



# Propellant Depot Alternate DRM 34B

Mission Risk, Reliability, and Availability Analysis

HAT/Depot Team TIM

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All estimates are PRELIMINARY

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# Mission Risk, Reliability, and Availability Team

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## Launch Availability Risk Analysis

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# Background

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## HEFT architecture study

- Concerns about risk due to high flight rate for propellant delivery
- Multiple launches, rendezvous, and dockings assumed to be a show-stopper
- Potential loss of depot due to MMOD or system failures was also a concern

## OSMA Research & Technology (R&T) Strategy Team recommends S&MA roles

- Includes providing guidance on R&T investment to drive real safety & reliability improvement
- Concern about negative consequences of outside recommendations on safety, reliability, and risk

## JSC S&MA introduced a concept of “contingency flights” with multiple providers

- Potential benefits of depot technologies appeared not to be getting adequate consideration
- JSC S&MA requested by OCT-PICS to re-assess risk of depot-based architectures

## Initial risk assessment results (March 2011) indicated:

- Very low additional risk for propellant delivery with contingency missions
- Other system-level effects could offset this additional risk, resulting in a net risk decrease
- Overall system risk reduced for re-use of operational depot for multiple DRMs
- High flight rate with relatively low cost payload seen as a reliability growth benefit
- Can mitigate depot MMOD & systems risk by partially off-loading propellant for launch
- Can re-allocate mass to increase shielding, add redundancy, & use greater design margins
- Same mass reallocation technique could also reduce risk for other elements

## S&MA was requested to perform reliability/risk analysis to assist in these trades



# Risk and Reliability Analyses

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## Task 1: Propellant Delivery Reliability with Contingency Missions

- Probability depot can be supplied using “n out of m” mission opportunities
- Drives number of contingency flights needed to assure some required level of reliability
- Use with Launch Availability and Depot Vehicle Reliability to estimate propellant delivery phase risk

## Task 2: Depot Vehicle Reliability and Risk Analysis

- Probability of loss of the depot over various time intervals
- Requested to help define planned life or time between servicing missions
- Identifies areas to consider for trades between increased redundancy and vehicle mass
- Evaluate effectiveness of increased MMOD shielding vs. mass
- Supports Mission Risk models for initial depot delivery, propellant delivery and “fill-up”, and propellant transfer to CPS phases

## Task 3: Launch Availability Analysis

- Probability that various planned launch sequences occur on time
- Needed to establish campaign start date to achieve a desired probability
- Drives depot on-orbit operational time requirement
- Needed to confirm adequacy of depot reliability / redundancy solution
- Defines boil-off allowances needed and confirm adequate margins with planned and contingency number of flights
- Establishes LEO loiter duration requirements for mission elements (CPS, DSH, MMSEV, MPCV)
- Establish crew buffer



## Risk and Reliability Analyses (cont.)

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### Task 4: Exploration Loss of Mission - Operational ( $LOM_O$ ) = LOM - LOC

- Risk Team requested to focus on LOM without LOC (However, some LOC work was done)
- Probability of mission loss once depot is fully filled and ready for DRM to start
- 1<sup>st</sup> element launch through landing/recovery
- All exploration elements from launch through end of service
- Depot reliability from 1<sup>st</sup> element launch through propellant transfer to CPS and undock

### Task 5: Loss of Mission - Operational ( $LOM_O$ ) for fill phase through first element launch

- Propellant launch/orbit insertion failure; non-catastrophic failure of AR&D or prop transfer
  - No loss of mission if failures are within planned contingency mission capability
- However, catastrophic fraction of AR&D or propellant transfer failures is LOM
- Depot systems failure or MMOD during this phase assumed to be LOM
- Investigated inclusion in Launch Availability, but PRA is not currently planned

### Task 6: Depot Loss of Mission - Operational ( $LOM_O$ ) after exploration mission departure

- Probability of depot being available to support a follow-on DRM
- Should include depot systems failure, MMOD, and any planned maintenance
- Not currently being assessed - No 2nd DRM with the depot identified for now and lack of funding

### Task 7: Integrate results and compare with non-depot missions

- Evaluate indicated risks, understand model & data limitations, develop conclusions



# Analysis Results

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## Task 1: Propellant Delivery Reliability with Contingency Missions

- 2 contingency missions shows 0.999 Ps for 10 flights at 0.980 per mission
- Only 8 missions actually required even with depot launched empty
- Actually fewer missions for first depot use due to launch partially full
- Worst case assessed as 0.937 with 10 missions at 0.92 per mission

## Task 2: Depot Vehicle Reliability and Risk Analysis

- Depot long-term reliability and life estimates are comparable to other satellites of similar size and complexity
  - Loss of Mission in LEO for 5 years: 1 in 5.6 (18%) without maintenance
  - MMOD shielding requirements similar to ISS can be accommodated and similar risk levels can be achieved with proper design-to risk requirements
  - Propellant load can be reduced for initial depot launch to increase MMOD protection if necessary to meet ISS-like MMOD requirements
  - EVA Project reports only one ISS MMOD shield ever replaced
    - MMOD was once believed to be dominant maintenance driver for ISS
    - Ref: SSF External Maintenance Task Team Final Report, 1990
  - More frequent depot visits than Hubble provide opportunities to perform periodic "human-tended" maintenance



## Task 3: Launch Availability Analysis

- **Launch availability with optimized buffers add very little risk**
  - 0.945 with depot versus previous 0.951 for HEFT II Study
  - Difference is probably not statistically significant
  - By increasing the crew launch buffer for this analysis we could achieve 0.951
- **No buffer with worst case other risk factors results in unrealistic but bounding case**
  - Largely driven by new assumption of a 4th mission for commercial crew vs prior crew launch in MPCV
  - Includes dedicated processing schedule time for both contingency flights rather than accommodating contingencies within buffers
  - Other risk factors were included in some model runs to approximate results of Task 5 which was not performed due to lack of adequate resources
    - Assumed AR&D catastrophic failure probability of  $1.5e-2$  vs. ISS experience of  $2.45e-5$  to  $9.7e-5$
    - Also assumed similar placeholder for element unreliability
    - No reduction of failure rates for dormant (non-operating) element states
    - Results in worst case of 0.478 with depot versus previous 0.681
    - Further review by Risk Team concludes this result is inconclusive due to excessive conservatism given above considerations
  - Full performance of Task 5 is recommended
- **"No buffer" case is not representative of realistic launch availability risk management**
- **A 90 day buffer case showed 0.640 launch availability versus previous 0.681**
  - Very little increase in risk from the baseline, even with the 4<sup>th</sup> launch



## Task 4: Exploration Loss of Mission - Operational ( $LOM_O$ ) = LOM - LOC

- **PRA LOM-Operational came out about equal for both DRMs due to high-level mission differences (fewer total number of elements, reduced transit times, etc.)**
  - 4.74e-01 for HEFT-II vs. 4.85e-01 with Depot (or about 1 in 2.1) for both cases
  - These are rough first order magnitude estimates which exclude maintenance
  - Originally done due to constraints on analysis time and lack of maintenance data for HEFT II
  - Early space station maintenance studies identified similar risks with no maintenance
  - Plan was to update the baseline Non-Depot case with maintenance, however, this activity was not funded or initiated
  - Depot case was run without maintenance to match original assumptions
- **The additional 4<sup>th</sup> launch for commercial crew significantly increased risk results**
  - Not just Launch Vehicle failure, but added launch unavailability, buffer time, additional on-orbit “reliability clock” and MMOD time on all the elements, an additional transit and AR&D, and failure of commercial crew vehicle itself
  - Depot case would have significantly lower risk after normalizing this difference
- **MMOD risk was based on the same level of protection used for both scenarios**
  - Simply increased flux for the LEO case to show increased risk for the depot case
  - Both cases were based on Orion MMOD risk levels (conservatively driven by TPS damage)
  - Alternate choice would be to assume a fixed “Probability of No Penetration” requirement similar to ISS for both options and design accordingly for the requirement
  - This would have further reduced the risk results for the depot case due to fewer elements in the assembly orbit configuration





## Conclusions

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### **Maturation and demonstration of depot technologies should be supported due to high potential to achieve Technology Roadmap goals in Safety and Reliability**

- This study does not support the perception that depots add an unacceptable level of risk and should not be considered due to the increased number of launches, AR&Ds, and transfers

### **Depot-based exploration missions have significant potential to reduce total End-to-End Loss of Mission (LOM) and Loss of Crew (LOC) risks**

- There are still many unknowns such as actual reliability of future propellant transfer
- Analysis results are very preliminary with both positive and negative effects that have not been fully quantified at the present time and will depend on actual implementation

### **Depot element may be added without significantly increasing total risk**

- Depot reuse can minimize launch risk due to a single launch supporting multiple missions
- Depot element on-orbit risk can be minimized by robust design and planning for maintenance

### **Risk due to multiple supply missions can be effectively managed**

- Propellant delivery reliability with contingency can equal or exceed single mission reliability
  - Possible even with less reliable launch vehicles than normally required for crew or high value/long lead cargo
- Consequence for loss of relatively low value propellant can be low
  - Net risk acceptable even if likelihood were elevated with low cost vehicles
  - “Loss of Opportunity” analysis and alternate destinations should be considered
- A minimum of two contingency missions by two separate providers using two separate facilities should be considered mandatory (but equal use of both in this case was sub-optimal)



## **Although some risk is likely increased at the beginning of the mission, depot-based architectures have potential to significantly reduce risk for mission phases following propellant delivery**

- Added flexibility enables alternate mission planning, design, and support options

## **Improves ability for optimization of “End-to-End” risk by enabling or facilitating additional options that can:**

- Reduce total number of other elements
- Eliminates unreliability of unnecessary elements (such as 2<sup>nd</sup> CPS, 2 SEPs)
- Decrease total mission time (eliminate need for slow SEP transfers)
- Less time with “reliability clock” running

## **Beneficial effects can easily exceed any risk increase for depot/prop delivery**

- Driver for improvement is that there are opportunities for elements and missions to be designed and operated in fundamentally different ways than without depots
- Architectures, missions, elements, and processes should be optimized differently to take best advantage of these opportunities to reduce mission risk and increase safety

## **Improvement evident even without including other effects such as:**

- Reliability growth, maturity, improved robustness, increased maintenance capability
- Opportunity for additional crew safety systems and environment countermeasures
- Potential for depot to serve as “safe haven”, providing backup power, etc. prior to departure
- Human reliability likely better for ground/mission personnel with constant vs. surge workload



**From the standpoint of S&MA's role in technology assessment and prioritization, it seems depot technologies should be a high priority for investment due to their potential to achieve Agency goals to achieve "Low Cost Reliable Access To Space", if the technology can be successfully developed, demonstrated, matured, infused, evolved, and applied in future architectures so as to fully realize its benefit.**



## Conclusions/Potential Forward Work

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- ◆ **The depot itself and launch availability for propellant delivery may slightly increase risk, although other changes can offset this increase**
- ◆ **Using a Propellant Depot in LEO enable more options for mission planning and design which can significantly reduce LOC and LOM risks.**
- ◆ **Having the Propellant Depot & assembling the integrated stack in LEO reduces overall exposure time for MMOD, # of propulsion burns, and subsystem operational time.**
- ◆ **Work with element teams to assess risk reduction options such as in-flight maintenance/repair, sparing, redundancy/cross-strapping schemes, etc.**
- ◆ **Perform focused trades to optimize overall mission LOC and LOM.**
- ◆ **Improve model fidelity with improved element operational assumptions (e.g., LOM definitions, operational usage options for partial failures), targeted reliability modeling of key subsystems or components, etc.**



## Tasks 5 - 7

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**Task 5: LOM<sub>0</sub> for fill phase through first element launch**

**Task 6: Depot LOM<sub>0</sub> after exploration mission departure**

**Task 7: Integrate results and compare with non-depot missions**

**Constraints on personnel available, time, and funding limited our ability to fully address these areas**

- PRA team was not authorized to work on Task 5
- Attempts to fill in for this using the Launch Availability model provided some insights but had little or no peer review of the data and methods used
- Depot Reliability provides reasonably good ROM results for Task 6
- Additional effort on depot maintenance demand should be considered
- Funding ran out and other priorities emerged, limiting efforts on Task 7
- Undiscovered overlaps or inconsistencies are likely between the PRA and DES efforts due to the high degree of coupling between these two models



# Some Final Thoughts

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## Propellant depots provide viable alternatives for exploration architecture

- No “show-stoppers” were found due to multiple launches, rendezvous, and docking
- From the S&MA technology assessment standpoint, depot technologies are expected to have good potential for meeting OCT Technology Roadmap objectives and themes of increasing safety and reliability

The depot could have potential to significantly decrease risk in future human and other spaceflight architectures at lower cost if all effects are considered and acted upon

- Off-loading propellant and re-allocating mass to solve other high-risk problems could achieve high reliability and safety with reduced overall time and effort
- May help achieve OCT-PICS objective for “Lower Cost Reliable Access To Space” (LCRATS) to improve reliability by order of magnitude and reduce cost by the same
- Provides relatively low risk framework for maturing new launch vehicles
- The approach could provide a safe environment for “rapid prototyping” and “streamlined testing” of new concepts

Potentially the most significant risk to achieving the potential benefits that could be enabled by depot technologies would be a cultural inability to make fundamental changes in the way we develop and operate our systems to take advantage of the opportunity these technologies could provide