

Comparison of Exploration Oxygen Recovery Technology Options Using ESM and LSMAC

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In preparation for long duration manned space flight, numerous technology development efforts are ongoing in the area of environmental control and life support (ECLS). In cooperation with international, industry, and academic partners, NASA seeks to leverage the International Space Station as a testbed for technologies targeted for Exploration-class missions. In recent years, Equivalent Systems Mass (ESM) analyses have been conducted to evaluate the relative breakeven points and to compare technologies as part of ECLS architectural trades. While these studies have provided important data pertaining to key engineering metrics, additional considerations are important to more fully understand the potential impacts and costs associated with selecting a specific architecture. A tool, called the Life Support Multi-Dimensional Assessment Criteria (LSMAC), was recently proposed by Sierra Nevada Corporation in an attempt to incorporate influences of these additional considerations including Maintainability, Risk Analysis, Technology Readiness Level, Radiation Impacts, Manufacturing Costs, Reliability, Human Factors, and Un-Crewed Operations. As a first step toward evaluating and implementing this tool, LSMAC was used to revisit the ISS oxygen recovery trade from the 1990's wherein Sabatier was selected over Bosch technology. Second, the tool was used to compare oxygen recovery developmental technologies currently in work. The results of these studies as well as a comparison with standalone ESM analyses are reported. Further, a discussion of the potential application of the tool across the ECLS portfolio and its potential use in future technology selection for ISS flight demonstrations is provided.

Nomenclature

C_2H_2	= Acetylene	$HCVD$	= Honeywell Carbon Vapor Deposition
C_2H_4	= Ethylene	$ILCF$	= Ionic Liquid-based Bosch Carbon Formation
C_2H_6	= Ethane	$ISAB$	= ISS-fidelity Sabatier Technology (TRL 9)
CH_4	= Methane	ISS	= International Space Station
$CBOS$	= Umpqua Continuous Bosch Technology	$MPPA$	= Methane Plasma Pyrolysis Assembly
CO	= Carbon Monoxide	PPE	= Personal Protective Equipment
$DSAB$	= Development Sabatier Technology (TRL 5)	$SBOS$	= Series-Bosch
$ECLS$	= Environmental Control and Life Support	$SCLT$	= System Capability Leadership Team
$ELEC$	= Electrolytic Oxygen Recovery	SSF	= Space Station Freedom
ESM	= Equivalent System Mass	TRL	= Technology Readiness Level
H_2	= Hydrogen	$VBOS$	= Vertical Bosch

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I. Introduction

IN the late 1980's and early 1990's, the National Aeronautics and Space Administration (NASA) was working diligently to baseline the regenerative environmental control and life support (ECLS) system intended for use on, what was then, Space Station *Freedom* (SSF).¹ Several technologies were under consideration for the architecture including two carbon dioxide reduction systems: Bosch and Sabatier. A trade study was conducted following head-to-head testing that included both quantitative and qualitative considerations. Ultimately, Sabatier was selected to meet the requirements for Space Station *Freedom*, and was subsequently baselined after transition to the *International Space Station* (ISS). A Sabatier Reactor Assembly was developed by Hamilton Sundstrand (now Collins Aerospace), delivered to ISS in 2009, and activated in 2010.² As operated, this system can theoretically recover and recycle ~54% of the oxygen from carbon dioxide produced by the crew due to the limited availability of hydrogen. The oxygen deficit is replenished by electrolyzing water which results in an operational approach that relies heavily on Earth-to-orbit resupply.

For future exploration missions such as a sustained Moon presence, transit to Mars, or a sustained Mars presence, it may not be feasible to rely on consistent and frequent resupply of consumables. For this reason, NASA and its commercial partners have developed a portfolio of low- and mid- Technology Readiness Level (TRL) advanced oxygen recovery technologies. The ECLS System Capability Leadership Team (SCLT) at NASA has also developed an Oxygen Recovery Roadmap in an effort to identify targeted infusion points, to specify key figures of merit, and to track the progress of each technology. Eleven unique developmental technologies are currently tracked on the roadmap. Six of these are in the range of TRL 3-5 and have infusion potential for the nearest-term missions. As we steadily approach Artemis deadlines, it becomes increasingly important to have standardized and effective methods to adequately assess and compare technologies against one another and against the mission goals.

In recent years, the primary evaluation scheme for comparison between life support systems is Equivalent System Mass (ESM). ESM specifically quantifies the resources required to deploy a system, including mass, volume, power, cooling required, and crew time as an aggregate value to simplify comparisons. However, as mission scenarios and requirements are more clearly defined, it becomes necessary to consider additional factors. In order to expand the set of characteristics used for comparative evaluations, a set of categories were developed by Sierra Nevada Corporation to supplement ESM criteria. These categories and processes, termed Life Support Multidimensional Assessment Criteria (LSMAC), could be used to augment ESM for evaluation and comparison of life support systems. Specifically, LSMAC addresses ESM in addition to the following evaluation criteria: Maintainability, Risk Analysis, Technology Readiness Level, Radiation Impacts, Manufacturing Costs, Reliability, Human Factors, and Un-Crewed Operations.³

As a first step, the LSMAC tool was evaluated for suitability for mid-TRL level technology trades by reassessing the Bosch vs Sabatier trade conducted in the early 1990's. The results of the LSMAC trade were compared to the results of the original trade as well as to the results of ESM alone. The LSMAC tool was then used to evaluate state-of-the-art Sabatier technology and the six O₂ recovery technologies currently in development for three mission scenarios: a 90 day Lunar surface mission in which crews returned to the surface repeatedly, a one-year transit mission to Mars, and a three-year Mars surface mission. The results were then compared with the results using ESM alone. Here we present the results of these analyses, propose modifications to the LSMAC tool, and discuss future uses for the tool.

II. Background

A. 1990's Oxygen Recovery Trade for Space Station *Freedom* and ISS

During ECLSS development for Space Station *Freedom*, two O₂ recovery technology approaches were considered: Bosch and Sabatier. Bosch technology has a theoretical maximum O₂ recovery of 100% from metabolic CO₂. The Bosch process is a combination of multiple reactions including the Reverse Water-Gas Shift (RWGS) reaction, a carbon monoxide hydrogenation reaction, and the Boudouard reaction. The final products of the process include water, which can be electrolyzed to produce oxygen for the crew, and solid carbon, which must be discarded or repurposed. The Sabatier technology has a theoretical maximum O₂ recovery of 50% (at a stoichiometric ratio of reactants). The Sabatier reaction, shown in equation 5, converts CO₂ and hydrogen (H₂) to water, like Bosch technology, and gaseous methane that must be vented or further processed.

Bosch was originally baselined for Space Station *Freedom*, primarily because at the time there was a "no venting" requirement, prohibiting the Sabatier technology and its waste CO₂/CH₄ stream. However, a change in the overall space station architecture to allow venting of waste gases through resistojets to be used for propellant allowed this trade to be re-evaluated.

A third generation Bosch built by Life Systems, Inc was tested head-to-head with a third generation Sabatier built by Hamilton Standard (now Collins Aerospace). Both subsystems were assessed to be at a TRL of 5.4 (pre-prototype tested at NASA). The comparative test Bosch consisted of two 60 crew-day capacity reactors and were able to process up to 8 crew’s CO₂. The comparative test Sabatier could also process 8 crew’s CO₂. For the comparative test, both subsystems were run concurrently for a total of 60 days. Test data and anomalies encountered were used to extrapolate to projected space station mission quantitative and qualitative parameters. Table 2 summarizes the quantitative resource comparison between Bosch and Sabatier. The numbers represent not only subsystem values but system impacts including waste gas processing. Negative values represent a net savings to the propulsion system. Table 1 summarizes the qualitative assessment in terms of major and minor strengths and weaknesses against 13 factors: safety, technical maturity, maintenance, maintainability, reliability, integration, complexity, noise, microgravity sensitivity, technology problems, contamination potential, performance (in a qualitative sense such as product purity), commonality, and programmatic considerations.

Based on the quantitative and qualitative assessment, NASA recommended changing the baseline from Bosch to Sabatier. The overriding rationale was that Sabatier weight, power, volume, and resupply resources were all much lower than the Bosch, the Sabatier was at a high level of technical maturity, the Space Station architecture at the time could process the CO₂/CH₄ waste gas from Sabatier through resistojets, the Sabatier fit much more easily into the Atmosphere Revitalization rack, and was considered to have a lower development risk than Bosch. The conclusions did note that the Bosch was still considered a desirable technology for long-duration missions with no resupply such as a lunar base or Mars missions.

Table 2. Space Station Freedom Comparative Test Quantitative Assessment.

Parameter	Bosch	Sabatier
On-orbit weight, kg	1839	497
Power, W (average)	1378	395
Power, W (max)	3050	628
On-orbit volume, m ³	5.92	0.65
Heat rejection, W (avionics)	944	226
Heat rejection, W (coolant)	505	84
90-day resupply weight up, kg	57	-156
90-day resupply weight down, kg	318	33
90-day resupply volume, m ³	0.85	-0.14

Table 1. Space Station Freedom Comparative Test Qualitative Assessment.

Bosch	Sabatier
Major Strengths	
Complete O ₂ loop closure	High technical maturity
	Low complexity
Minor Strengths	
	No regular maintenance
	Reliability
	Ease of integration
Major Weaknesses	
Difficulty in packaging	Impacts to waste gas system
Major design revisions needed for flight	Water carryover from separator
Carbon formation in undesirable locations	
Could not achieve 8-crew rate	
Minor Weaknesses	
Regular maintenance required	Incomplete O ₂ loop closure
Low reliability	Possible external contamination concerns
More complex integration	
Carbon contamination of recycle loop	

B. 2020’s Oxygen Recovery Technology Options to Trade for Artemis and Beyond

Six O₂ recovery developmental technologies currently warrant a TRL 3-5 designation and are under consideration for exploration missions in addition to state-of-the-art Sabatier (designated ISAB) technology (TRL 9).⁴ Additional technologies are in development at lower TRL levels and may be considered for mission infusion once adequately matured, but will not be discussed here. Each of the O₂ recovery technologies evaluated in this trade study are described in the following sections.

1. Methane Post-Processing Assembly

A system with the capability of recovering and recycling hydrogen (H₂) from Sabatier-produced methane (CH₄) will increase the overall O₂ recovery rate of the current Sabatier reactor. A methane post processor, Plasma Pyrolysis Assembly (MPPA), is currently under development, which uses a magnetron to ignite a H₂/CH₄ plasma targeting a conversion to H₂ and acetylene (C₂H₂).⁵ Although the outlet stream of the MPPA is H₂-rich, the outlet stream also consists of C₂H₂, unreacted CH₄, trace amounts of water, carbon monoxide (CO), ethylene (C₂H₄), ethane (C₂H₆), and solid carbon. This effluent mixture is due to the secondary reactions that occur with CH₄ and the reaction that occurs with the residual water vapor. In order to fully recover and recycle H₂ back to Sabatier, a H₂ separator and carbon filtration is required. The current MPPA architecture implements an electrochemical separator, developed by Skyre, LLC (East Hartford, CT), to separate C₂H₂ from H₂.⁶ Prior to H₂ separation, a carbon capture unit⁷ is required in order to prevent carbon fouling of the downstream H₂ separator. This base technology is currently at a TRL level 5, but

hydrogen separation and carbon formation systems are at TRL 3, thus an overall TRL of 3.

2. *Honeywell Carbon Vapor Deposition (HCVD)*

Honeywell Aerospace is developing a Carbon Vapor Deposition reactor system that has a theoretical O₂ recovery of nearly 100% when coupled with a Sabatier⁸. The HCVD system accepts CH₄ product from a Sabatier reactor and converts it to H₂ gas and solid carbon, operating at approximately 100 torr and 1150°C. The product H₂ gas, unreacted CH₄, and residual water vapor are recycled back to the Sabatier reactor for continued reduction of CO₂. The carbon is deposited on and within carbon fiber substrates resulting in an easy to handle, soot-free carbon product. This process would eliminate the difficulties in managing the carbon product typical of O₂ recovery systems. The product is a hard “puck” with no carbon soot and is currently at a TRL of 4.

3. *Umpqua Continuous Bosch*

The Continuous Bosch Reactor (CBOS) utilizes a single reactor that converts a feed of CO₂, H₂ and a recycle stream into water vapor and solid carbon. Water vapor is removed from the product stream via a condensing heat exchanger. As solid carbon is produced in the reactor, a motorized attritor shaft breaks up the solid material and helps force the material out of the reactor body and into a carbon collection system. A vacuum is used to periodically remove the product carbon from the carbon collection system. Unreacted gases are recycled back to the reactor. Catalyst pellets are injected into the reactor during operation. The proposed design eliminates the need for down time for catalyst addition and carbon removal. This technology is being developed by Umpqua Research Company and is currently at a TRL level 3.

4. *Series-Bosch*

The Series-Bosch (SBOS) system can theoretically achieve 100% oxygen recovery from metabolic CO₂ (Eq. 10). This system consists of two main reactors, a Reverse Water Gas Shift Reactor (RWGSR) and a Carbon Formation Reactor (CFR). During the process, CO₂ first enters a Hydrogen Extraction Assembly (HEA) membrane (Proteus) in order to pick up H₂ from the recycle stream. The H₂ is and then combined with the CO₂ recovered by the Carbon Dioxide Extraction Assembly (CDEA) membrane (Polaris). The combined CO₂/H₂ stream is then sent to the RWGSR where the RWGS reaction, shown in Eq. 7, occurs. The Polaris effluent is sent to the CFR where the CO Hydrogenation and/or the Boudouard reactions, shown in Eqs. 8-9, occur. The RWGSR and CFR outlet streams enter a compressor where the streams are mixed and then sent to a condensing heat exchanger. Water vapor is condensed out of the stream and the gases are recycled back to Proteus. The CFR includes multiple reactor housings operated in tandem, which allows a single housing to be shut-down at any given time for carbon removal. Solid carbon is removed from the individual housing using a vacuum while the remainder of the system continues to function. This proposed technology is being developed by Marshall Space Flight Center (MSFC) in partnership with pH Matter, LLC and is currently at a TRL level 3, but approaching a TRL 4.

5. *Ionic Liquid (IL) Based Bosch Carbon Formation Reactor*

MSFC is also developing an IL-based carbon formation reactor (ILCF), reported previously, that is intended to complement the Series Bosch technology described above in Section 4 “Series-Bosch”.^{9,10} The proposed architecture assumes the use of a RWGSR and membranes from the S-Bosch. When carbon fouling of the CFR catalyst occurs or if the pressure drop of the system exceeds acceptable limits, the CFR catalyst must be replaced. This technology utilizes ILs to eliminate the need to replace the catalyst by dissolving the catalyst from the reactor’s catalyst substrates and generated carbon. During the process, the carbon is filtered from the IL, allowing the deposited carbon to be collected. The IL, containing dissolved catalyst, can then be used to re-plate the metal onto the now carbon-free catalyst substrates, which is then used to continue the carbon formation process as before. This technology is currently at a TRL level 3.

6. *Electrolytic O₂ Recovery (ELEC)*

Another approach to maximize O₂ recovery is an electrochemical system centered on a microfluidic electrochemical reactor (MFECR), as reported previously.¹¹ The MFECR is based on the electrochemical reduction of CO₂ to ethylene (C₂H₄) using H₂O as a proton source, and has a theoretical O₂ recovery rate of 73%. The proposed architecture for the MFECR O₂ recovery system involves CO₂ entering the MFECR, and to complete the reaction, an electrical potential is applied across the electrodes of the cell. O₂ is produced in the anode of the cell and C₂H₄ is produced in the cathode of the cell. Although the cathode outlet stream consists of mainly C₂H₄, the stream also contains H₂, unreacted CO₂, and trace amounts CO, CH₄, and H₂O. The cathode outlet stream is sent to a condenser, where H₂O is condensed prior to entering an H₂ separator. H₂ is separated and sent to a fuel cell, and the effluent is sent to an additional separator where the residual CO₂ is separated and recycled back to be processed by the MFECR.

The current electrolyte used in the process is a potassium hydroxide (KOH) and H₂O mixture. During the process, H₂O is consumed but KOH is not. In order to maintain H₂O volume, H₂O may be occasionally added from the Water Processing Assembly (WPA). This development effort is a collaboration between NASA and University of Texas Arlington and the current TRL of this system is a 3.

III. Methods

First introduced in 2017¹², and further refined in 2019³, the LSMAC method could be used to evaluate multiple life support technology by assessing the criteria defined in Table 3.

Table 3. LSMAC Criteria Summary.

Criteria	Description
Maintainability	The Maintainability criteria relates to complexity and path-dependency of maintenance and includes two categories: Preventive and Restorative
Risk Analysis	Risk Analysis evaluates the likelihood of budget, scheduling, or development-related technical risks for a given hardware option
TRL	Uses existing NASA TRL scale as basis with an additional level added that correlates to there being a market of options
Radiation	Radiation assesses extent that hardware can shield from or is susceptible to space radiation
Manufacturing Cost	Manufacturing Costs include assembly and fabrication, etc., of one or more units
Reliability	Reliability assesses the parameters that affect the probability of repair or replacement
Human Factors	Human factors looks at subjective and objective criteria related to crew health and comfort
ESM	ESM is calculated based on prior literature
Un-Crewed Ops	UCO assesses hardware states and conditions when a crew is not present

The LSMAC framework defines each of these criteria, provides system scoring guidelines, and allows methods with which to compile a weighted aggregate score that considers all criteria. Weighting for each criterion largely depends on the pertinence of each criteria vis-à-vis mission type and duration. The mix of weight factors is subject to the program objectives, schedules, and resources. A detailed explanation of the LSMAC criteria and how they are applied can be found in Morrow *et al.*³ For the purposes of this trade, minor

Table 5. Mission Scenarios.

Mission Number	Description	Total Crewed Duration (days)
1	Low Earth Orbit Space Station ¹	3650
2	Lunar Surface South Pole (10 x 90 days) ¹³	900
3	Mars Transit/Deep Space Habitat (1100-day, contingency) ¹³	1100
4	Mars Surface (550 days) ¹⁵	550

modifications were made to the original design of LSMAC. Criteria modifications are described in each relevant section below. Four mission scenarios were considered for the evaluation, as shown in Table 5. Mission 1 assumptions were generalized based on the original report for the 1992 head-to-head testing down-select of closed loop life support architecture for Space Station *Freedom*. The trade assumed a 10-year mission with 8 crew and made direct comparisons between technologies for both quantitative and qualitative factors as mentioned above. Assumptions for Missions 2-4 were based on derivations of several studies previously conducted including by the Lunar Architecture Team-2 and Goodliff *et al.*^{13,14,15} The weighting of each LSMAC criteria is highly dependent on the mission scenario. For the purpose of this trade, inputs from twelve systems engineers, technology subject matter experts, and project managers were combined and averaged to achieve a combined sum of weights equal to 100. This was completed for each of the proposed mission scenarios, resulting in the weights shown in Table 4.

Table 4. LSMAC criteria weighting factors for each mission scenario.

Criteria	SSF (10 yr)	Lunar Surface (10 x 90 day)	Mars Transit (1100 day contingency)	Mars Surface (550 day)
Maintainability	10.00	9.50	11.50	11.25
Risk Analysis	8.25	8.00	8.50	8.50
TRL	12.00	8.50	8.50	8.50
Radiation	3.50	8.00	9.00	7.75
Manufacturing Cost	11.25	6.50	5.00	4.50
Reliability	12.75	14.00	17.25	16.25
Human Factors	10.00	7.50	9.50	8.50
ESM	28.50	25.00	26.25	26.00
Un-Crewed Ops	3.75	13.00	4.50	8.75

IV. Technology Analysis

A total of nine technologies were evaluated using the LSMAC technique. Absolute and derived LSMAC scores for each criteria are shown in Table 6. Details of how the technologies were rated for each criteria are provided below.

Table 6. Derived and Absolute LSMAC Scores for all Parameters and Technologies.

Tech	Maintainability	Risk Analysis	Tech Readiness Level	Radiation	Manufacturing Cost	Reliability	Human Factors	ESM	Un-Crewed Ops
ISAB	5.6	See Table 9	9.0	10.0	10.0	7.9	4.8	See Table 11	9.8
HCVD	3.1		3.0	10.0	3.7	5.5	4.8		8.8
CBOS	3.4		3.0	10.0	3.7	6.6	4.8		8.6
SBOS	3.4		3.5	10.0	2.5	5.3	4.8		8.7
ILCF	3.8		3.0	5.0	2.5	4.4	4.8		6.0
ELEC	3.9		2.5	10.0	4.9	3.9	4.8		6.1
PMPA	4.4		3.0	10.0	4.9	4.3	4.5		8.6
VBOS	3.6	See Table 9	5.4	10.0	2.0	7.9	4.8	See Table 11	7.3
DSAB	5.6	Table 9	5.4	10.0	9.0	4.3	4.8	Table 11	9.8

A. Maintainability

The objective of the Maintainability criterion is to rate technologies based on the effort required to keep the hardware operational (Preventive Maintenance) and to bring systems back online after failures (Restorative). In this assessment, Preventive Maintenance was further broken into Frequency and Complexity in an effort to decouple the impacts of each. Table 7 provides an updated breakdown and definition of the modified metric and the relative weights for each parameter and Table 8 provides the absolute and weighted scores for each technology.

Table 7. Modified Parameters for Maintainability Criteria.

Score	Preventive Maintenance		Restorative Maintenance
	Frequency	Complexity	
Weight	25%	25%	50%
10	No Maintenance Required	Autonomous or minimal crew support required, few if any tools, direct access to component, timeline on order of minutes	Can be diagnosed and repaired autonomously
7.5	Yearly Maintenance	(Interpolate)	Simple diagnostics remotely (ground support) with no crew support required; repaired autonomously
5	Monthly Maintenance	Up to 2 crew members required, limited tools, minimal removal/adjustment of "other" components to access maintenance item, on the order of a few hours to complete.	Common or on-orbit manufactured spares; operations restored via repairing or replacing the lowest level component
2.5	Weekly Maintenance	(Interpolate)	Hardware restored with replacement or repair one or more sub-system components; software testing and calibration require crew support
1	Daily Maintenance	2+ crew members required, Multiple tools required, Multiple subsystems/components removed to access maintenance item, Many hours or days to complete	Extensive disassembly/reassembly required, extensive crew involvement

1. Preventive Maintenance

During development of the DSAB, maintenance was assumed to be unnecessary for a flight system. Several years of operation of ISAB on ISS was able to demonstrate the accuracy of that assumption. Accordingly, both systems scored "10" in this metric. HCVD, CBOS, and SBOS all rely on the ability to remove solid carbon in their concept of operations. Due to the quantity of carbon produced from a crew of 4 (over 1 kg/day), it was assumed that a minimum of weekly removal would be required for maintenance. HCVD produces carbon in convenient non-fouling pucks which are removed through some level of external access, while CBOS and SBOS assume vacuum removal of

accumulated carbon (hands-off), likely conducted autonomously. For these reasons, each was given a high score for complexity. VBOS required replacement of catalyst cartridges at ~90 day intervals. Removal required access to the cartridges and some level of exposure to carbon dust. This resulted in mid-range scores for both frequency and complexity.

The frequency of preventive maintenance for ILCF and ELEC are on the order of several months or more and involve recalibration of sensors and measuring and adjusting the concentration of electrolyte and IL.

In both cases, this involves a moderate level of crew involvement. Lastly, MPPA requires annual preventive maintenance that involves replacing the magnetron and redundant carbon filter, and cleaning the outlet tube of any accumulated carbon. This effort involves relatively intrusive access to the system, will require Personal Protective Equipment (PPE) to protect the crew, and may require several hours for completion.

2. Restorative Maintenance

During development of DSAB and VBOS, orbital replacement units (ORUs) with ground support was the baselined maintenance approach and the technologies were scored accordingly. For developmental technologies, the baselined maintenance approach will be autonomous diagnostics and component-level repair or replacement. For each technology, the worst case failure was assumed when rating this parameter. The MPPA and HCVD hardware scored highest in restorative maintenance due to relatively simple sub-systems and components that can be replaced without intrusive disassembly of any critical sub-system. It should be noted that this score assumes redesign of an integrated Sabatier reactor sub-system to accommodate this type of restorative maintenance approach. The ISAB score assumes ISS heritage with no modifications to the design or maintenance interval. Because of the number of valves required for operation of the ILCF, failure or fouling of a reactor will require a relatively complex, multi-component maintenance unit for repair. ELEC received a relatively low score on this parameter due to concerns with KOH as an electrolyte. If the failure was caused by corrosion, extensive replacement of hardware would be required to restore operation of the system. SBOS and CBOS received similar ratings due to the primary catastrophic failure mode of internal blockage due to various causes, including carbon. Both systems would require extensive disassembly of the reactors to mitigate the failures and use of considerable PPE due to carbon hazards.

B. Risk Analysis

The goal of the Risk Analysis criterion is to evaluate the likelihood of budget (independent of the actual cost of manufacturing), scheduling, or development-related technical risks for a given hardware option. Because schedule and budget risks were similar for all technologies assessed, the analysis focused more on the technical risks of each option. Similarly, the consequence of any of the technologies not overcoming their technical risks is that the technology will not be chosen for a mission. As such, each technology was instead evaluated based on the Likelihood of Success in overcoming technical challenges in time for mission flight builds (SSF timeline, 2025 for Lunar Surface, ~2030 for Mars Transit and Mars Surface), with extremely high likelihood scoring a 9, and extremely low likelihood scoring a 1. DSAB and VSAB values were derived based on the described strengths and weaknesses in Table 1. ISAB, which has already been demonstrated on ISS for prolonged periods, has an extremely high likelihood of overcoming technical risks for both Exploration missions. Values for each technology and mission are provided in Table 9.

C. Technology Readiness Level (TRL)

Technology Readiness Level (TRL) measures the development stage of hardware or systems, on a range from “basic principles” to “flight-proven” as defined by NASA procedural requirements for systems engineering.¹⁶ The LSMAC system adds a level beyond “flight-proven,” which corresponds to a market of options or multiple vendors

Table 8. Maintenance Scores for each technology.

Tech	Preventive Maintenance Frequency	Preventive Maintenance Complexity	Restorative Maintenance	Weighted Final Score
ISAB	10.0	10.0	2.5	5.6
HCVD	2.5	7.5	5.0	3.8
CBOS	2.5	10.0	1.0	3.4
SBOS	2.5	10.0	1.0	3.4
ILCF	6.5	6.0	2.5	3.8
ELEC	6.5	7.5	1.5	3.9
MPPA	7.5	2.5	5.0	3.8
VBOS	4.5	5.0	2.5	3.0
DSAB	10.0	10.0	2.5	5.6

Table 9. Risk Analysis Scores.

Tech	SSF	Lunar Surface (2025)	Transit/Mars Surface (~2030)
ISAB	N/A	9	9
HCVD	N/A	4	6
CBOS	N/A	3	4
SBOS	N/A	4	6
ILCF	N/A	2	4
ELEC	N/A	2	5
MPPA	N/A	6	5
VBOS	5	N/A	N/A
DSAB	7	N/A	N/A

existing for a flight-ready hardware. For hardware that consists of several sub-systems of varying TRL, the lowest TRL score is applied for the entire system. For systems that have been demonstrated at a given TRL, but are nearing completion of testing that demonstrates compliance with the next higher TRL, a decimal of 0.5 is applied. VBOS and DSAB were assessed in 1992 with a slightly different metric, thus the observed decimal TRL allocation.

D. Radiation

In the original LSMAC assessment, Radiation criterion assesses two parameters: susceptibility and shielding. In this assessment, none of the technologies was deemed to be significantly different than any of the others in its ability to act as a radiation shield. Therefore, only Radiation Susceptibility was scored. Each technology was assessed based on the sub-systems and did not include considerations for electronics common to all systems (e.g. power supplies, control boards, etc.). Among the options, only ILCF technology was determined to have a possible susceptibility to radiation due to the unknown effects of radiation on the ionic liquids themselves. For this reason, ILCF was scored a “5” while all other technologies were scored “10.”

E. Manufacturing Cost

Manufacturing Cost assesses the relative cost of manufacturing among alternative technologies. The cost does not include research and development (non-recurring) costs in order to make hardware flight ready. The costs include assembly, procurement, fabrication, etc., of one or more copies of the technology. The score for each technology is derived as described previously.³ VBOS and DSAB were evaluated as per Mission 1. All other technologies were evaluated together as options for Missions 2-4. Manufacturing costs were evaluated based on the costs of historical flight demonstrations for similarly scaled life support hardware. Ultimately, the total values related directly to the total rack space (e.g. ¼ rack, 1 rack, etc.) required for each technology implementation.

F. Reliability

Reliability is a more subjective correlated measure that assumes certain hardware characteristics make one hardware technology less reliable than another hardware technology that lacks those characteristics. Of the technologies assessed, none had high pressure components and all had active components that had a high effect on reliability (0 and 1.5 multiplier, respectively). There were minor differences in intake/exhaust vulnerabilities and inherent redundancy, but the most significant variations were due to differences in number of components, as seen in Table 10. Examples of components included key sub-systems (e.g. reactors), heater, valves, pumps, etc., but did not include those items which would be common across all systems and with significant uncertainty on total numbers required (e.g. pressure transducers, thermocouples, etc.). Both ISAB and CBOS had the lowest total number of components and received correspondingly higher scores in reliability. It should be noted that the scores for VBOS and DSAB were calculated only as compared to one another (not the other suite of technologies), and thus can only be evaluated as related to one another.

Table 10. Number of components for each technology option.

Tech	# Components
ISAB	12
HCVD	33
CBOS	20
SBOS	45
ILCF	63
ELEC	46
MPPA	32

G. Human Factors

Human Factors address concerns with how the crew interacts with the hardware. All technologies scored identically to one another with the exception of the MPPA in the “light” parameter where the flicking plasma may affect crew interaction (scored 0.5 vs 1.0 for other technologies).

H. Equivalent System Mass (ESM):

Due to the current uncertainty in mission requirements, ESM (without crew time) was calculated¹⁷ for 1024 binary combinations of maximum and minimum assumptions for 1) hardware mass densities, 2) volume, power, and cooling equivalencies, 3) scaling or no scaling of an integrated oxygen generator and water purification system, 4) failure tolerances, 5) metabolic profile, and 6) water storage penalty. Mass power, volume, and resupply estimates were provided by technology developers. The fidelity of the estimates varied greatly among technologies. The ESM calculations did not consider net surplus water scenarios or scenarios involving additional H₂ production to provide O₂ for extravehicular activities. Such scenarios would reduce the relative ESM of technologies that otherwise recover less O₂ from CO₂.

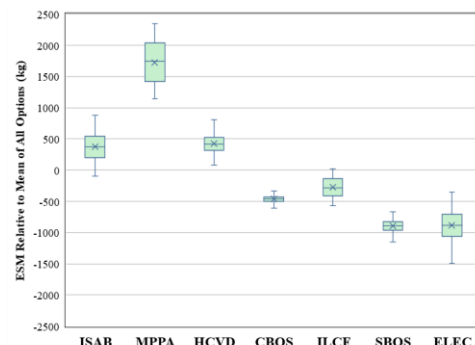


Figure 1. ESM Box and Whisker Plot for Mars Transit.

The result, as seen in Figure 1, is a range of ESM values. For all mission scenarios evaluated here, the average ESM value (shown as an “x” in the box and whisker plot) was used for the derived LSMAC calculations. The ESM for VBOS and DSAB relied heavily on the information from the original trade. A key difference in the assessment for these systems versus the effort in 1992, was consideration for Propulsion effects. When designing for SSF, DSAB had an added benefit in that the venting gases were planned to be used as a propellant. This resulted in a net mass savings to the mission because it reduced the total propellant required to be launched to the vehicle. LSMAC calculations cannot accommodate negative ESM values. Therefore, for the purposes of this analysis, the effect of propellant mass savings was eliminated from the calculation. Because of the significant differences in mass between the VBOS and DSAB, this did not result in a different outcome for the rankings of the two systems. All derived LSMAC scores for ESM can be seen in Table 11.

Table 11. LSMAC Derived Scores for ESM.

Tech	SSF (10 yr)	Lunar Surface (10 x 90 day)	Mars Transit (1100 day, contingency)	Mars Surface (550 day)
ISAB	N/A	5.0	5.0	5.8
HCVD	N/A	4.9	5.0	4.8
CBOS	N/A	5.8	5.9	5.6
SBOS	N/A	6.3	6.4	6.1
ILCF	N/A	5.8	5.7	5.2
ELEC	N/A	6.4	6.4	7.0
MPPA	N/A	4.3	4.1	4.0
VBOS	4.6	N/A	N/A	N/A
DSAB	9.7	N/A	N/A	N/A

I. Uncrewed Operations

The Uncrewed Operations criterion assesses the requirements for implementing and sustaining Uncrewed Operations in a space habitat that must remain dormant for some period of time before or between crewed visits. This area is of particular concern for Mission 2 where the Lunar Habitat will be dormant for months or even years between each 90-day visit, and Mission 4, where the habitat will be dormant on the surface of Mars prior to the arrival of the crew. Of the seven parameters evaluated, both “thermal expansion” and “data monitoring” resulted in very similar scores for all technologies. The parameter “Chemical degradation” was a concern for only ELEC, where potassium hydroxide is used as an electrolyte and may cause significant damage if not properly mitigated during dormant periods. Maximum quiescence was considered indefinite for all technologies except ILCF, ELEC, and MPPA. There is currently insufficient data on the stability of the ILs in ILCF to conclusively determine its score for this parameter. However, based on observations in the laboratory, it is believed that the IL will remain stable for longer than a year (scored 1.5). For ELEC, there are long-term stability questions with respect to the cell stack catalyst and support material (scored 1.5). Finally, membrane embrittlement is an area of concern for the hydrogen separator system used as part of MPPA. The development team has confidence in a one-year total stability, but no data beyond that time frame (scored 1.0). Due to the inherent use and/or production of water for all O₂ recovery technologies, each is susceptible to microbial growth. A common score of 0.8 was assessed for all technologies that require water condensation and separation from its product stream. The two exceptions were ILCF and ELEC (scored 0.5). Each of these technologies requires water flow as a significant characteristic of the fundamental operation of the system and subsequently has significantly more wetted parts. Parameters related to activation and de-activation were scored based on known concepts of operations and varied significantly between technologies.

V. Results and Discussion

The compiled LSMAC scores for all missions are shown in Table 12. A discussion of these scores is provided below.

A. Reassessment of Trade for SSF

In 1992, Sabatier technology was selected to replace Bosch technology as the baseline for Space Station *Freedom* based on a trade that included both objective and subjective criteria. In this assessment, an evaluation of ESM was conducted both with and without considering the effect of propellant resupply. In both cases, DSAB traded significantly better than VBOS. In the LSMAC analysis, DSAB had higher (better) scores than VBOS for all criteria except reliability. VBOS was determined to be less

Table 12. Compiled LSMAC results for all missions.

Tech	SSF (10 yr)	Lunar Surface (10 x 90 day)	Mars Transit (1100 day, contingency)	Mars Surface (550 day)
ISAB	N/A	7.5	7.1	7.4
HCVD	N/A	5.5	5.5	5.5
CBOS	N/A	5.7	5.6	5.6
SBOS	N/A	5.7	5.7	5.7
ILCF	N/A	4.5	4.6	4.5
ELEC	N/A	5.2	5.3	5.5
MPPA	N/A	5.3	4.9	5.0
VBOS	5.0	N/A	N/A	N/A
DSAB	7.3	N/A	N/A	N/A

susceptible to catalyst fouling and, due to multiple reactors in parallel, had the benefit of inherent redundancy. These factors resulted in a better overall score for reliability. A basic sensitivity analysis was conducted on this criteria to determine at what point VBOS would trade better than DSAB based on the importance (weight) of reliability.

To do this, the weight of the Reliability criteria was varied while keeping the relative weights of all other criteria consistent with one another. In the assessment, Reliability was weighted at 12.75% of the cumulative LSMAC score. As can be seen in Figure 2, VBOS only begins to trade better than DSAB when reliability is weighted at >45% of the total LSMAC score. For the purposes of SSF, reliability was not so critical given the readily available access to replacement parts and resupply from Earth.

Overall, both ESM and LSMAC gave consistent results with both each other and with the original trade for Space Station *Freedom*. This gives a level of confidence in the LSMAC approach and further provides an opportunity to evaluate the effect of changes to the relative importance of each criteria for a given mission.

B. Oxygen Recovery Trade

A total of six developmental technologies and state-of-the-art Sabatier technology were traded against one another using both ESM and LSMAC approaches. Technologies were ranked from most favorable (lowest ESM and highest LSMAC score) to least favorable (highest ESM and lowest LSMAC score) for each mission. A side-by-side comparison of each approach can be seen in Figure 3 - Figure 5. For all missions and both approaches, SBOS and CBOS consistently ranked in the top four technologies. ISAB ranked highest in the LSMAC assessment for all missions, but varied from 5th for the Lunar and Transit missions, to 3rd for the Mars Surface mission. ELEC ranked very high in the ESM (1st in both Lunar and Mars Surface missions, 2nd in Transit), but varied between 4th and 6th in the LSMAC assessment. MPPA, HCVD, and ILCF were consistently in the bottom four for both approaches and all missions. A key observation from the LSMAC trade was that ISAB ranked highest for all missions and had significantly higher scores than the other technologies for all criteria except Human Factors, where all technologies had approximately the same score, and ESM, where

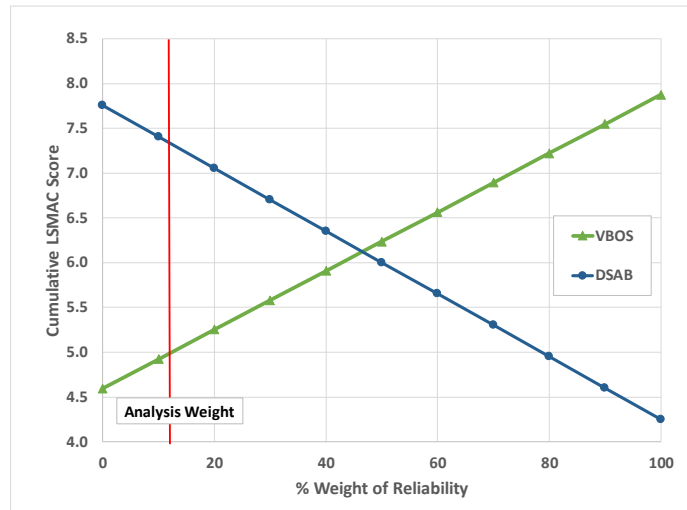


Figure 2. Effect of Reliability weight on Cumulative LSMAC score.

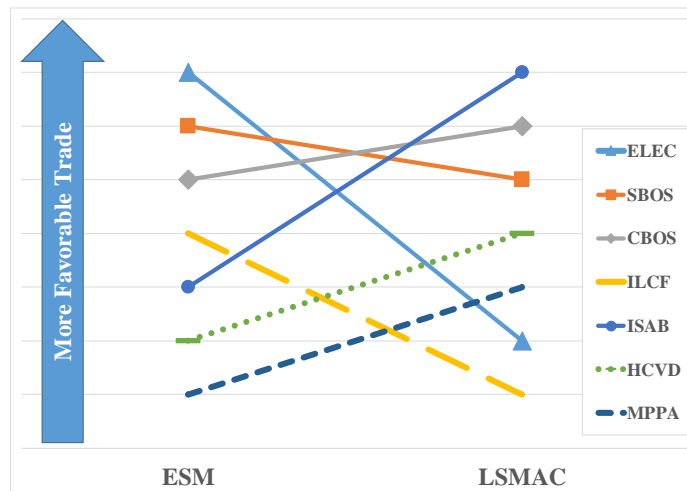


Figure 3. ESM and LSMAC Trade Comparison for Lunar Surface.

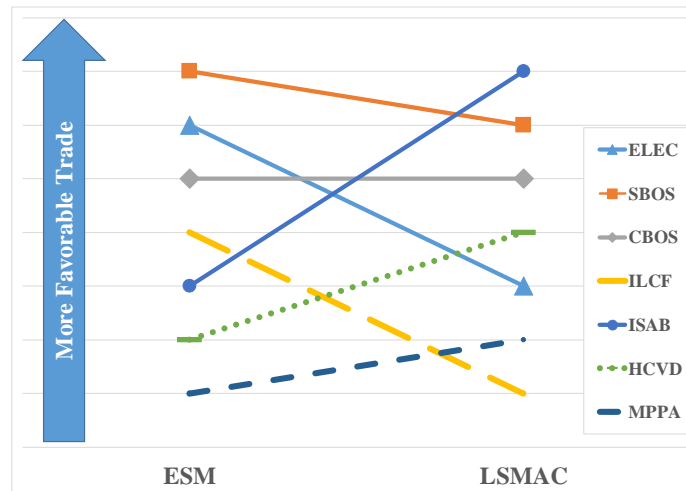


Figure 4. ESM and LSMAC Trade Comparison for Mars Transit.

there was considerable variability among the technologies.

For this reason, a sensitivity analysis was conducted on the weighting factor for ESM to determine how this changed the outcome of the assessment. Similar results were observed for all missions. Data for the Lunar surface mission is shown in Figure 6. As the the ESM weight increases beyond the 25% used for the assessment, considerable changes occur in ranking of technologies. HCVD and MPPA continue to decrease in ranking, following the overall ISAB trend. CBOS remains relatively consistent across all weighting, which is consistent with its ESM being close to the mean of all options. SBOS, ELEC, and ILCF steadily increase in cumulative LSMAC score as the ESM weighting value increases. This graph provides a clear visualization of the considerable impact of evaluating other criteria besides ESM and understanding the relative importance (appropriate weight) of each criteria on specific missions. Finally, the ISAB technology rated consistently high across all LSMAC criteria with the exception of ESM. The Sabatier technology’s limited maintenance requirements, low risk (due to demonstrated flight), its low flight cost due to relatively small size and system simplicity, and the minimum requirements for dormant operations, all contributed to much higher LSMAC values in the assessment. However, additional development and/or demonstrated performance on ISS (or other flight proving ground), could provide better assessments and scoring of the criteria for each of these technologies, thereby potentially changing the overall outcome.

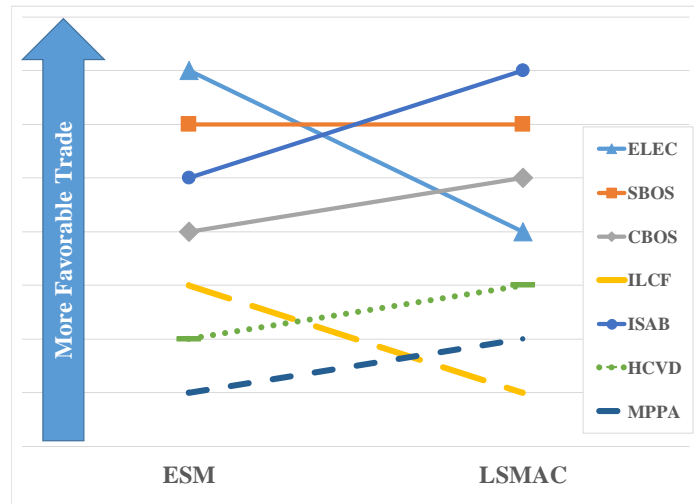


Figure 5. ESM and LSMAC Trade Comparison for Mars Surface.

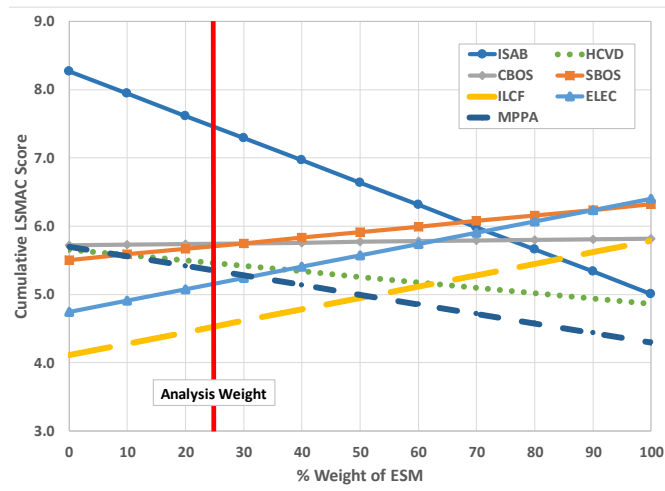


Figure 6. Impact of ESM Weighting on Cumulative LSMAC Scores.

VI. Conclusions

LSMAC was found to result in consistent findings with both an ESM analysis and a historical quantitative/qualitative trade for O₂ recovery in SSF. When used to evaluate development-level O₂ recovery technology options, LSMAC and ESM identified similar top and bottom technologies, but the relative rankings of each changed significantly depending on the weighting values of ESM in the LSMAC study. In this analysis, CBOS and SBOS ranked highly in both analyses and for all missions while HCVD and MPPA ranked among the lowest. Several LSMAC Criteria, including human factors, maintainability, and radiation, were found to have no significant impact on the analysis due to considerable similarities between the technologies.

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