HyPerPLSS:

Development of a Single-Fluid Consumable Infrastructure for Life Support, Power, Propulsion, and Thermal Control

Dr. David Akin
Craig Lewandowski

Dr. Carol Smidts
Jinny McGill

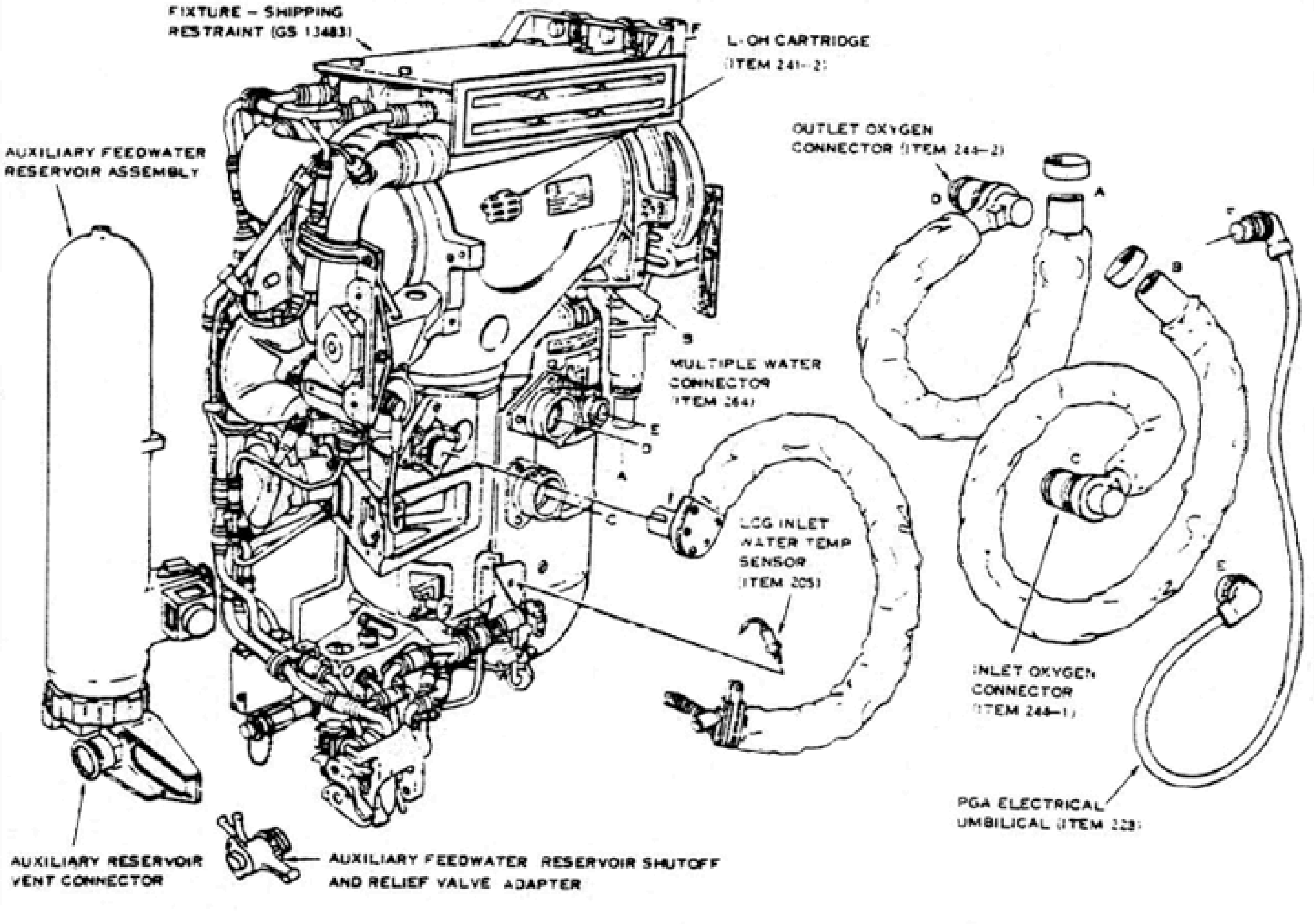
Presentation Outline

- Background and Concept Overview
  - Dr. David Akin
- Chemistry, Thermodynamics, and Components
  - Craig Lewandowski
- Reliability and Risk Analysis
  - Dr. Carol Smidts
  - Jinny McGill
- System Applications
  - Dr. David Akin

EVA Life Support Background

- Portable life support system (PLSS) required for unrestricted extravehicular operations (EVA)
- Supplies oxygen, power, cooling
- ~120 lbs (Earth) weight on back

Apollo PLSS Internal Layout

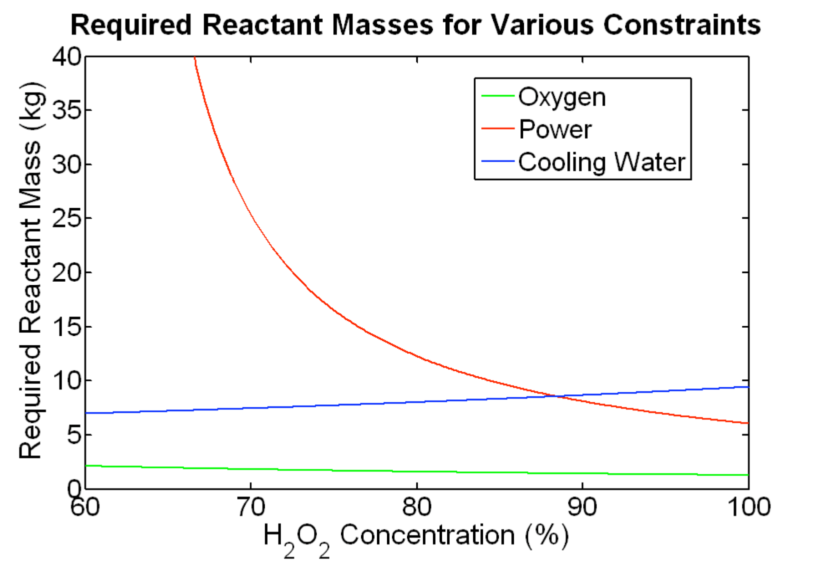


Genesis of the Concept

- Current PLSS recharge requires battery replacement, water refill, high pressure oxygen recharge, contamination control cartridge replacement - each with external support requirements
- Observe that $2\ H_2O_2 \rightarrow 2\ H_2O + O_2 + \text{heat}$
- Hydrogen peroxide (room temperature liquid) might be able to supply all requirements for life support → Hydrogen Peroxide PLSS → "HyPerPLSS"

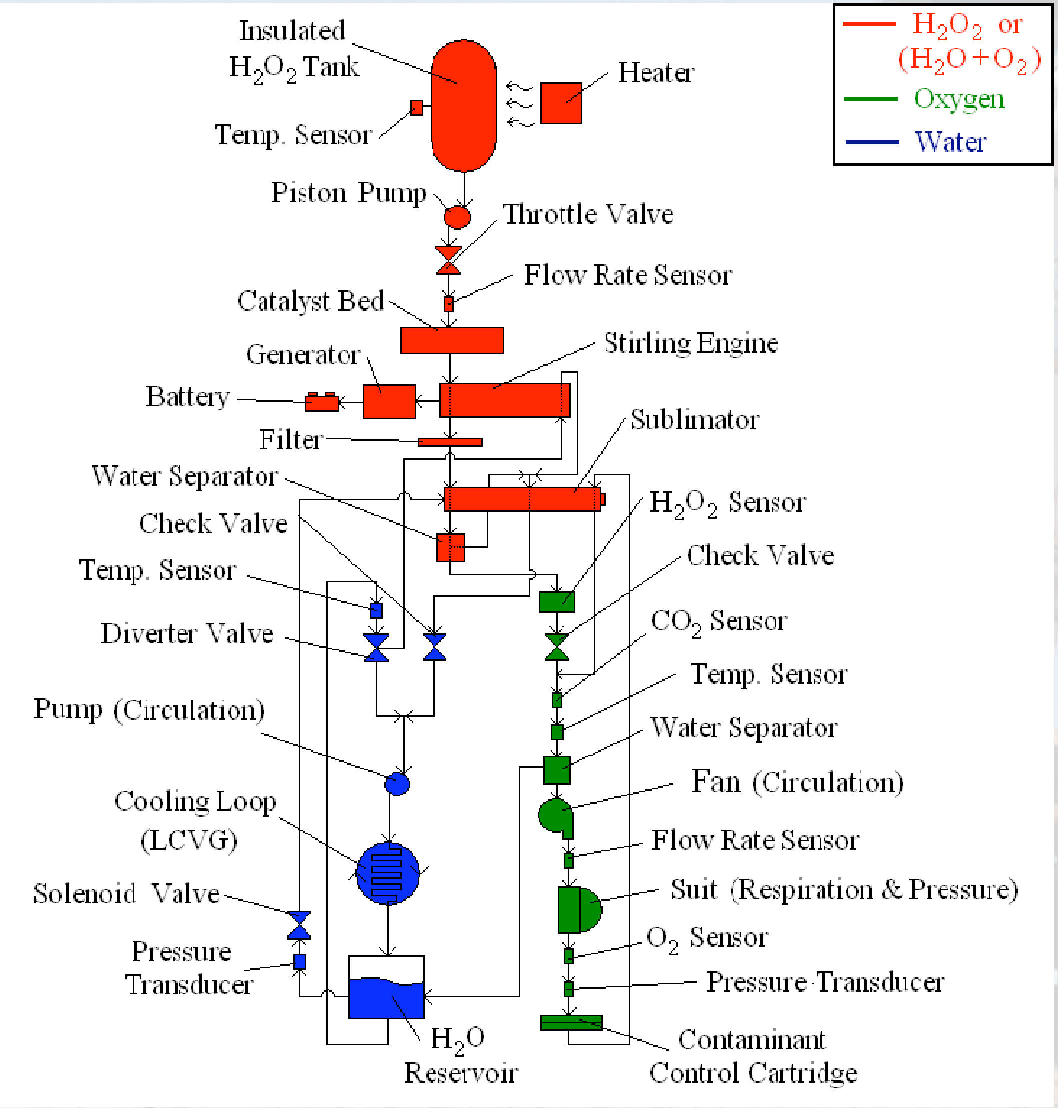
H2O2 Requirements

- Assumed requirements
  - 0.6 kg O2
  - 5 kg of H2O
  - 800 W·hr of electrical energy



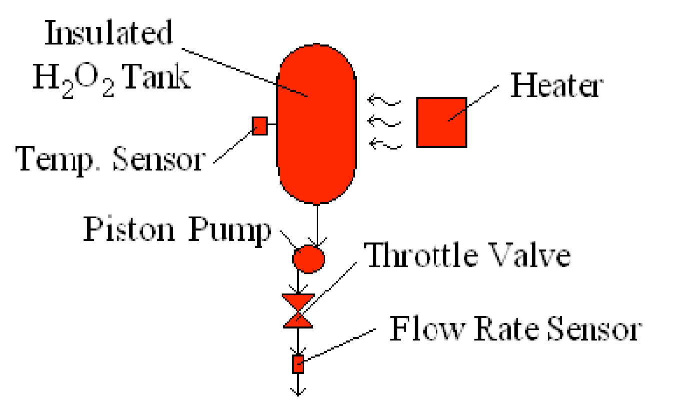
- 88.5% => minimum mass (chemistry only)
- Increased to 95% to generate enthalpy needed by power system (thermodynamics added)
- Required H2O2 mass = 10.9 kg

System Schematic



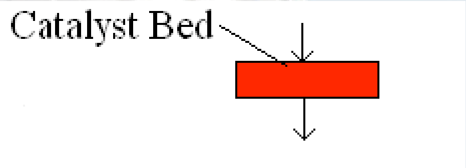
Component Description

- 2.10 gallon tank
- Protection against freezing
  - Band heater
  - Temperature sensor
- Flow adjusted with varying demand requirements
  - Pump
  - Throttle valve



H2O2 Catalyst Bed

- Significant knowledge base exists for H2O2 propulsion
- SOA: Silver-based catalyst beds
- General Kinetics Inc. COTS product
  - Silver screens
  - L = 3.3 in, D = 0.75 in
- Ensure H2O2 decomposition by increasing residence time

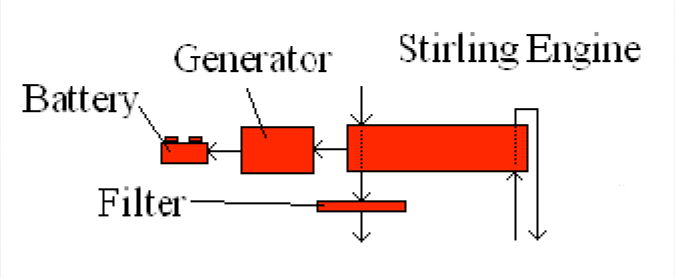


H2O2 Gas Generator

(www.gkllc.com)

Power System

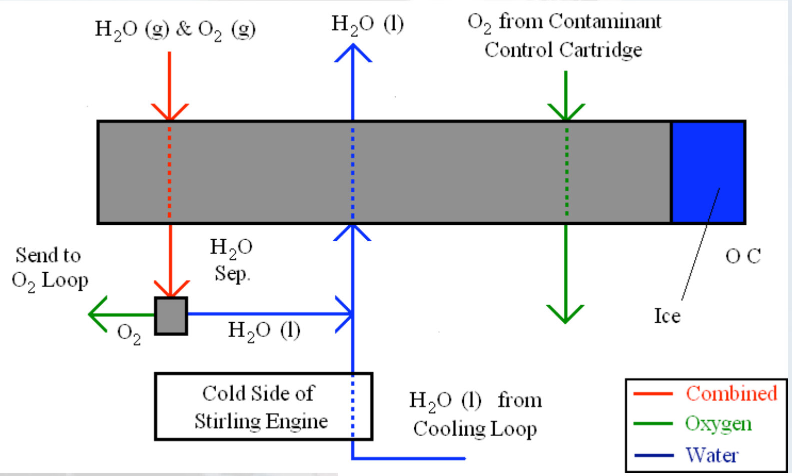
- Convert thermal energy to electricity
- Stirling engine
  - Sunpower ASC COTS system
    - 80 W, 36% efficiency
  - H2O to generate temperature gradient
- Battery provides and stores excess energy

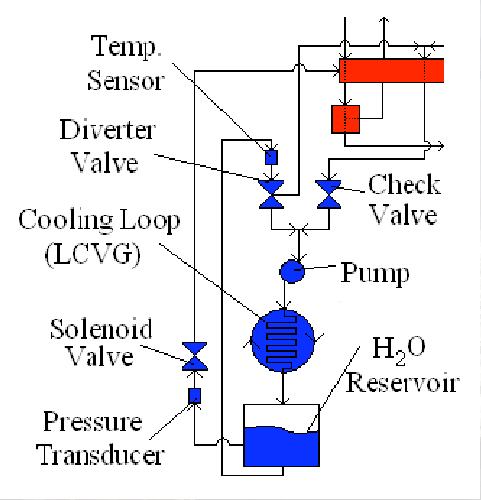


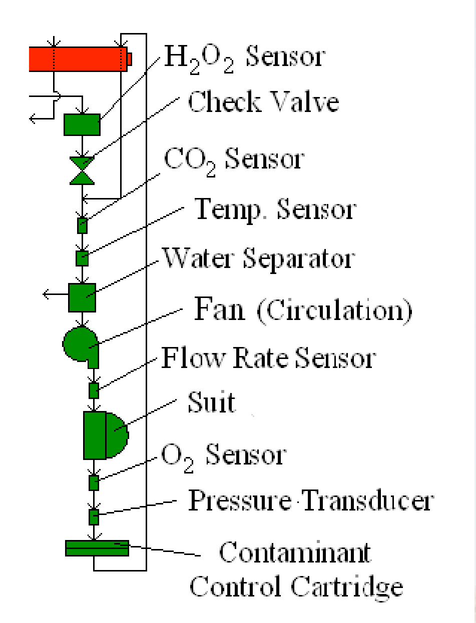
Sunpower ASC
(Wong et.al)

Sublimator and Supply Loops

- Sublimator overview
  - Phase changes
  - Heat removal
- HyPerPLSS fluids
  - H2O phase change
  - Cooled streams
- Water separator
- Conventional supply loops





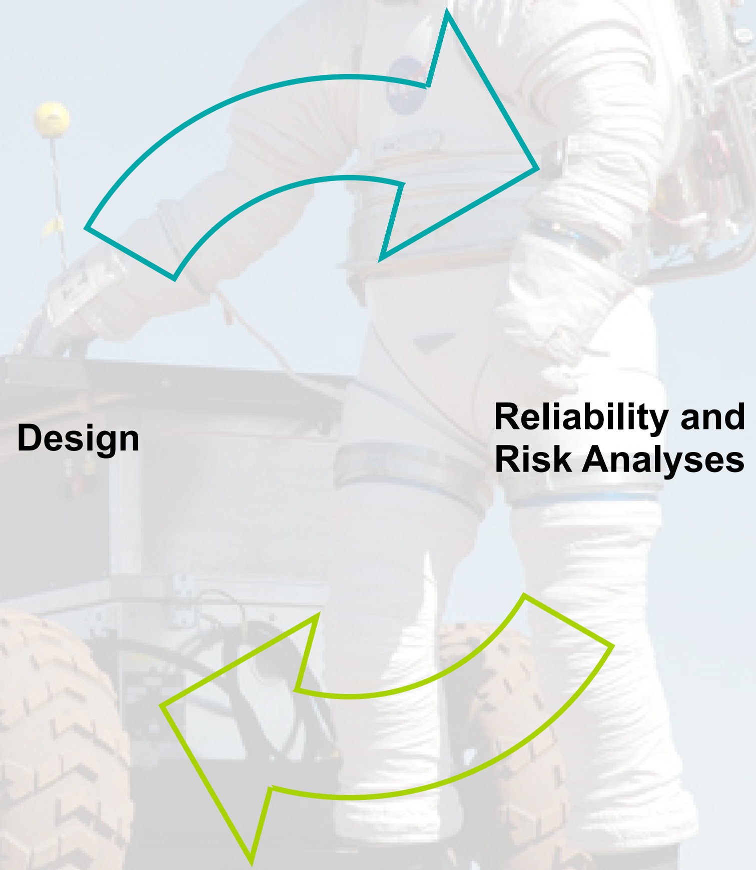


Reliability and Risk Analysis Motivation

- Inform design decisions with considerations of reliability and risk
  - Increase reliability of system
  - Decrease risk of design
- Consider hazards to equipment and crew health
  - Hydrogen peroxide can cause spontaneous combustion with organic materials and is incompatible with many metals (e.g., iron, copper, brass, silver, zinc).
  - Corrosive to skin, membranes, and eyes at high concentrations.
  - Vapors from concentrated solutions of hydrogen peroxide can result in significant morbidity.

Parallel Process

- Conceptual design
- Reliability analyses
  - Failure Modes and Effects Analysis
  - Fault Tree Analysis
- Parallel process with feedback between design and analyses



Failure Modes and Effects Analysis

ID#	Function	Components	Failure Modes and Causes	Mission Phase / Operational Mode	Failure Effects			Failure Detection Method	Compensating Provisions	Severity Class	Remarks
					Local	Next Level	End				

- Technique for reliability analysis
- Describes failure causes and effect on system
- Results are used to consider design changes that may be necessary to reduce unreliability and risk

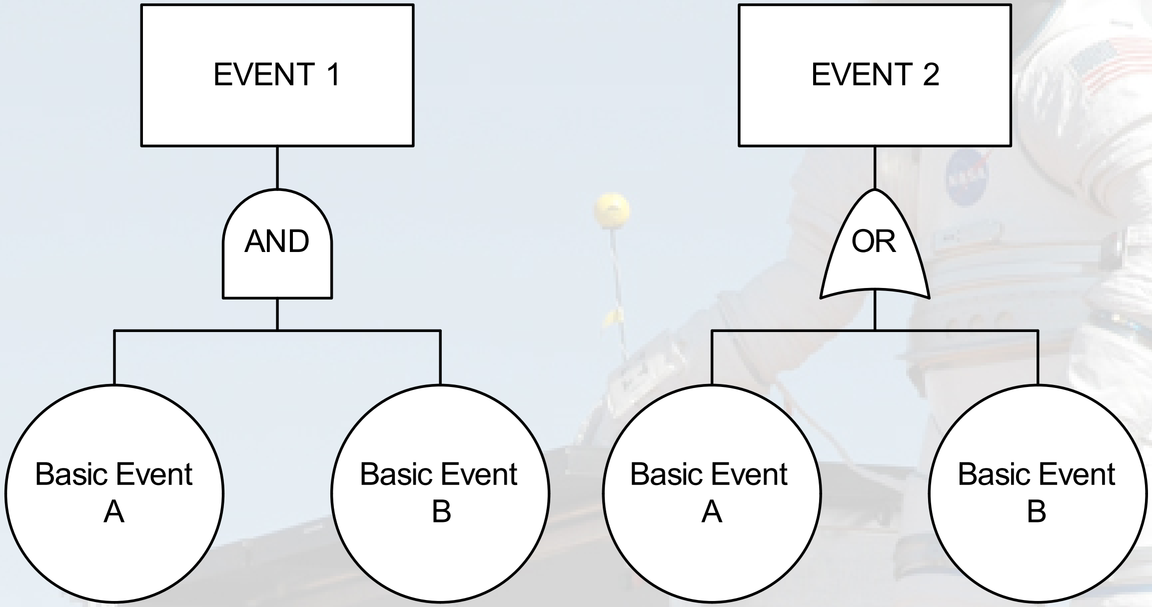
Failure Modes and Effects Analysis

- Failure Modes
  - Manner of the failure
  - Tumer et al. (5) provides an updated failure mode taxonomy
- Severity
  - Qualitative rating assigned for the worst possible effect
  - MIL-STD-1629A severity levels were modified to differentiate between Loss of Crew and Loss of Mission

Primary Identifier	Secondary Identifier	Failure Mode
(Impact)	Separation into 2 or more parts	Impact fracture
Impact load of large magnitude	Plastic or elastic deformation	Impact deformation
	Mating parts Small lateral displacements Joints not intended to move	Impact fretting

Effect	Rating	Description
Catastrophic	1	Loss of crew
	2	Loss of mission
Critical	3	Major system degradation
Marginal	4	Minor system degradation and may require maintenance or repair.
Minor	5	Does not cause system degradation but may require maintenance or repair.

Fault Tree Construction

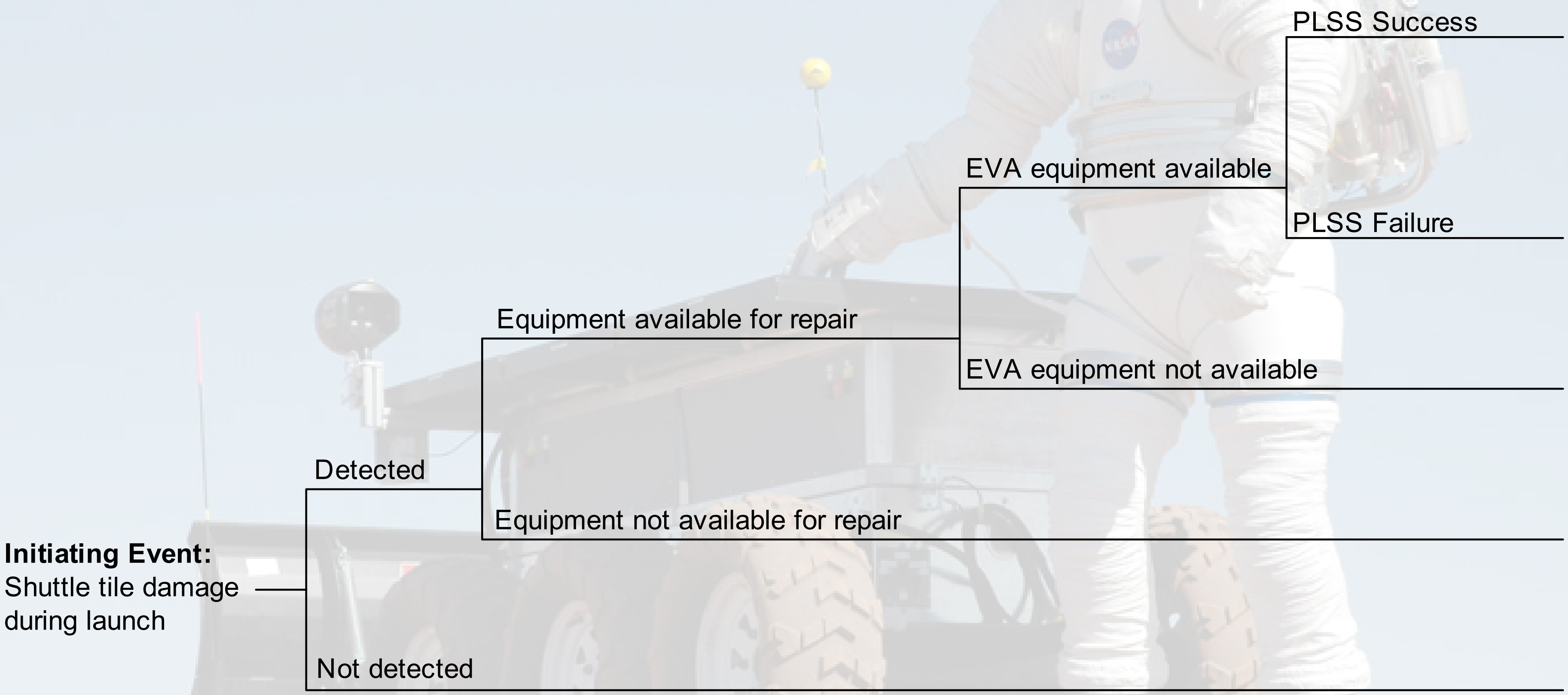


- The top level event is the undesirable event (e.g., system failure)
- Lowest level events are basic events (e.g., component failure)
- Boolean logic gates are used to communicate event effects on the system

Fault Tree Analysis

- The Boolean expression for the fault tree is written, then expanded
- This expression is simplified (i.e., Boolean reduction) to achieve the simplest logical expression from which the minimum cut sets can be obtained
- Birnbaum importance measure represents the change in system risk with respect to changes in basic event probabilities

Event Tree


PLSS Success
EVA equipment available
PLSS Failure
Equipment available for repair
EVA equipment not available
Detected
Equipment not available for repair
Initiating Event:
Shuttle tile damage
during launch
Not detected

Quantification

- Fault tree analysis gives qualitative results in the form of cut sets; quantitative results can also be obtained
- Probabilities (or frequencies) of basic events are used to compute probability of top level events
- Failure probabilities (or frequencies) can be obtained in several ways:
  - Databases of component failure frequencies
  - Expert elicitation
  - Human Reliability Analysis Models (e.g., THERP)

Scope of Analyses

- Operation phases/modes for HyperPLSS include and are not limited to:
  - Storage for launch
  - Maintenance
  - Power operation
- Analyses thus far have focused primarily on the power operating mode during EVA
- Direct functional dependencies are considered in the FTA; common cause failures have not been considered

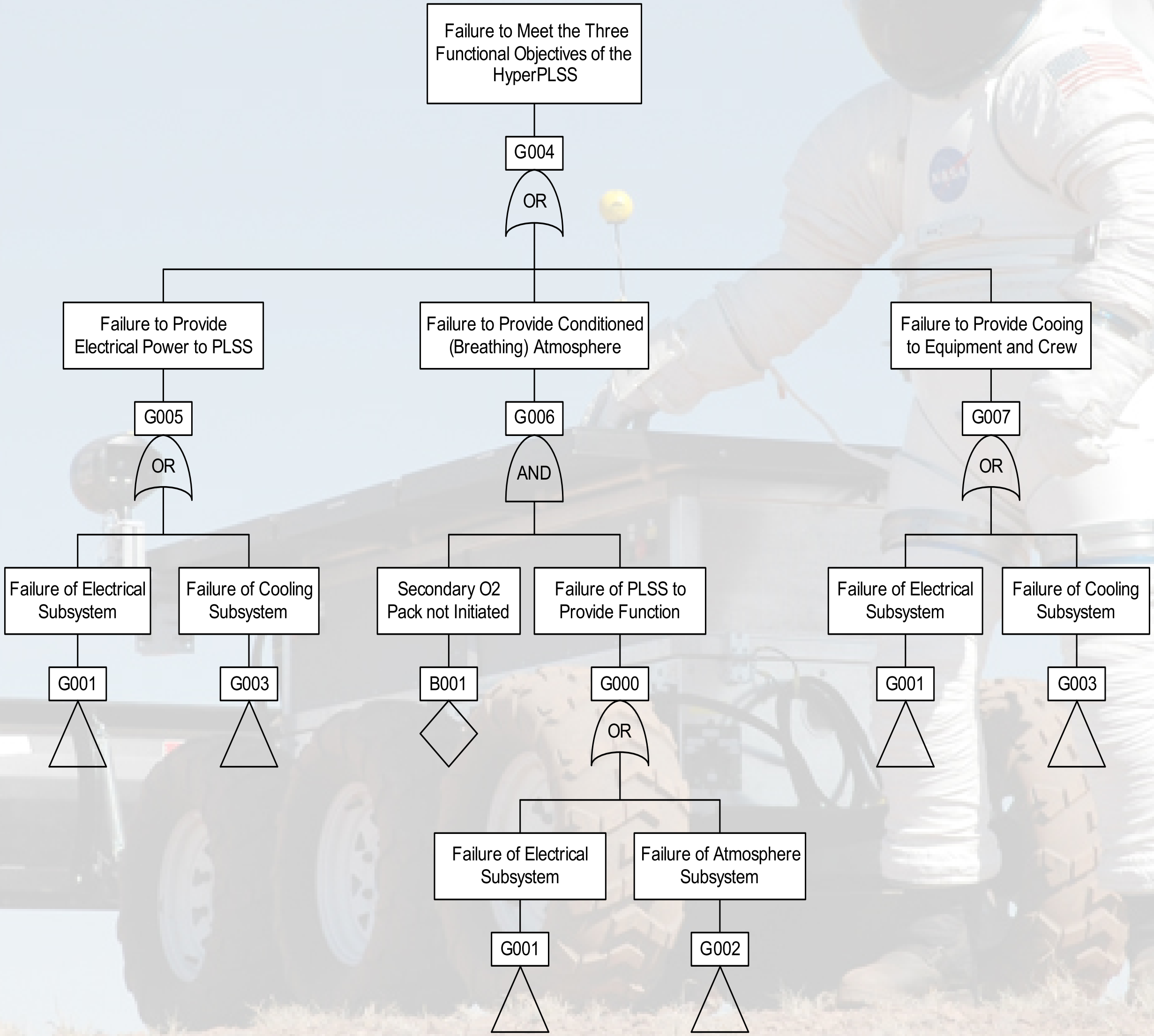
Scope of Analyses

- Several system aspects are not yet modeled in detail
  - Electrical system
  - Piping system
  - Stirling engine
  - Packaging structures and insulation
  - Software (control system)
- Failure is assumed rather than degraded states
- Qualitative analyses only thus far (no probabilities or frequencies have been applied yet)
- Risk analysis has been limited to a review of the hazards of hydrogen peroxide to health

FMEA Example

			Failure Effects						
Components	**ID**	**Failure Modes and Causes**	**Local**	**Next Level**	**End**	**Failure Detection Method**	**Compensating Provisions**	**Severity Class**	**Remarks**
Throttle Valve (mechanical)	**5A**	Surface fatigue wear	Pitting, cracking, scaling of rubbing surfaces	Reduced performance or control	Repair	Noise; inconsistent settings w/ flow indication		4	Determine expected life for parts that can wear.
		Impact fracture	Separation of parts	Loss of valve; leaking H2O2	Loss of equipment, system, or combustion	System failure / flow rate sensor 1		1	Consider robustness and packaging.
		Impact deformation	Deformation of parts	Loss of valve	Loss of system	System failure / flow rate sensor 1	Back-up O2 system and battery, Abort mission	2	Flow sensor was added.
		Galling	Surface destruction of rubbing surfaces	Reduced performance or control	Repair	Noise		3 or 4	Material choices for component may affect.
		Seizure	Two parts virtually welded together	Loss of valve	Loss of system	System failure / flow rate sensor 1	Back-up O2 system and battery, Abort mission	2	Material choices for component may affect.
		Cycle fatigue	Fracture	Loss of pumping	Loss of system	System failure / flow rate sensor 1	Back-up O2 system and battery, Abort mission	2	Flow sensor was added.

Fault Tree Example

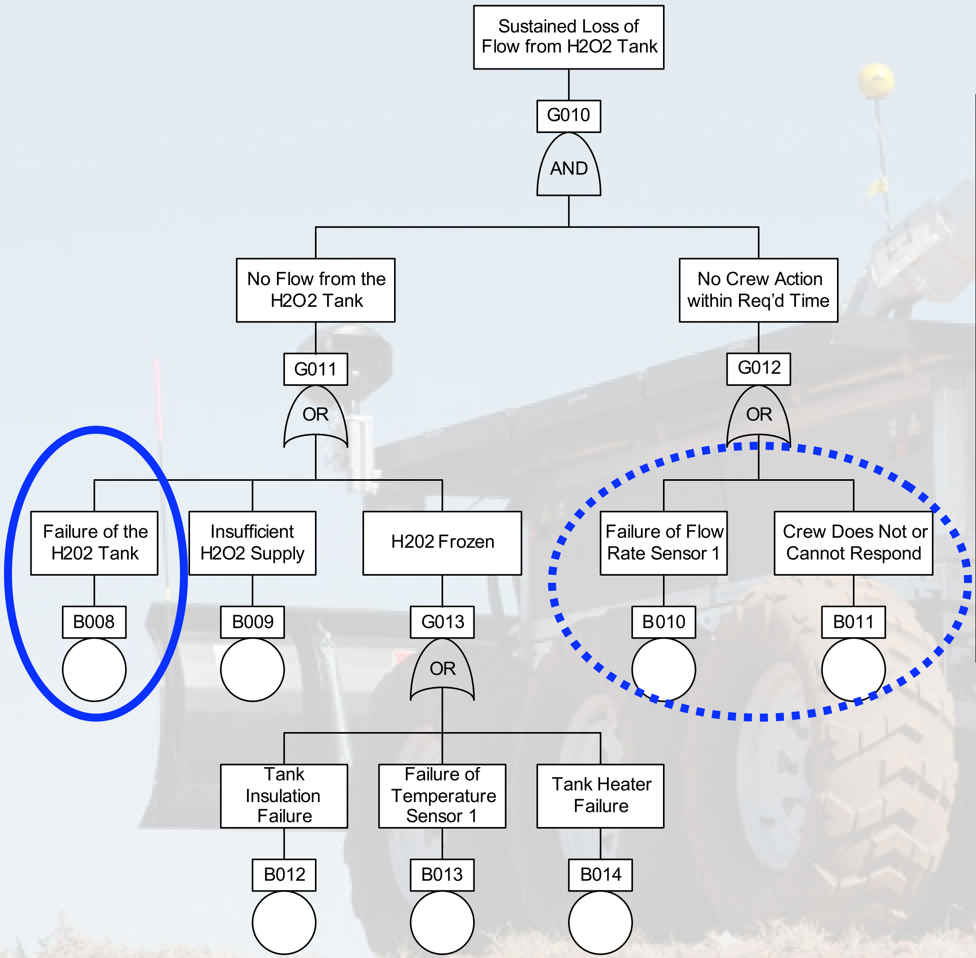


Fault Tree: Cut Sets

Single Events	Double Events		Triple Events		
B002	B008	B010	*B001*	*B022*	B027
B003	B008	B011	*B001*	*B022*	B028
B004	B009	B010	*B001*	*B023*	B029
B005	B009	B011	*B001*	*B023*	B030
B006	B012	B010			
B007	B012	B011			
	B013	B010			
B031	B013	B011			
B032	B014	B010			
B033	B014	B011			
B034					
B035	B015	B001			
B036	B016	B001			
B037	B017	B001			
B038	B018	B001			
B039	B019	B001			
B040	B020	B001			
B041	B021	B001			
B042					
	B024	B001			
	B025	B001			
	B043	B044			
	B043	B045			

LEGEND: Basic Event
Undeveloped event

Fault Tree Example



B008	Failure of the H2O2 tank resulting in reduced or no flow of H2O2
B009	Insufficient H2O2 tank available resulting in reduced or no flow of H2O2
B010	Failure of flow rate sensor 1 resulting in necessity for troubleshooting
B011	Crew does not or cannot troubleshoot problem with flow rate sensor 1
B012	Tank insulation fails to keep temperature of H2O2 tank adequate
B013	Failure of temperature sensor 1 results in inadequate heating of H2O2 tank
B014	Tank heater failure results in inability to keep H2O2 from freezing

Comments about the Process

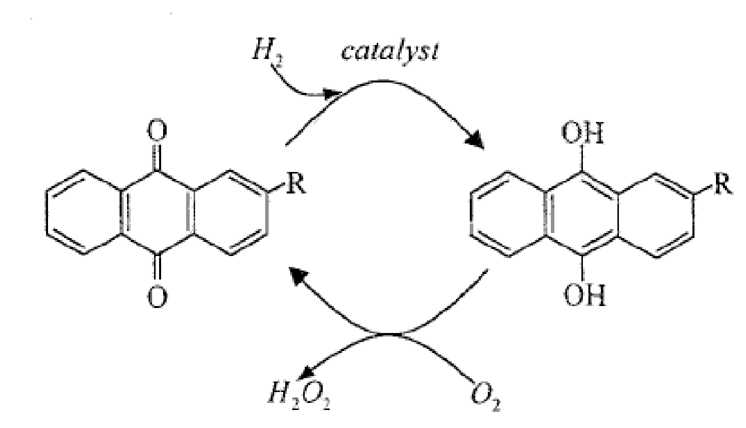
- For systems where reliability and risk are of concern, these analyses should be performed in parallel with design
- Such a parallel process requires that a structured approach be taken; configuration control can become an issue during conceptual design phase
- Feedback early during the FMEA and FTA has resulted in several HyperPLSS design changes (e.g., addition of a filter downstream from catalyst bed)

Reliability Conclusions and Future Work

- Consideration of other operating modes (e.g., storage, maintenance)
- Identify and gain access to sources of failure probabilities (frequencies) for quantitative analyses
- Bayesian framework will be devised to combine sources of relevant data
- Safety (risk) analysis; scenario development and event tree construction

In-Situ Production of H2O2

- Anthraquinone Process
  - Requires H2 and O2
  - Transport H2 from Earth
  - Moon: O2 from regolith
  - Mars: O2 from atmosphere
    - $CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$
    - $2H_2O \rightarrow 2H_2 + O_2$
- Produces 30% Concentration
- Increase to 90% with vacuum distillation
- Electrolysis-based production also feasible



H2O2 Manufacturing Process
(Ventura and Yuan)

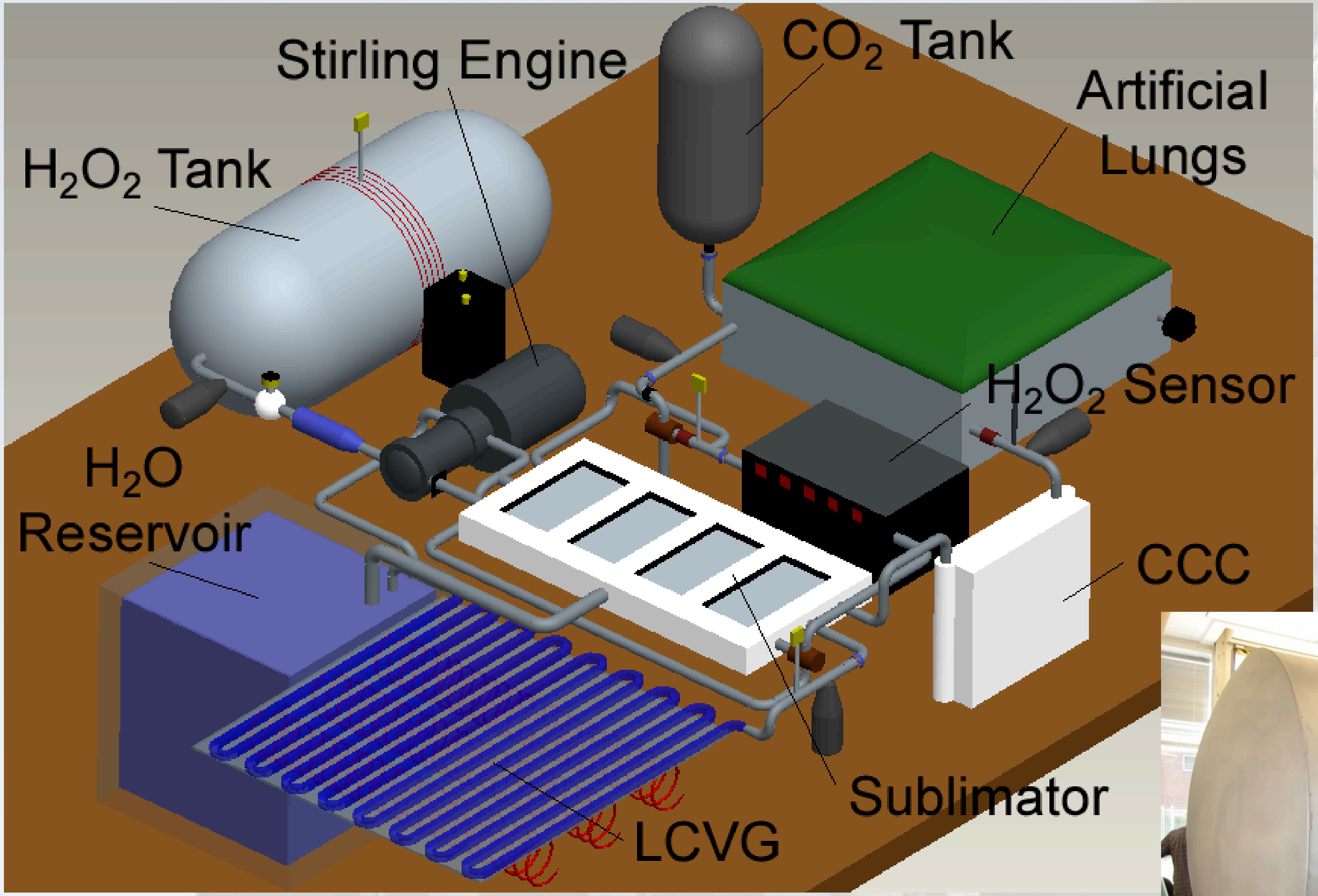
Synergistic Growth Opportunities

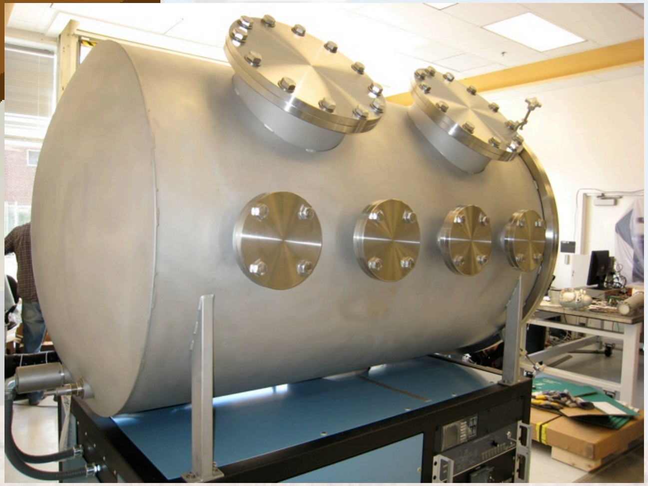
- In-backpack regeneration of metal oxide CO2 scrubbers using waste heat
- Use of surplus products for in-space propulsion
  - Oxygen cold gas
  - H2O2 monopropellant thrusters
- The "hydrogen peroxide economy"
  - H2O2 single-supply for PLSS
  - H2O2 energy source for small rovers
  - H2O2 + fuel for large/long-range rovers

Plans for Phase 2

- Refine thermodynamic modeling
- Extend and enhance reliability and safety analysis
- Extensive experimentation
  - Prototyping of H_2O_2 feed system/catalytic reactor
  - Prototyping of multipass sublimator
  - Development of human respiratory/metabolic simulator
- Phase 2 milestone - full HyPerPLSS breadboard operating in thermal vacuum chamber

Phase II Test Bed





UNIVERSITY OF MARYLAND

Research Status

- We have demonstrated that the HyPerPLSS concept is technically feasible (TRL 1)
- Remaining Phase 1 goals are to
  - refine end-to-end thermodynamic cycle analysis
  - complete FMEA and PRA
  - detail requirements for in-situ H_2O_2 production
  - develop non-sublimation cooling concept for Mars
  - conceptualize EVA packaging and operations approach
- Phase 2 will experimentally demonstrate PLSS operations in space environment (TRL 3-4)

Conclusions

- The "hydrogen peroxide economy" offers unique advantages for future space operations
  - Single-point recharge for EVA (easy to do in field)
  - EVA duration is unlimited by life support system
  - Logistics simplified by single room-temperature liquid
  - Shared consumables between EVA and robotic systems
  - Readily replaceable from in-situ resources

➡ Successful development of the HyPerPLSS can revolutionize human exploration of Moon/Mars

References

- Reliability Engineering and Risk Analysis: A Practical Guide, M. Modarres, M., New York, N.Y., 1999.
- Risk Analysis in Engineering: Probabilistic Techniques, Tools and Trends, M. Modarres. Taylor & Francis Group, LLC, Boca Raton, 2006.
- Collins, J. A., Failure of Materials in Mechanical Design, John Wiley & Sons, 1993.
- Fault Tree Handbook with Aerospace Applications, Prepared for NASA Office of Safety and Mission Assurance; August 2002.
- Requirements for a Failure Mode Taxonomy for Use in Conceptual Design; International Conference on Engineering Design ICED 03, August 19-21, 2003; Irem Y. Tumer et al.
- An implementation of reliability analysis in the conceptual design phase of drive trains Avontuur, G.C.; van der Werff, K. Reliability Engineering & System Safety, Aug. 2001, vol.73, no.2, pp. 155-65 : Elsevier, Journal Paper.
- Risk-informed design guidance for future reactor systems Delaney, M.J.; Apostolakis, G.E.; Driscoll, M.J. Nuclear Engineering and Design, June 2005, vol.235, no.14, pp. 1537-56.
- A risk evaluation approach for safety in aerospace preliminary design Fragola, J.R.; Putney, B.F.; Mathias, D.L. Annual Reliability and Maintainability Symposium. 2003 Proceedings, 2003, pp. 159-63, xviii+622 pp. USA, Piscataway, NJ..
- Practical solutions for multi-objective optimization: An application to system reliability design problems Coit, D.W., et al. Reliability Engineering & System Safety, March 2007, vol.92, no.3, pp. 314-22.
- Medical Management Guidelines for Hydrogen Peroxide (H2O2), Agency for Toxic Substances & Disease Registry, Department of Health and Human Services; accessed on 25 January 2007, http://www.atsdr.cdc.gov/MGMI/mmg174.html
- Wong, W. A., Anderson, D. J., Tuttle, K. L., and Tew, R. C. "Status of NASA's Advanced Radioisotope Conversion Technology Research and Development," NASA/TM, 2006.
- General Kinetics Product Catalog, General Kinetics Inc. http://www.gkllc.com, accessed 15 February 2007.