Cabin Environment Physics Risk Model

Chris Mattenberger, Science & Technology Corporation
Donovan Mathias & Susie Go, NASA ARC
Engineering Risk Assessment Team
NASA Ames Research Center, Moffett Field, California

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Overview

- Engineering Risk Assessment Team Introduction
- Probabilistic Risk Assessment Methodology
- Cabin Environment Physics Risk (CEPR) Model
- Application of CEPR Model to Generic ISS Mission Architecture
- “Blow and Bleed” Sensitivity Study
- “Feed the Leak” Sensitivity Study
- Risk-Informed Design Examples
- Summary and Conclusions
ERA Programs & Projects

- Blast overpressure, debris, fireball physics modeling
- Ascent abort effectiveness assessment

- Campaign analysis, long-term operations and repair
- LOM/LOC and availability estimates

ERA also supports analysis of satellites, sample return missions and asteroid defense
• **Risk-informed decision support**
  – Requirement verification
  – Risk-informed design support
  – Part selection/procurement

• **Probabilistic risk assessment is informative, not predictive**
  – Provides quantitative answers to specific questions
  – Always driven by specific application
  – Based on traditional methods and extended as appropriate

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**Iterations/responsive modeling approach**

- Pessimistic bounds
- Architecture
- Model inputs
- Physical model
- Assess risk drivers
- Risk acceptable?
- Assumption driven?
- Architecture driven?
- Solution reached
- Design trades
- Refine inputs

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**Risk model maturity** tracks design maturity and engages engineers early in the design process, rather than a post facto analysis
ERA Team Methodology

• Dynamic nature of failures
  – Time dependence
  – State dependence
  – Partial & interactive failures

• Physics-based analysis
  – External hazards
  – Failure evolution

• Traditional static models
  – Lower part levels
  – Typically reliability based

\[ R(t) = e^{-\lambda t} \]

Combines traditional PRA methods with dynamic methods for increased accuracy of representation of system risk
Cabin environment is impacted by many traditional spacecraft subsystems.
Cabin Environment Physics Risk (CEPR) Model

Estimates time interval from loss of functionality to hazardous environment

Estimates time from loss of functionality to onset of hazardous environment
GoldSim provides a graphical representation of data flow within model.
CEPR tracks partial pressures of key cabin atmospheric constituents

\[ PV = nRT \]
CEPR model captures dynamic interaction of spacecraft subsystems
CEPR model captures physics-based impacts of component functionality

Mission concept of operations used to demonstrate CEPR model implementation
Assumptions

- **Cabin Properties**
  - 16 m$^3$ air volume
  - Leakage rate of 0.036 lbm/day
  - $297$ K constant temperature
  - Perfectly controllable $O_2$ mass flow rate and $O_2$ sensors
  - Perfect pressure vessel
  - Perfect Mixing
  - Ideal Gas

- **Initial Nominal Cabin State**
  - 3.234 psi pp$O_2$
  - 0.058 psi pp$CO_2$
  - 11.408 psi pp$N_2$

- **Crew**
  - 4 Crew
  - Consume 0.2434 kg/hr of $O_2$
  - Produce 0.2554 kg/hr of $CO_2$

- **Consumables**
  - 44.7 kg of $O_2$ at 100% Full
  - 167 kg of $N_2$ at 100% Full
  - $297$ K constant temperature

- **LiOH Canisters**
  - Removes 0.2554 kg/hr of $CO_2$ at 100% effectiveness level

- **LOC Thresholds & Return Time**
  - Minimum pp$O_2$ is 2.3 psi
  - Maximum pp$CO_2$ is 0.87 psi
  - Return Time is 4 Hours

Green indicates Simplifying Assumption / Blue indicates Uncertain Assumption / Black indicates Uncertain Design Requirement
Design Insights for Risk-Informed Decisions: “Blow and Bleed” Sensitivity Study

CEPR model yields design insights to inform mission rules
Design Insights for Risk-Informed Decisions: “Feed the Leak” Sensitivity Study

Time to LOC vs. Leakage Rate

ppO2 = 2.3 psi

\[ \dot{m} = CA \sqrt{\gamma \rho P \left( \frac{2}{\gamma + 1} \right)^{\frac{\gamma + 1}{\gamma - 1}}} \]

CEPR model yields design insights to aid in risk-informed decision making
Dynamic Mission Risk Model

Integrated dynamic risk model captures time- and state- dependent behavior
Monte Carlo simulation enables CEPR results to impact overall mission risk.
Risk-Informed Design Example: Risk Driver Ranking

ERA Spacecraft LOM Risk Drivers

ERA Spacecraft LOC Risk Drivers

Excessively conservative assumptions can impact relative risk results
## Risk-Informed Design Example: Risk Reduction Trade Study

### Trade Study Options

<table>
<thead>
<tr>
<th></th>
<th><strong>EPS - Enhanced</strong></th>
<th><strong>ECLSS - Enhanced</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Fuel Cell Stack</strong></td>
<td>10.7 lbs</td>
<td>Manual Valve 0.3 lbs</td>
</tr>
<tr>
<td><strong>Heater</strong></td>
<td>1 lb</td>
<td>Manual Valve 0.3 lbs</td>
</tr>
<tr>
<td><strong>Heat Exchanger</strong></td>
<td>0.65 lbs</td>
<td>Manual Valve 0.3 lbs</td>
</tr>
<tr>
<td><strong>Pressure Regulator</strong></td>
<td>0.635 lbs</td>
<td>Manual Valve 0.3 lbs</td>
</tr>
<tr>
<td><strong>Pressure Sensor</strong></td>
<td>0.22 lbs</td>
<td>Manual Valve 0.3 lbs</td>
</tr>
<tr>
<td><strong>Hydrogen Purge Valve</strong></td>
<td>0.1 lbs</td>
<td>Manual Valve 0.3 lbs</td>
</tr>
<tr>
<td><strong>Water Separator</strong></td>
<td>0.5 lbs</td>
<td></td>
</tr>
<tr>
<td><strong>Total Mass Delta</strong></td>
<td>13.805 lbs</td>
<td>Total Mass Delta 1.8 lbs</td>
</tr>
</tbody>
</table>

### Diagrams

**EPS**
- Heat Exchangers
- Operational Heaters
- Electrical Control Units
- Fuel Cells (2 hot spare)
- Hydrogen/Oxygen Tanks

**ECLSS**
- DC/DC Converter & Regulator
- Shunt Regulator Unit
- Fault Detection Circuit
- Subsystems/Loads
- Internal/External Heaters

### Legend
- DC Power Distribution Unit @28 VDC
- Manual Valve
- Isolation (Solenoid) Valve
- Pressure Regulator
- Temperature Sensor
- Vents
- Line Heaters

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Risk-Informed Design Example: Risk Reduction Trade Study

Risk Reduction Efficiency = $\Delta$Risk / $\Delta$Mass

LOC Risk Reduction Trade Study

Excessively conservative assumptions can alter trade study results dramatically
Summary & Conclusions

- **CEPR model** is used to predict the time for an initial ECLSS failure to propagate into a hazardous environment and trigger a LOC event
  - Can be utilized as a stand-alone model to aid in decision-making
  - Allows for integration of model results into dynamic mission risk models
  - Enables the risk analyst to remove the assumption that loss of functionality triggers LOC

- **The assumption that loss of functionality triggers LOC has been shown to be excessively conservative**
  - Impacts overall risk driver ranking
  - Impacts risk reduction trade study results
  - Could lead to a suboptimal design that inherently increases the risk of LOC

- **Incorporating CEPR results yields more accurate design insights**
Future Work

**POWER**
- Production
- Storage
- Distribution

**Pressure Vessel**
- Environment
  - O2
  - CO2
  - N2
  - H2O
  - Trace Contaminants
  - Temperature

**Activity Cycle**
- Crew

**AVIONICS**
- Command
- Control
- Data Handling

**PCS**
- O2
- N2
- PPRV / NPRV
- Sensors

**ARS**
- CO2 / Trace / Humidity / Temperature
- Sensors

**Space**
- Pressure, Temperature, Radiation

**TCS**
- LCG Loop
- ARS HEX
- Primary Loop