Purpose of Satellite Dead Bus Architecture - 2024 Space Power Workshop

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Agenda

2024 Space Power Workshop - Power Systems Architecture

- BLUF
- Purpose of Depleted Battery Prevention (DBP)
- Comparison: With DBP And Without
- Key Considerations for DBP
- Additional Considerations of including DBP
- Dead Bus Recovery (DBR)
- Summary of considerations for DBP and DBR
- Mission Risk without Depleted Battery Prevention (DBP)

BLUF

- Depleted Battery Prevention (DBP) protects Li-Ion batteries from significant degradation and possible catastrophic events rendering the SV useless with potential for space debris
  - *Isolate battery from discharging prior to damage threshold*
- Increases likelihood of recovery from significant battery degradation but not a guarantee
  - *Likely SV mission failure if battery over-discharged and no DBP installed*
  - *Addresses unforeseen failures (e.g. computer issue, loss of attitude control, unknown unknowns)*
- Customers and contractors may want to consider inclusion of DBP
  - *Could protect against complete loss of a Space Vehicle (SV)*
  - *Small relative investment for opportunity to recover SV*
  - *Consider vehicle value, resilience, risk tolerance, constellation (and backup assets)*
  - *Consider single satellite or smaller constellations where the loss of one vehicle significantly impacts mission vs large constellations where the loss of an individual vehicle has far less impact to mission*
  - *Contractor may reasonably identify and mitigate known failures but cannot for unforeseen failures*
- With DBP - Optimizes probability of surviving & recovering from dead bus event (ref 1, & 2)
- Without DBP - likely SV mission failure if battery over-discharged (ref 1.)
- Dead Bus Recovery (DBR) – a system for recovering a vehicle after DBP initiates

On-orbit experience shows dead bus architecture provides higher probability of satellite recovery experiencing a dead bus scenario

Purpose of Depleted Battery Prevention (DBP)

- Depleted Battery Prevention (DBP)
  - *Purpose of dead bus protection is to protect the battery (Li-Ion in general) from failure due to over discharge rendering the SV useless*
  - *Unlike missions with Nickle hydrogen batteries, Li-Ion is not tolerant to over discharge*
  - *Including DBP brings risk of Li-Ion systems roughly inline with that of past Ni-hydrogen systems*
    - Increase in likelihood of recovery from critically *low voltage* but not a guarantee
    - Unforeseen dead bus events like computer issue, loss of attitude control may take from days to months for SV recovery
      - *May not be able to recover during eclipse season or from undesired attitudes with no attitude control*
  - *DBP should remove discharge path at critically low state-of-charge (SOC) (battery voltage)*
    - Ensure battery charge allowed above critical temperature during DBP and Dead Bus Recovery (DBR) phases
  - *Protection should be considered by customers especially on high reliability, high dollar value, or to address resilience requirements in single or small constellation mission*
    - Requirements to include a DBP and DBR system should be considered by the customer given over-all risk tolerance – a customer ultimate decision
  - *Note that Load shedding due to undervoltage or low battery SOC is not DBP*

On-orbit experience shows dead bus architecture provides higher probability of satellite recovery experiencing a dead bus (ref. 1 and 2)

Comparison: With DBP And Without

WITH
Depleted Battery Prevention

- Optimized probability of surviving & recovering from dead bus event (ref 1. & ref 2.)
- Batteries are isolated from discharge, but still allowed to charge
- Complete loss of SV minimized
  - *Batteries are not reconnected until there is enough charge to support SV recovery operations*
  - *Provides power for de-orbit/super sync if needed*
- Maintains ability to support mission in eclipse if SV is recovered

WITHOUT
Depleted Battery Prevention

- SV mission failure likely if batteries over discharged (ref 1.)
- Batteries can be fully depleted and no longer accept charge
- Complete loss of SV possible
  - *Unit start up times may not allow for attitude control to be restored when operating from just the solar arrays*
  - *SV dead in orbital slot (e.g. GEO)*
- If SV is recovered, batteries may not be able to support the mission through eclipse
  - *Sun may need to be reacquired after every eclipse, causing extended outages*

NOTE: In both cases, thermal control of the SV is lost, loads are not guaranteed to be recoverable if units drop below survival temperatures or experience rapid temperature swings

Key Considerations for DBP

Risk Tolerance / Importance of SV Recovery

- How high value is the vehicle? And how long is its design life?
  - *DBP may be a small relative investment for the opportunity to recover an expensive SV over a long design life. Or may be unreasonably expensive for small sats with a short design life.*
- How high value is the orbital slot? And what would the consequence of losing the SV in slot be?
  - *DBP is a last line of defense for orbital slots that are essential to current and future missions. Unrecoverable vehicles essentially become space debris, while recovered vehicles can be operated/ de-orbited/ super synced as needed.*
- Does the mission require a single satellite or a constellation? Can the constellation operate with the loss of a SV? Can the mission tolerate periods of non-operation during eclipse?
  - *Single satellite missions may be more or less risk tolerant depending on mission. DBP is less typical on these missions but has been used to meet resiliency requirements. Similarly, DBP is less typical on large proliferated constellations that can tolerate the loss of multiple SVs without impacting mission. Small constellations that would experience significant impact to mission with the loss of a single SV or outages during eclipse see the largest benefit from DBP.*
- Does SV design or mission merit extra protection against unknown failures? And are there backup assets?
  - *Unproven SV designs may benefit from DBP. This might apply to the bus design or any load that is tied directly to the main bus and cannot be removed by load shed operations. But backup assets may be sufficient to mitigate these risks depending on mission*

The choice to implement DBP is dependent on a number of mission specific considerations

Additional Considerations For Including DBP

- If included, DBP should separate protection from that of the main SV computer
  - *Once battery voltage (state of charge) drops to a sufficient critically low voltage, automatic dead bus sequencing can lower loads then removal the battery discharge*
    - Non-mission critical loads and heaters – turned off and latched off
    - Mission-critical loads - turned off until adequate power is available
    - Reconfigure Telemetry and Command path
    - Battery discharge path electrically isolated from the bus and battery
  - *Battery temperature should be above its critical damage threshold before charging*
    - Li-Ion cells can be permanently damaged if charged under a critical temperature
- Thermal control is not guaranteed to maintain SV survival temps depending on time in a dead bus event due to power limitations and possible satellite attitude control health

Dead Bus Recovery (DBR)

After DBP initiated (separate consideration from DBP, albeit related)

- Dead Bus Recover (DBR)
  - *Once sun is back on solar array*
    - First priority; Ensure battery temperature threshold above critical damage threshold
      - *Battery charging can then autonomously initiate when excess solar array power is achieved via the DBR system*
    - Once battery achieves a predefined SOC threshold the battery can autonomously reconnect to the bus and satellite recovery can then be initiated by ground intervention
- Dead bus sequence protects the lithium-ion battery from overdischarge and charging at cold temperatures, which is necessary to preserve battery health and maintain safe environment
  - *For Lithium-Ion, batteries should be above a minimum temperature to avoid potential catastrophic lithium plating while charging*
  - *Prior nickel hydrogen battery chemistry could tolerate some overdischarge and charging at cold temperature without significant consequences unlike most Lithium-Ion chemistries*
  - *DBP on Li-Ion system increase SV reliability to roughly previous Ni-Hi systems that did not generally incorporate DBP system*

During recovery, DBR should allow autonomous charging with a minimum battery temperature, plus autonomously reconnect the battery at an upper SOC threshold

Summary of considerations for DBP and DBR

- DBP on Li-Ion system increase SV reliability to roughly previous Ni-Hi systems that did not generally incorporate DBP system – will be reviewed by Aerospace Reliability
- Arguments pertaining to main computer processor low state of charge protection against dead bus events:
  - *May be valid for well understood failures*
  - *May not be valid given unforeseen or unknown events causing discharge below the critical Li-Ion voltage threshold*
  - *Unforeseen dead bus events like computer issue, loss of attitude control may take from days to months for SV recovery and may not be able to recover during eclipse season*

DBP can Increase likelihood of SV recovery from critically low overdischarge but not a guarantee depending on vehicle attitude, season and type of failure

Mission Risk without Depleted Battery Prevention (DBP)

- Reduced (limited) probability of SV recovery if electrical power is lost
  - *Difficult to charge battery to sufficient state-of-charge to recovery Satellite*
    - When the battery is electrically connected to the bus, the battery discharges every time you lose sun, thus hard to regain battery energy for satellite recovery
  - *When battery is discharged to low voltage some (many) individual cells can be driven below critically low damage threshold resulting in internal hard short (cell(s) is lost)*
  - *Battery at risk of lithium plating if remaining cells are charged at cold temperatures, resulting in internal short -> cell thermal runaway -> cell-to-cell propagation -> space debris*

- Recommend that contractor(s) of Government assets consider implementation of dead bus architecture within the electrical power system capable of protecting Li-Ion batteries without satellite processor

If overdischarged below a critical voltage threshold, Li-Ion will likely become completely damaged yielding loss of SV mission

Contributions

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- James Walker (EPSD)
- Kelsey Dougherty (EPSD)
- Mark Peterson (Systems Integration & Test Office)
- Andrews Y Hsu (Reliability)

References

1. 2018, April 6. Dead Bus Recovery: History, Causes, and Mitigation. TOR-2018-00526. Aerospace – Brian Lenertz, Valerie Ang
2. 2018, July 24. Architecting a Dead Bus Recoverable Earth Orbiting Spacecraft. TOR-2018-00556. Aerospace - David Landis, Arnold Arst

Backup

Qualitative Risk Assessment

Risk Assessment

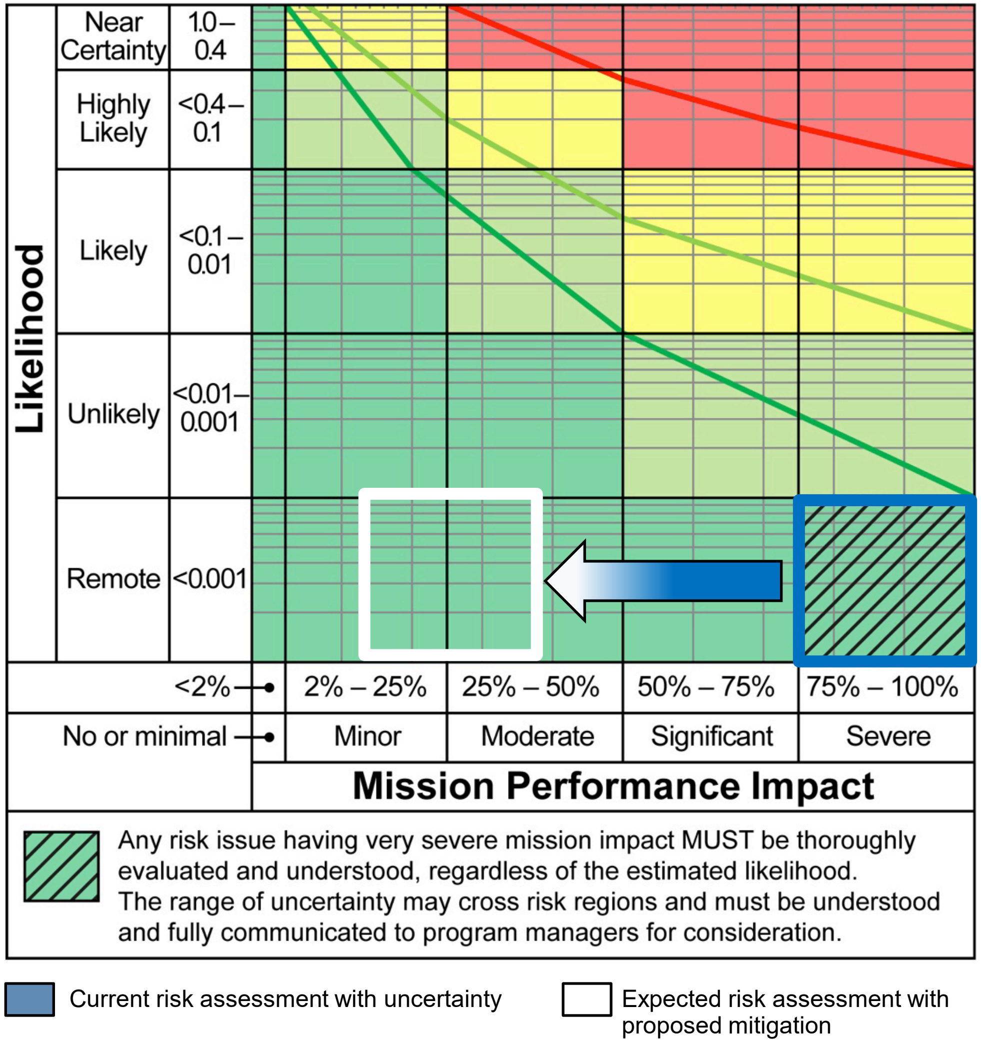
Of dead bus scenario

- Boxes are realization of likelihood and mission impact of a dead bus scenario
  - *Batteries discharged to lowest allowable State of Charge (SOC)/ Batteries fully depleted*

- **BLUE BOX - Without DBP** - Requires multiple failures/ anomalies. Remote likelihood. Mission performance impact, complete SV mission failure possible

- **WHITE BOX - With DBP** - Optimizes probability of surviving and recovering from dead bus event

- Quantitative metrics not currently available, determined using engineering judgment



Implementation of DBP minimizes mission performance impact, but does not further reduce likelihood of a dead bus event

Risk Assessment

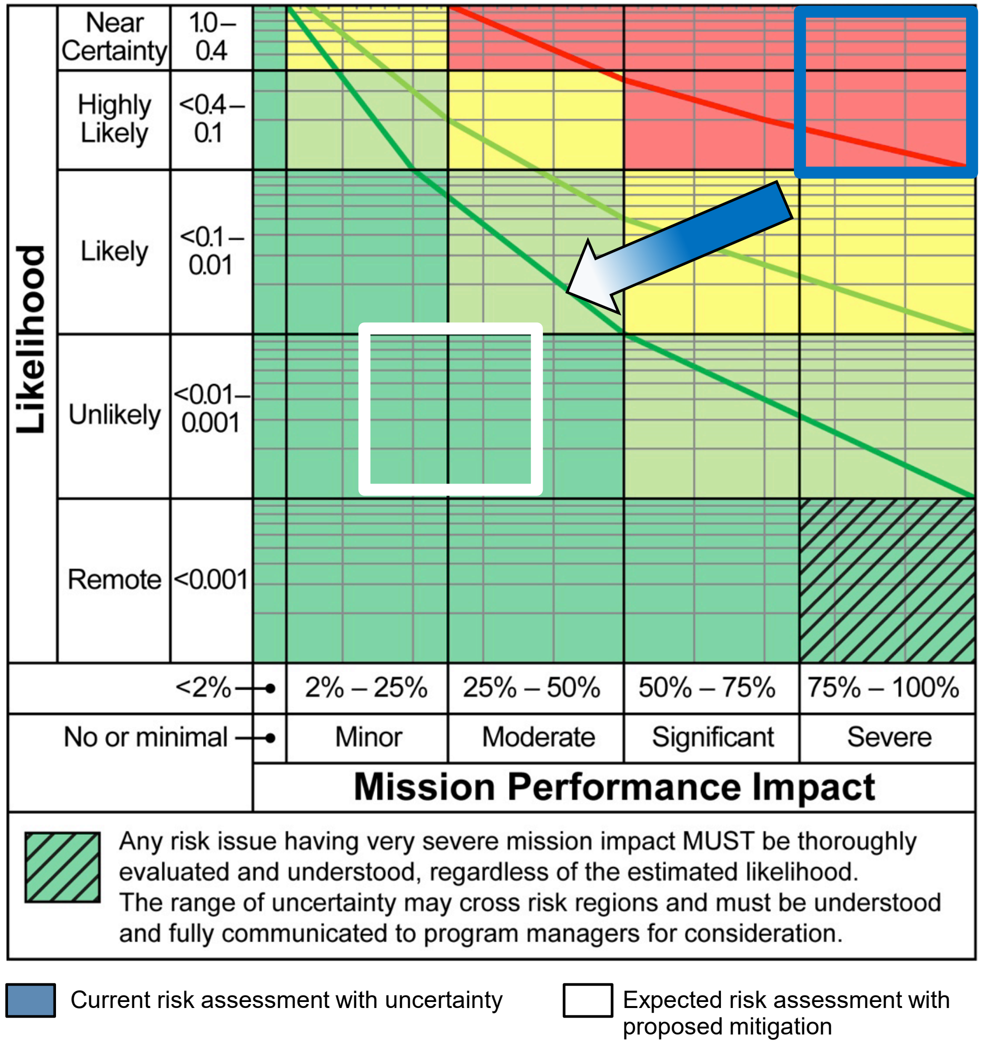
Of damage to the battery with immanent dead bus scenario

- Boxes are realization of likelihood and mission performance impact of battery damage from a dead bus scenario

- **BLUE BOX - Without DBP** – Li-ion batteries have poor recovery from over discharge and experience rapid degradation and cell shorting below a certain SOC. This constitutes a severe mission performance impact and can result in loss of SV or mission. The likelihood of battery damage if a dead bus event is experienced without DBP is near certainty, given the condition indicates a depleted battery.

- **WHITE BOX - With DBP** – Likelihood of battery damage is dramatically reduced by DBP since battery discharge is inhibited at dead bus scenario. Mission performance impact is also reduced, though not entirely eliminated given the unknowns associated with a dead bus condition.

- Quantitative metrics not currently available, determined using engineering judgment
  - *Considers past loss of key high value assets*
  - *Includes classified program failures that cannot be discussed openly*



If DBP is not implemented then risk of battery damage as a result of over discharge could result in SV mission failure & loss of orbital slot