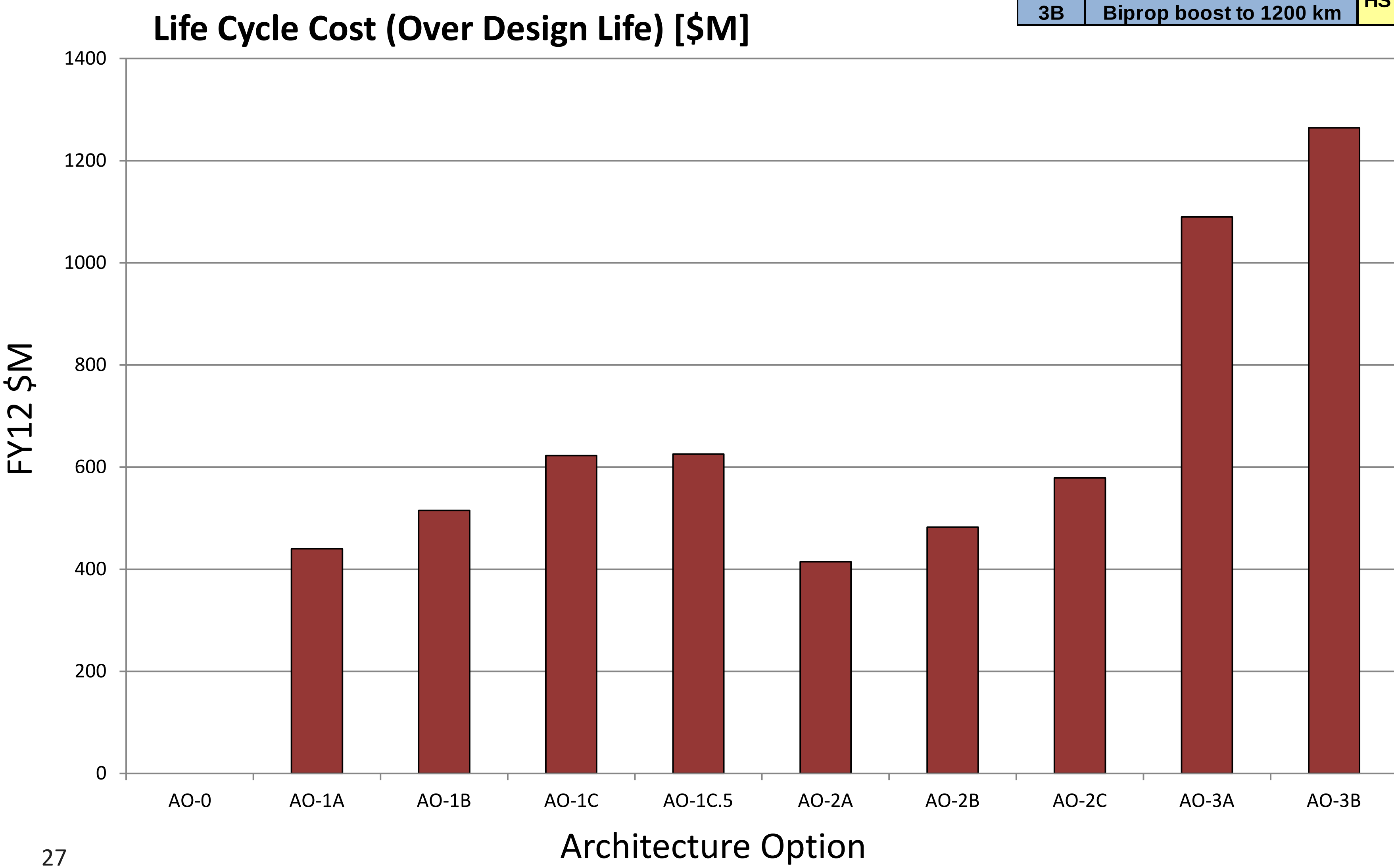
One Single Docking Attempt Reliability	**0.9**	**0.9**	**0.9**	**0.9**	**0.9**	**0.9**	**0.8**	**0.8**	**0.8**	**0.8**	**0.8**	**0.8**	**0.7**	**0.7**	**0.7**	**0.7**	**0.7**	**0.7**
Probability of Residual Dependence between Attempts	*0*	*0.1*	*0.2*	*0.3*	*0.4*	*0.5*	*0*	*0.1*	*0.2*	*0.3*	*0.4*	*0.5*	*0*	*0.1*	*0.2*	*0.3*	*0.4*	*0.5*
4 Attempts Total Docking Reliability	**0.9999**	**0.998**	**0.994**	**0.986**	**0.975**	**0.962**	**0.998**	**0.992**	**0.98**	**0.96**	**0.94**	**0.91**	**0.992**	**0.98**	**0.95**	**0.92**	**0.89**	**0.85**

ADL: Architecture Options

0	**Uncontrolled Reentry**	
1A	**Biprop deorbit**	**Dead bird**
1B	**Biprop to 1200 km**	
1C	**SEP to 2000 km**	
1C.5	**SEP to 2000 km (High Rel)**	
2A	**Biprop deorbit**	**No science, ACS working**
2B	**Biprop to 1200 km**	
2C	**SEP to 2000 km**	
3A	**Biprop boost and deorbit**	**HST working**
3B	**Biprop boost to 1200 km**	

ADL: HDV Cost

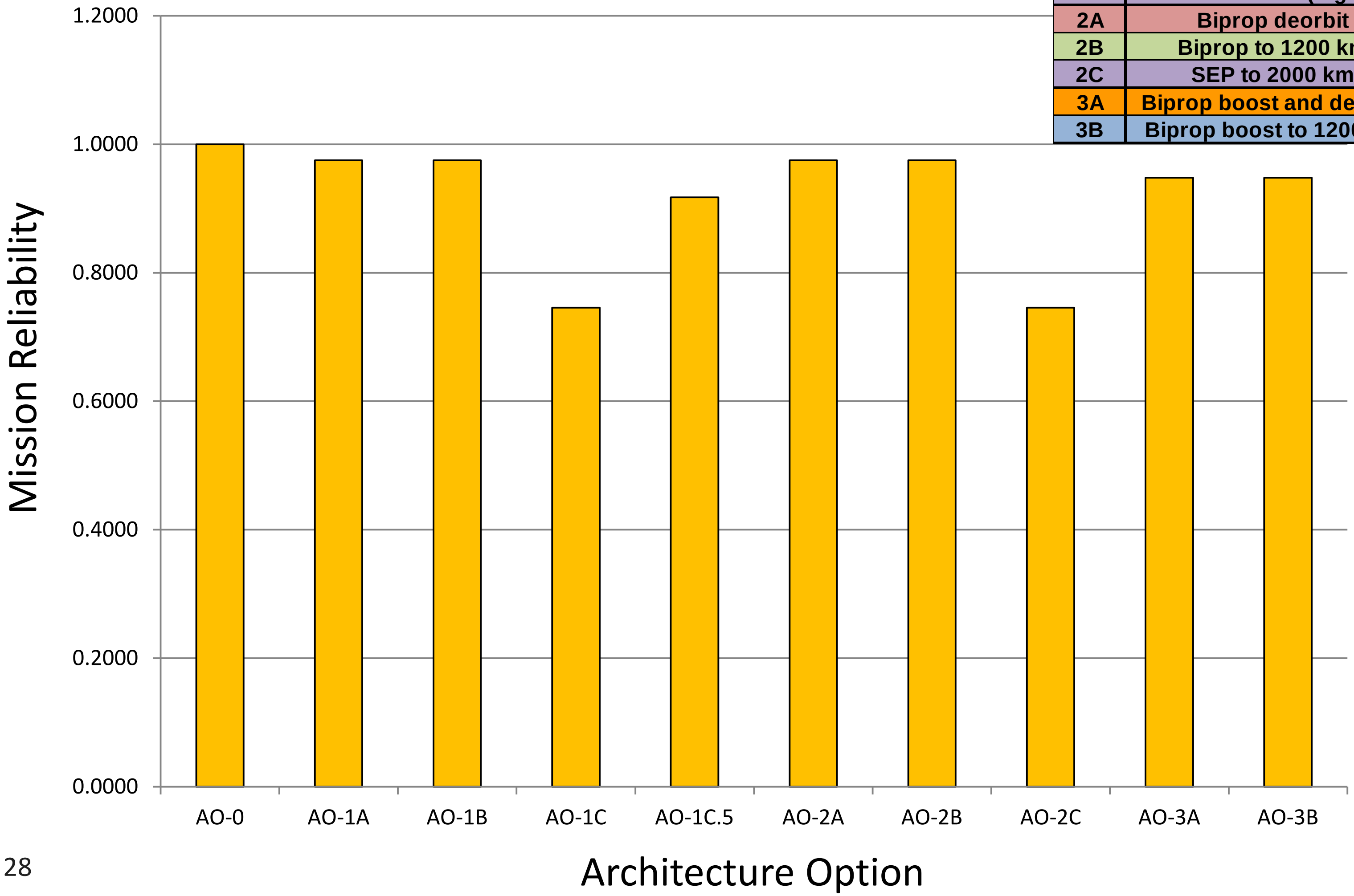
0	Uncontrolled Reentry	
1A	Biprop deorbit	Dead bird
1B	Biprop to 1200 km	
1C	SEP to 2000 km	
1C.5	SEP to 2000 km (High Rel)	
2A	Biprop deorbit	No science, ACS working
2B	Biprop to 1200 km	
2C	SEP to 2000 km	
3A	Biprop boost and deorbit	HST working
3B	Biprop boost to 1200 km	



ADL: End-to-End Mission Reliability

(at $P_{s\text{-}capt}$ = 0.90 per attempt, no res. dependence)

0	Uncontrolled Reentry	
1A	Biprop deorbit	Dead bird
1B	Biprop to 1200 km	
1C	SEP to 2000 km	
1C.5	SEP to 2000 km (High Rel)	
2A	Biprop deorbit	No science, ACS working
2B	Biprop to 1200 km	
2C	SEP to 2000 km	
3A	Biprop boost and deorbit	HST working
3B	Biprop boost to 1200 km	



Study Plan

Backup Material

HST Disposal

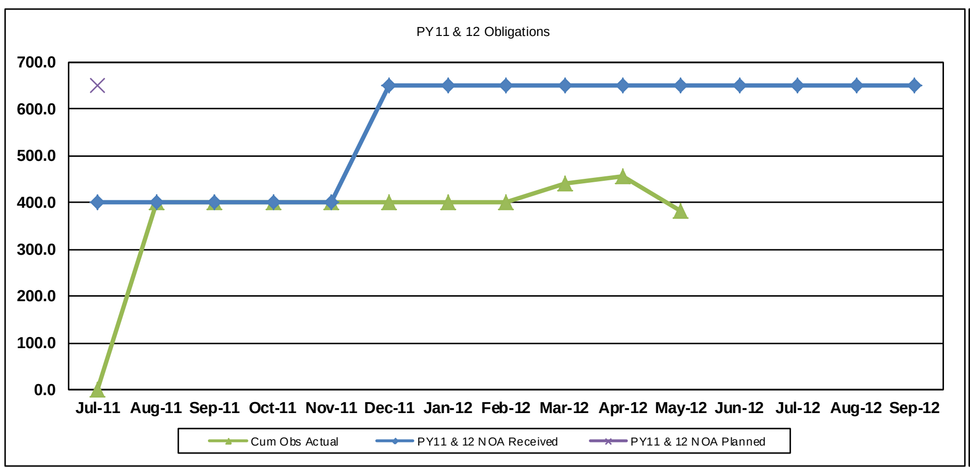
COR SR&T (141108)

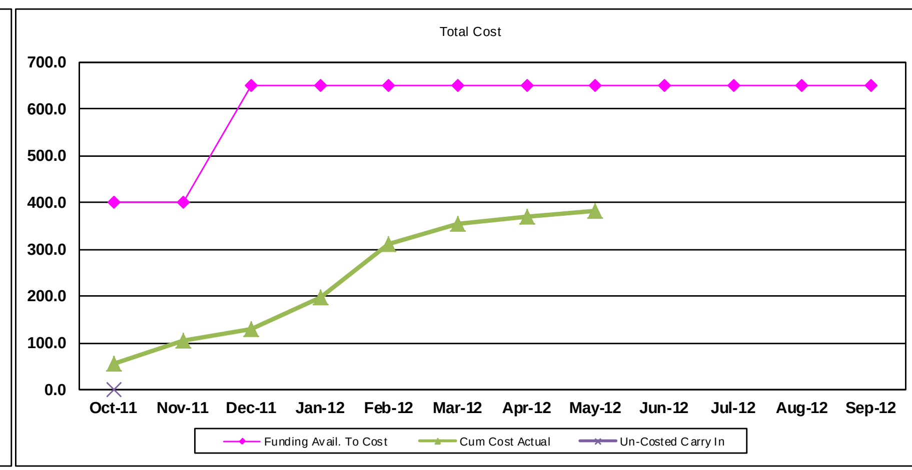
(Dollars in thousands)

Financial Status - GSFC Only

PY11 & 12 Funds - Obligations	PY11 & 12 NOA Planned	Jul-11	Aug-11	Sep-11	Oct-11	Nov-11	Dec-11	Jan-12	Feb-12	Mar-12	Apr-12	May-12	Jun-12	Jul-12	Aug-12	Sep-12	Carry Out
PY11 & 12 NOA Received	650.0	400.0	400.0	400.0	400.0	400.0	650.0	650.0	650.0	650.0	650.0	650.0	650.0	650.0	650.0	650.0	
Cum Obs Actual		-	400.0	400.0	400.0	400.0	400.0	400.0	401.9	439.1	454.9	380.8					-
Cum Unobligated $					-	-	250.0	250.0	248.1	210.9	195.1	269.2	-	-	-	-	

Total Cost - all years	Un-Costed Carry In	Jul-11	Aug-11	Sep-11	Oct-11	Nov-11	Dec-11	Jan-12	Feb-12	Mar-12	Apr-12	May-12	Jun-12	Jul-12	Aug-12	Sep-12	Carry Out
Funding Avail. To Cost	0.0	400.0	400.0	400.0	400.0	400.0	650.0	650.0	650.0	650.0	650.0	650.0	650.0	650.0	650.0	650.0	
Cum Cost Actual		-	-	55.9	54.3	104.8	128.6	196.2	310.4	354.5	370.3	380.8					-
Cum Uncosted $					345.7	295.2	521.4	453.8	339.6	295.5	279.7	269.2	-	-	-	-	

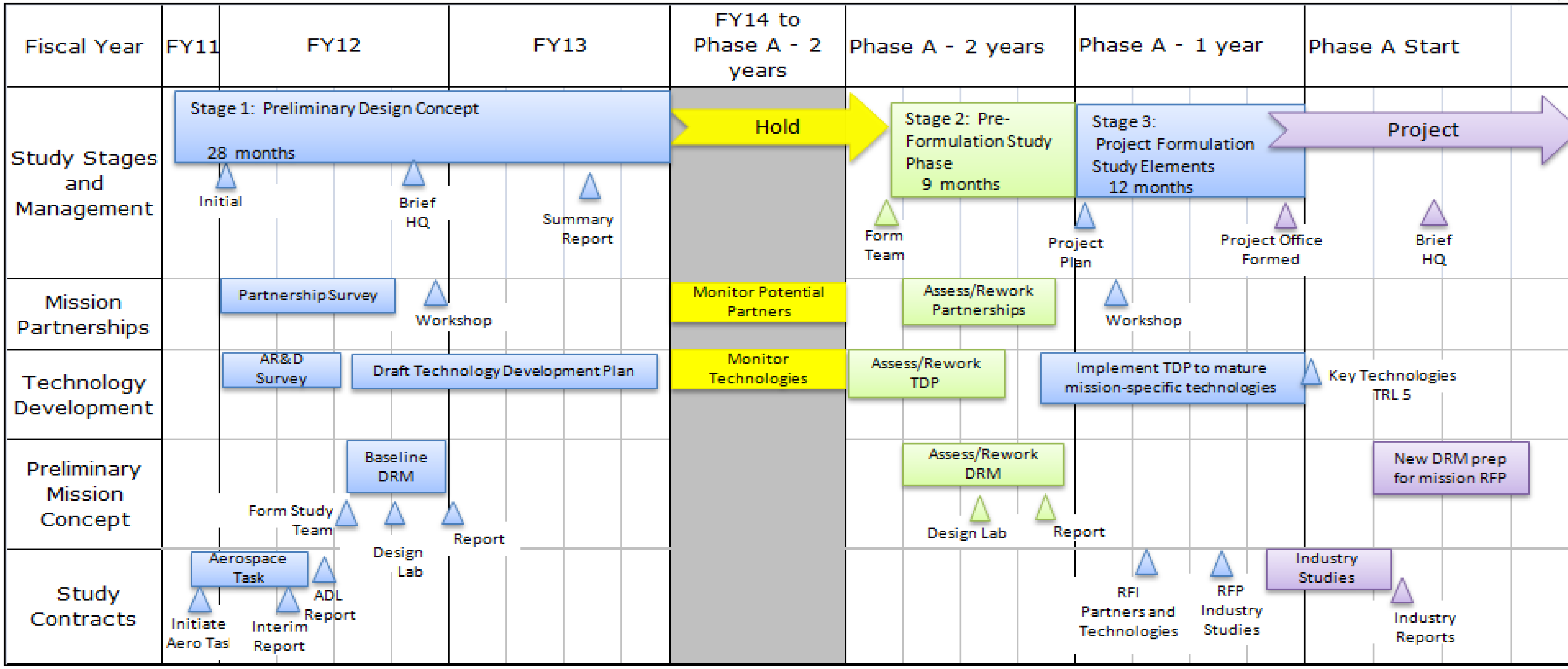




Budget Profile: Baseline

HST Disposal Study - Requirements Baseline	FY 13	FY 14	FY 15	FY 16	FY 17	FY 18
Total Requirements	**$280k**	**$286k**	**$292k**	**$299k**	**$1,601k**	**$2,113k**
Program Office Support Cost	*$230k*	*$236k*	*$242k*	*$249k*	*$255k*	*$262k*
Study Team & Procurement Cost	*$50k*	*$50k*	*$50k*	*$50k*	*$0k*	*$0k*
Future Mission: HST Disposal	-	-	-	-	*$1,345k*	*$1,851k*
Total FTE's / WYE's	***1.1***	***1.1***	***1.1***	***1.1***	***4.3***	***4.4***
Civil Servant (FTE)	*1.0*	*1.0*	*1.0*	*1.0*	*2.9*	*3.0*
Contractor (WYE)	*0.1*	*0.1*	*0.1*	*0.1*	*1.4*	*1.4*
Technology Development Cost	**-**	**-**	**-**	**-**	**-**	**-**

Proposed Schedule / Cost: HST Disposal Study



	Stage 1	Hold	Stage 2	Stage 3
Cost ($k)	$250 + $50 = $300 (FY12, FY13)	**$150***	$1,345	$1,851

HST DISPOSAL STUDY REQ's less (PO SUPPORT/PPBE14): $3,396 ($k)

w/ FY12 + 250 ($k)

TOTAL **$3,646 ($k)**

* Hold Phase baseline is 3 years at $50k/year. If Hold extends beyond 3 years, then add $50K per year.