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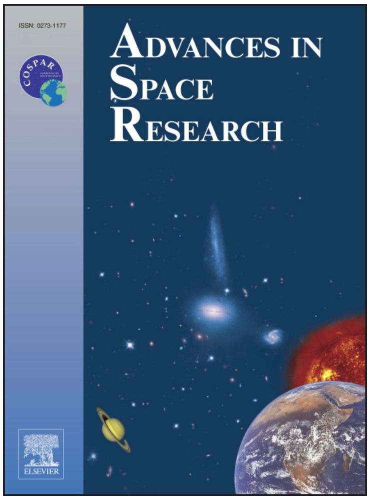

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Reliability versus Mass Optimization of CO_2 Extraction Technologies for Long Duration Missions

The aim of this paper is to optimize reliability and mass of three CO_2 extraction technologies/components: the 4-Bed Molecular Sieve, the Electrochemical Depolarized Concentrator and the Solid Amine Water Desorption. The first one is currently used in the International Space Station and the last two are being developed, and could be used for future long duration missions. This work is part of a complex study of the Environmental Control and Life Support System (ECLSS) reliability. The result of this paper is a methodology to analyze the reliability and mass at a component level, which is used in this paper for the CO_2 extraction technologies, but that can be applied to the ECLSS technologies that perform other tasks, such as oxygen generation or water recycling, which will be a required input for the analysis of an entire ECLSS. The key parameter to evaluate any system to be used in space is mass, as it is directly related to the launch cost. Moreover, for long duration missions, reliability will play an even more important role, as no resupply or rescue mission is taken into consideration. Each technology is studied as a reparable system, where the number of spare parts to be taken for a specific mission will need to be selected, to maximize the reliability and minimize the mass of the system. The problem faced is a Multi-Objective Optimization Problem (MOOP), which does not have a single solution. Thus, optimum solutions of MOOP, the ones that cannot be improved in one of the two objectives, without degrading the other one, are found for each selected technology. The solutions of the MOOP for the three technologies are analyzed and compared, considering other parameters such as the type of mission, the maturity of the technology and potential interactions/synergies with other technologies of the ECLSS.

Keywords: Reliability optimization, long-duration missions, CO_2 extraction, spare parts

4BMS	4-Bed Molecular Sieve
ALiSSE	Advanced Life Support System Evaluator
CDRA	Carbon Dioxide Removal Assembly
ECLSS	Environmental Control and Life Support System
EDC	Electrochemical Depolarized Concentrator
ELISSA	Environment for Life Support System Analysis
ESM	Equivalent System Mass
HPP	Homogeneous Poisson Process
ISS	International Space Station
LiOH	Lithium Hydroxide
MOOP	Multi-Objective Optimization Problem
RELISSA	Reliability ELISSA
SAWD	Solid Amine Water Desorption
TRL	Technology Readiness Level

λ_i	Failure rate of the i-th part type
a_{il}	Contribution of the i-th part type to f_R for a specific spare level s
f_M	Mass function
f_R	Logarithmic reliability function
k	Number of different part types

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L Maximum number of spare parts considered
m_i Mass of parts of the i-th part type
$M_C(t)$ Component Mass
$M_{Cs}(t)$ Component Mass with Spare Parts
n_i Number of spare parts of the i-th part type
N_i Number of parts of the i-th part type
$R_C(t)$ Component Reliability
$R_{Cs}(t)$ Component Reliability with Spare Parts

1. Introduction

The manned space missions carried out since the beginning of the space era have been either short missions (14-days missions to the Moon surface) or long duration missions in Earth "proximity" (400-km Low Earth Orbit). Space agencies and private companies are planning long duration missions to further destinations in the coming decades, with destinations such as an asteroid or Mars, which could have a mission duration ranging from a year and up to three years.

It is well known that mass is a design-driver for any space mission, as the launch cost is proportional to the mission mass. However, not only the actual mass of the technology/component is important, but also, which implication it has, regarding its volume, required power and cooling, and the time the crew will need for operation and maintenance. Therefore, in the last years, the Equivalent System Mass (ESM) system has been used. The ESM translates these parameters in mass, using equivalency parameters, that depend on the mission and the technologies used in other subsystems (Levri et al. 2000, 2003).

However, for long duration missions, due to its distance to Earth, other parameters gain more importance, for example sustainability or reliability. It is necessary to ensure that all systems will work during the entire mission, as resupply or a rescue mission are not considered as an option. An example of it is the ALiSSE (Advanced Life Support System Evaluator) program by the European Space Agency. (Sherpa Engineering, 2015) This tool allows the evaluation and comparison of different ECLSS architectures, considering relevant criteria such as mass, power, energy, efficiency, reliability or risk for humans. This paper focuses in the analysis of one of these parameters, reliability and its influence on the system mass.

In manned missions an Environmental Control and Life Support System (ECLSS) is needed to ensure the required conditions for human survival in space are met. An ECLSS has to fulfill different tasks: oxygen production, CO_2 extraction, water recycling, etc. Several technologies have already been used or are under development to carry out each of these tasks. Several publications (Eckart, 1996; Messerschmid and Bertrand, 1999; Norberg, 2013; Wieland 1998) summarize the different technologies developed in the last years. Each technology has different inputs and outputs, and depending on the technologies selected for a specific ECLSS, synergies will appear within the system. As a consequence, it is necessary to analyze the ECLSS as a whole, both regarding mass and reliability. A methodology to carry out this analysis has been developed, as a PhD thesis, by the main author of this paper (Detrell 2015). The result is a simulation software, *Reliability ELISSA* (RELISSA) (Detrell et al., 2011), based on the ECLSS simulation software from the Institute of Space Systems – University of Stuttgart, ELISSA. In RELISSA, the user can select from a wide range of technologies, with choices according to specific mission requirements. The simulations result is the system reliability, which is estimated using a Stochastic Dynamic Discrete-Event simulation methodology. In order to make this analysis, the reliabilities of each technology need to be estimated. This paper shows how this problem has been addressed with the technologies intended to extract the CO_2 from the atmosphere, and how a methodology can also be applied to technologies in charge of performing other tasks of the ECLSS.

For CO_2 extraction, only two types of technologies have been used so far: the non-regenerable LiOH, and the 4-Bed Molecular Sieve (4BMS). However, many new technologies have been investigated in the last decades. These technologies may offer a lower system mass, and therefore, even if they have not been used in space yet, are potential technologies to be used for future long duration missions. The parameter to evaluate the technology maturity is the Technology Readiness Level (TRL) (Mankins, 1995).

Current studies show that presently used ECLSS technologies reveal a low reliability for long duration missions. (Jones, 2009) Thus, it is necessary to take into account that for such long duration missions, the system will need to be repaired, and as a consequence, replacement parts are needed to be taken. The more replacement parts are taken for each possible part in the system, the higher the reliability of the system, but also the higher the total system mass. As a consequence, it is crucial to find a balance between "desired" reliability and maximum allowable mass.

In this paper, CO_2 technologies are compared regarding reliability and mass. A mission of 1000 days, for a crew of six has been selected. First, the components are analyzed individually to optimize the spares required and then the synergies that may appear with other subsystems are analyzed. The objective of the presented methodology is to provide a mean of comparison at a very initial design phase, in order to select the technology that better fits the requirements for a specific mission. Further studies, providing an absolute value of reliability for the selected component will be required once the design process moves forward.

2. CO_2 extraction technologies

The ECLSS task analyzed in this paper is CO_2 extraction from the atmosphere. Astronauts produce about 1 kg CO_2 per day that would accumulate in the atmosphere. CO_2 in high concentrations is toxic for humans. The maximum allowable CO_2 partial pressure is 1.01 kPa, although higher levels are permitted for limited time exposure (Law et al., 2000). Therefore, it is necessary to have an extracting system, and to ensure it works during the entire mission.

2.1. Selected technologies

The different technologies (in general for ECLSS), can be divided into three groups: non-regenerable, physico-chemical and biological. Different types of technologies can be combined, obtaining thus a regenerative hybrid system (using both physico-chemical and biological technologies).

Non-regenerable options, such as Lithium Hydroxide (LiOH), have been widely used in manned missions, and have proved their robustness. Each cartridge (including structure) weights 7 kg and is able to extract 4 kg of CO_2. (Larson and Pranke, 2000) Considering an average daily production of 1 kg/person, a mission of 1000 days, with a crew of six, would require 10.5 tons of LiOH. Regenerable technologies can reduce this mass considerably. Therefore, the use of non-regenerable systems as the main technology is discarded, and can only be considered as a back-up or system contingency.

In the International Space Station (ISS), today a regenerable technology, the 4BMS, is used. Moreover, two other technologies have been developed in the last decades, which might be used in future long duration missions, the Electrochemical Depolarized Concentrator (EDC) and the Solid Amine Water Desorption (SAWD).

The 4BMS is a technology currently in use, in the American *Carbon Dioxide Removal Assembly* (CDRA) (ElSherif and Knox, 2005) and the Russian system *Vozdukh* (Matty, 2010). Therefore, it is a well-known technology, with a TRL of 8-9. Two molecular sieve beds (of synthetic zeolites) are used alternately to adsorb and desorb carbon dioxide. Two extra beds to extract water from the air are required, as moisture would reduce the molecular-sieve CO_2 adsorption capacity. In the desorption phase, heat and vacuum are required to extract the trapped CO_2. Its main disadvantage is the high mass and power requirement.

The EDC working principle is similar to a fuel cell. Carbon dioxide reacts with oxygen and hydrogen, producing two separate streams, CO_2 and H_2 in the anode side and clean air in the cathode side. Similar to fuel cells, it produces electrical energy. It requires 0.36 kg O_2, 0.05 kg H_2 and produces 0.41 kg water vapor per day per person. This technology is still under development and has a current TRL of 6 (prototype demonstration in a relevant environment). However, its low mass makes it a potential future solution.

The SAWD working principle is similar to the 4BMS. By using granulated amine resin beds, the need of extracting water is eliminated, and thus, reducing the number of beds required. The adsorbing beds need to be humidified, as water reacts with the resin, creating amine hydrates that react with the carbon dioxide, forming bicarbonate. In the desorption phase, a water stream is used, the heat breaks the bicarbonate bond, and the bed gets humidified for the next adsorption phase. Compared to the 4BMS, it requires a lower mass, as only 2 beds and no vacuum are required. However, its TRL is currently 6.

Biological systems can also be used to extract CO_2, using algae and plants. The use of plants requires a high volume of plants (up to 15 - 20 m^2 per Astronaut) (Eckart, 1996), which could also provide enough oxygen and food for the crew, allowing to create a completely closed system. The use of plants poses another challenge, namely to maintain the balance in the closed system. Experiments of a closed environment have been carried out on Earth and small experiments using plants have taken place in space. However, further studies are required, in order to use plants as a full system for an ECLSS. For the mission duration to be analyzed, algae systems have similar mass requirements as physico-chemical systems (Belz et al., 2010). Biological systems have a self-repair ability, which allows them to restore after being damaged (for example after a mechanical failure). (Drysdale, 1996; Gitelson and Lisovsky, 2003) However, they add complexity to the system, as the mechanisms of instability might be less known for space applications.

Although biological systems might be used for future missions, and even required for a human settlement, this paper will focus on physico-chemical technologies, which fit within the type of missions to be studied.

3. Analysis approach

Ideally, to define the reliability of a component, historical failure data for the specific technology used with the same environment conditions should be applied. Space, and specially, manned space missions, are rather unique, and such failure data is not available.

The only possible available data of a regenerative CO_2 extraction technology is for the 4BMS, as it is the only one that has (and currently is) being used in space. Several problems have been reported in the American CO_2 extraction system the CDRA (NASA Spaceflight, 2015). A study on growth rate, analyses the failure rate of the CDRA, using published data from the last decade (Jones, 2014). However, for other components, still in development phase, such information does not exist, and other methods are required, in order to compare the different options.

Providing a component reliability without actually testing and measuring the product capabilities is defined as reliability prediction (European Power Supply Manufacturers Association, 2004). As it assumes that only random failures occur, that the failure of every part will cause a component failure and the failure data used are valid, it does not provide an absolute figure for reliability. A reliability estimation can be used at a first design phase to compare different technology options.

There are four methods generally used to predict reliability for mechanical parts, depending on how the failure data is obtained: a part failure data analysis (use of historical data of the parts of the system), empirical reliability techniques (use of empirical correlation between reliability and different parameters such as dimensions or materials), stress-strength interface analysis (characterization of statistical distributions for stress applied in a part and its strength) and handbook databases (use of generic failure rates of parts in different environments). The required information to carry out the first three methods is not available for the three studied components at this point, and therefore handbook databases will be used.

With this analysis the only failure mode considered is the mechanical failures of the component parts. However, other failure modes might be of even more importance. As the goal of the analysis carried out in this paper is to compare the technologies at a very initial design phase, failure modes that will be common for the three technologies do not play an important role at this stage. For example, the three studied components require power, thus a failure in the power system, will cause a CO_2 extraction failure (independently of the chosen technology). However, the failure of other components in the system may have a different influence in the CO_2 extraction system. Therefore, the synergies with other subsystems will also be discussed.

3.1. Mass and reliability data

From the three selected technologies, only the 4BMS has been used in space, whereas EDC and SAWD have been under development for the last decades. Even for the 4BMS, it is not possible to find a significant amount of failure information to estimate its reliability. Moreover, it is to be considered that the technologies need to be repaired during the mission, and therefore, it will be necessary to split them up in "parts", such as valves, heat exchangers, etc., i.e. in smaller entities for which reliability information can be found in different databases and past studies.

Each of these technologies will be called from now on a system. To study each system, it will be necessary to identify its parts and how they are connected to form the system. The information required for each part will be its failure rate and mass.

A table for each system has been developed (see appendix), including the different type of parts, the required number, and their failure rates and masses.

Information of the system structure has been found in several studies, from the ISS ECLSS (Wieland, 1998), or analysis of the technologies being developed for future missions (Yakut, 1972). Finding reliability data, in this case the parts failure rates, is a complex task. Two different sources have been identified: generic databases, such as the Nonelectronic Parts Reliability Data from the Reliability Information Analysis Center (RiAC, 2015), or space specific studies (Handford, 2004; Jones, 2011; Yakut and Barker, 1968).

3.2. Reliability estimation

The reliability of each component/technology, R_C, can be easily calculated: from the reliability point of view, the three technologies can be considered to be connected in series, as the failure of one of its parts will make the system fail. Therefore, the reliability can be estimated using equation 1 and its mass, M_C, by using equation 2. The parts have been classified in types, each type includes all parts with the same mass, m_i, and the same failure rate, λ_i. Each part type is represented by the sub-index i, being N_i, the number of parts of each type included in the system, and k, the total number of different types of parts.

$$R_C(t) = \prod_{i=1}^{k} e^{-N_i \lambda_i t} \quad (1)$$

$$M_C = \sum_{i=1}^{k} N_i m_i \quad (2)$$

Table 1 shows how the reliability of each component changes over time. It can be seen that for long duration missions (longer than a year), the system will have to be repaired (i.e. parts will need to be changed), as after only a month, the reliability would decrease to 70 - 78%.

Considering the three technologies as non-repairable systems, it can be seen that EDC offers the lowest mass, while SAWD offers the highest reliability. It is necessary to evaluate how mass and reliability change when spare parts are considered.

Table 1. Mass and reliability of the three technologies

		Reliability		
	Mass	at a week	at a month	at a year
4BMS	202.7 kg	93.38%	73.82%	2.8%
EDC	71.9 kg	92.33%	70.24%	1.56%
SAWD	152.6 kg	94.77%	78.82%	6.06%

3.3. Reliability estimation – redundancy

The use of spares can be considered mathematically as having an extra item in parallel, not working until the original one fails. This process is known in the literature as "perfect repair or replacement as good as new". In order to analyze a system formed by one item and its spare items, n is defined as the total number of items required (the original one and $n-1$ spares). This system will fail when all spares have been used and have failed. If this item has a constant failure rate, λ, the failure times are independent and exponentially distributed. (Hoyland and Rausand, 2004

This type of behavior model is called Homogeneous Poisson Process (HPP), and is mathematically defined in equation 3.

$$R(t) = \sum_{j=0}^{n-1} \frac{(\lambda t)^j}{j!} e^{-\lambda t} \quad (3)$$

The repair or replacement can take place at part or component level. The advantage of replacing the entire component is that it does not require a high expertise of the crew on finding the problem and changing the required part. However, the required mass will be extremely high, as for each failure, the whole component would be replaced. As it can be seen in figure Figure 1, 16 spare components would be required in a 1000 days mission, to obtain a reliability higher than 90%. As a consequence, the system mass would be 17 times the mass of a single EDC unit.

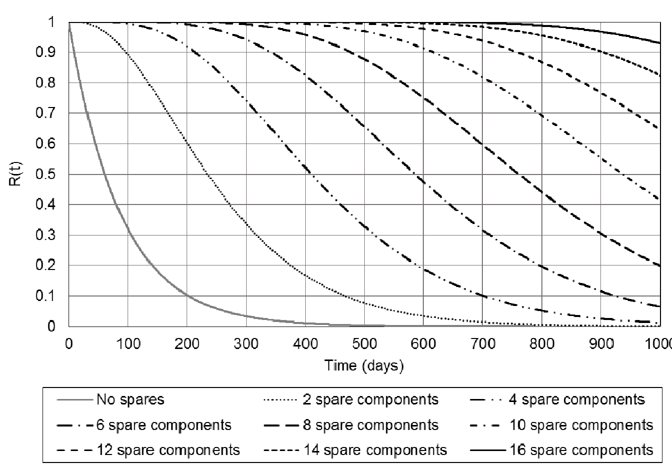

Figure 1. EDC example

As explained before, the studied technologies are formed by multiple parts. Thus, another option would be to take spare parts, to be replaced in the component. The parts of the components are connected in series from a reliability point of view (the failure of a part, implies a failure in the system). Combining equation 1 and 3, the reliability of the system using spare parts (R_{Cs}) is defined and calculated by equation 4. For each part, the number of items (original part plus spare parts) to be used is defined as $\vec{n} = [n_1. n_2. \ldots. n_k]$, with n_i the number of items to be taken for the i-th part.

$$R_{Cs}(\vec{n}; t) = \prod_{i=1}^{k} \left(\sum_{j=0}^{n_i - 1} \frac{(\lambda_i t)^j}{j!} e^{-\lambda_i t} \right)^{N_i} \qquad (4)$$

The number of spare parts required will define the total mass of the system (M_{Cs}), equation 5.

$$M_{Cs}(\vec{n}) = \sum_{i=1}^{k} n_i N_i m_i \qquad (5)$$

From equations 4 and 5, it can be seen that both the reliability of the system and its mass will depend on the number of spare parts to be used for each type of part.

3.4. Spare parts optimization

To obtain a high system reliability, a high number of spare parts will be required, resulting in an increase of system mass. It will be necessary to find a compromise between "desired" reliability and mass.

The number of items to be taken for a specific part, n_i, can take integer values from 1 to infinite, and is a priory independent from the other parts of the system. However, it is important to consider that each part has its specific mass and failure rate. Therefore, it is necessary to find, within the infinite combinations of $\vec{n}$, the combination that maximizes the reliability of the system and minimizes its mass.

The problem to solve is called the Multi-Objective Optimization Problem (MOOP). There are different combinations of spares to be taken for each part, which would be feasible solutions. As both criteria, maximum reliability and minimum mass, cannot be satisfied at the same time, multiple solutions will satisfy that they cannot be improved in one of the objectives, without degrading the other one. Each of this options is called a nondominated solution. The problem will have multiple nondominated solutions; therefore, a decision maker will be required to select the most optimal one for each case.

In order to linearize the problem, the logarithm of equation 4 is used, as it satisfies $\max(R_{Cs}) = \max(\ln(R_{Cs}))$.

$$f_R(\vec{n}) = \ln\big(R_{Cs}(\vec{n}; t)\big) = \sum_{i=1}^{k} N_i \cdot \ln\left(\sum_{j=0}^{n_i - 1} \frac{(\lambda_i t)^j}{j!} e^{-\lambda_i t} \right) \qquad (6)$$

To solve the MOOP, the matrix A, formed by the contribution (a_{il}) to f_R for a specific part and a specific value of $n_i = l$, is found, see equation 7. Theoretically, l can be any integer value from 1 to infinite. However, as the higher the l, the higher is the system mass, l can take, for this study case, values from 1 to 8.

$$a_{il} = \ln\left(\sum_{j=0}^{s-1} \frac{(\lambda_i t)^j}{j!} e^{-\lambda_i t} \right) \qquad \begin{matrix} i = 1,2, \ldots, k \\ l = 1,2, \ldots, L \end{matrix} \qquad (7)$$

To define each combination, it will be necessary to select for each part, which value of l is used, i.e. how many spare parts are used. A binary matrix can be used to define the selected value of l Each row represents a part type, and the columns, the different values l can take.

$$x_{il} = \begin{cases} 1 & if\ n_i = l \\ 0 & otherwise \end{cases} \qquad \begin{matrix} i = 1,2,\dots,k \\ l = 1,2,\dots,L \end{matrix} \qquad (8)$$

As only one number of spare parts should be selected for each part, the addition of each row must equal 1.

Using the parameters defined in equations 7 and 8, the logarithmic-reliability (f_R) and the mass function (f_M) are defined as:

$$f_R(x) = \sum_{i=1}^{k}\sum_{l=1}^{L} N_i a_{il} x_{il} \qquad (9)$$

$$f_M(x) = \sum_{i=1}^{k}\sum_{l=1}^{L} (l \cdot N_i \cdot m_i) x_{il} \qquad (10)$$

The objective is to maximize f_R and minimize f_M. Both requirements cannot be satisfied, in absolute terms, at the same time. Two different type of solutions can be found, providing:

A) the minimum required mass, for a given reliability value
B) the maximum achievable reliability, for a given mass value

In this analysis, for criterion A different values of reliability are used, starting from 0.95, with increments of 0.005.

For criterion B, the initial mass is the one obtained by a reliability of 0.95, with increments of about 15% of the system's mass.

The results for problems A and B are found using the Excel solver.

4. Results

The results of implementing this methodology to the three studied CO_2 extraction components are presented in this section. A discussion of the results, considering further parameters can be found in section 5.

For each studied technology, the methodology presented in 3.4 has been used to solve A and B to find the combination of spare parts.

A) For the criterion A, the required minimum mass to obtain a reliability of at least 0.95 is shown in Table 2. An increment of 0.005 in reliability is used to find the minimum required mass.
B) For the B criteria, the masses shown in Table 2 have been used as initial mass. Increments of 30kg, 10 kg and 23 kg have been used for the 4BMS, EDC and SAWD respectively.

Table 2. Required mass for a reliability of 0.95

	Mass (kg)	Times its mass
4BMS	614.8	3.03
EDC	197.4	2.74
SAWD	457	3

The results are shown in Figure 2, Figure 3 and Figure 4.

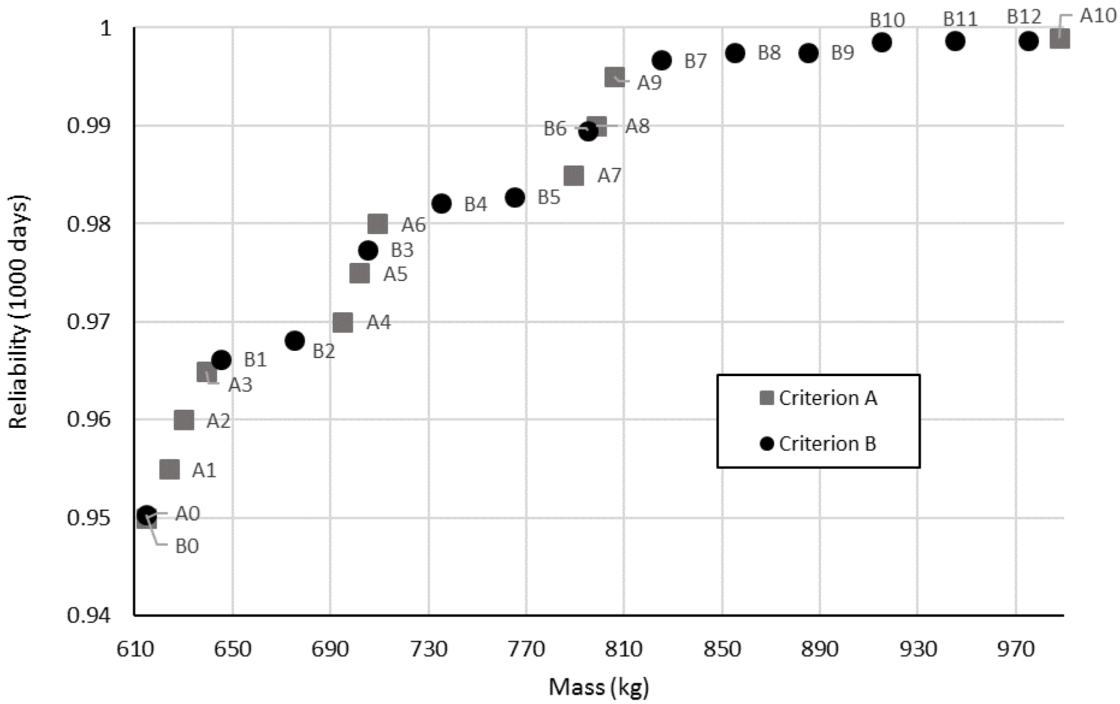

Figure 2. 4BMS mass and reliability optimization results.

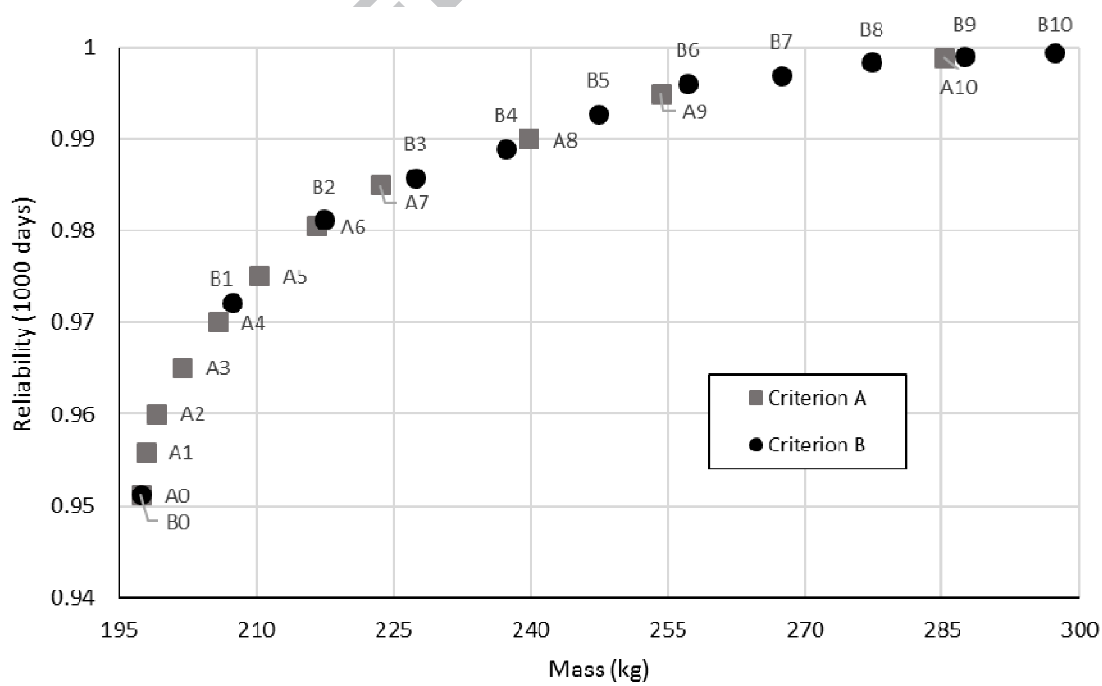

Figure 3. EDC mass and reliability optimization results

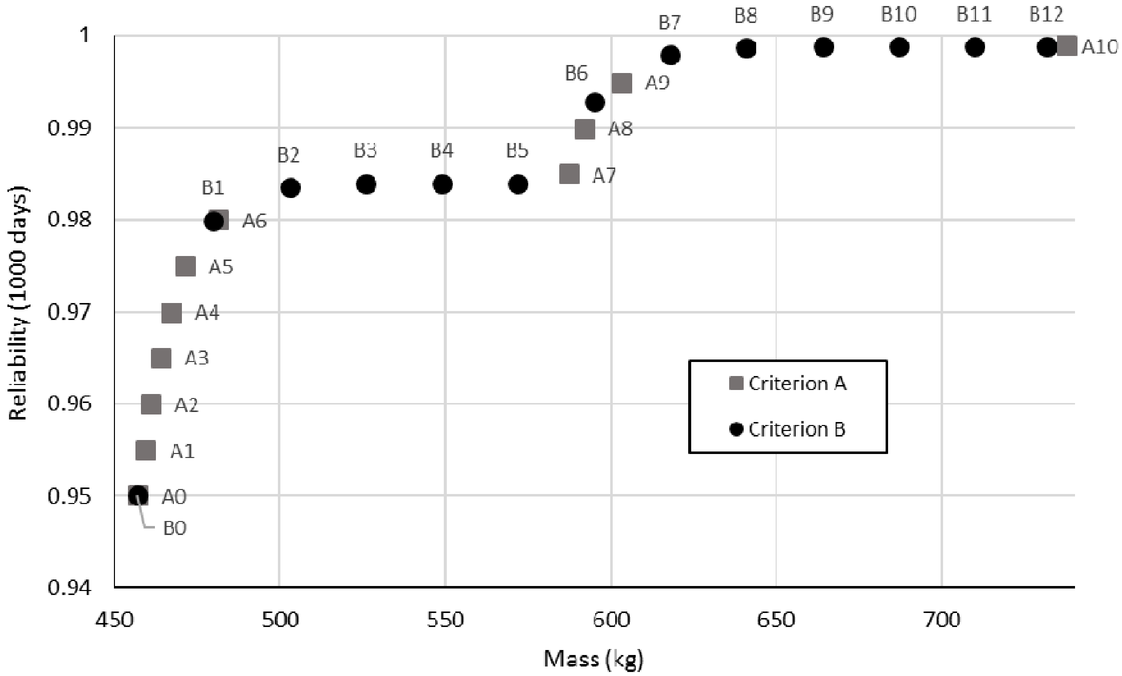

Figure 4. SAWD mass and reliability optimization results

For the 4BMS, Figure 2, the results from criterion A can be separated in four groups: A0 – A3, A4 – A6, A7 – A9 and A10. The results within each group show a small increment in mass, while the groups are separated by high increments of mass.

For example, within the first group the highest mass increment is 9.4 kg, while the difference between A3 and A4 is 55.7 kg. This mass difference between the 4 groups can be explained, as the parts of the system have very different masses. This system has two parts (*i*=11, 12) with a mass 17.3 and 23.6 kg, while the lighter parts of the system (*i*=1, 2, 3, 4) have a mass of 0.1 kg.

Results A0 to A3 consider taking two spare parts of the two heaviest elements, and combine different number of spares of the lightest parts. However, a point is reached where reliability cannot be improved without increasing the spare parts of the heaviest elements. In consequence, results A4 to A6 consider three spare parts of part *i*=11, and 2 of *i*=12.

In the following group, A7 to A9, a spare part of the heaviest element *i*=12 is added. As a result, the mass increment between A6 and A7 is 80.2 kg.

Finally, in A10, to obtain a reliability over 0.999, four parts of the two heaviest elements are required. The spares of both *i*=11 and *i*=12 have incremented, and therefore, the mass difference is higher than in the last two previous cases (181.8 kg).

The results from criterion B follow the same tendency as the results from criterion A.

In the EDC, the difference in mass between the parts of the system is much smaller than in the 4BMS, therefore, the results do not show clearly identifiable groups, as in the previous case. This smooth behaviour demonstrates more clearly than in previous cases that for low reliabilities (ranging from 0.95 to 0.98), a small increment in reliability can be obtained with a small increment in mass. On the other hand, for high reliabilities (over 0.99), a high amount of mass is required to slightly increase the reliability.

The SAWD results present a behavior similar to the 4BMS, where different groups of results can be identified. The SAWD has one part with a much higher mass (30 kg). In this case, A0 to A6 and B0 to B5, consider two spare parts of the heaviest element, and different combinations of the other elements. A7 to A9 and B6 to B12 consider three spare parts of the heaviest element, and finally A10, four spares.

To compare the three technologies, its mass and number of spares required are listed in Table 3, for three different reliabilities at 1000 days.

It is clear that the lowest mass, in all cases, is provided by the EDC technology. However, the number of spare parts required for SAWD, and thus, the number of failures in the system that need to be identified and replaced is lower. The maintenance required for the EDC will be more interventionist than for the SAWD.

Table 3. Mass and number of spare parts for different reliability values

		Reliability at 1000 days		
		0.98	0.99	0.999
CO_2 extraction technologies	4BMS	709 kg 134 spares	799 kg 115 spares	987 kg 167 spares
	EDC	217 kg 132 spares	240 kg 139 spares	285 kg 179 spares
	SAWD	481 kg 109 spares	592 kg 98 spares	738 kg 120 spares

5. Discussion

In all technologies, for low reliabilities (95-98%) a high increment in reliability can be obtained with a low increment in mass. On the other hand, for high reliabilities (over 99%) a high increment in mass is required for a small improvement in reliability.

The 4BMS is the system with a higher technology maturity, with a TRL 8-9. As a consequence, it is the most known technology. However, the required mass for a long duration mission would be between four and five times the system mass. Considering that the technology mass required for a crew of six would be 202.7 kg, the use of other technologies is advisable.

The two potential CO_2 extraction technologies for long duration missions, EDC and SAWD have a TRL 6, which means that some development efforts are still required. However, the reliability versus mass results show their clear advantage compared to the 4BMS.

The SAWD technology has a higher mass than EDC for all reliabilities. For low reliabilities (0.95), SAWD mass is twice the required for EDC, but as reliability increases, the difference between both technologies also increases, being almost 2.6 times higher. However, the SAWD is more efficient, since maintenance needs less intervention, as less spare parts will be required.

The interactions/synergies of the CO_2 extraction technologies with the rest of the ECLSS will depend on the technologies selected to fulfil the other ECLSS tasks, and can therefore be different for each specific mission design. As a consequence, for each mission scenario, the different ECLSS options should be analyzed. However, a first assessment, analyzing the inputs and outputs of each component, can provide a first idea of interaction problems or potential synergies with other systems.

Regarding interaction, the 4BMS requires heat for the deabsorbing phase, the SAWD requires heat to convert water in vapor, and the EDC requires heat rejection. An ECLSS external failure could cause the system to fail. This external failure probability will depend on the design of different subsystem, which will be specific for each mission.

The EDC and the SAWD require consumables to work, and a lack of them would cause the component to stop working. The EDC consumes oxygen from the cabin air (stoichiometric ratio: 0.36 kg O_2/kg CO_2) and hydrogen (stoichiometric ratio: 0.05 kg H_2/kg CO_2), producing water (stoichiometric ratio: 0.41 kg H_2O/kg CO_2). If the EDC is used, the system will be penalized in mass, as more oxygen will be required, hydrogen will be necessary and the water, which will condensate, will need to be recovered. However, a small amount of water can be provided, which in case of a problem with the water recycling system, can ensure a small amount of water per astronaut. The SAWD requires water, which can fully be recovered. It will be necessary for each specific mission and ECLSS design, to see the influences of the consumables required/produced by the CO_2 extraction technology on the rest of the ECLSS system. For example, if an EDC wants to be used but the rest of the ECLSS does not produce an excess of hydrogen, this will need to be provided (the amount will depend on the mission duration), as well as a tank to store it.

6. Conclusions

CO_2 extraction is a crucial task within the ECLSS. For long duration missions, regenerable technologies will be required. Currently the 4 Bed Molecular Sieve is being used in the ISS, but other physico-chemical technologies, still not used in space systems, could reduce the system mass: the EDC and SAWD.

For the technologies still in a development phase, the information regarding its parts and their failure rate are dispersed. Therefore, it has been necessary to develop a table for each studied technology, including the required information to evaluate its reliability, from different sources. They include the different type of parts of the system, how many are required, and its mass and failure rate.

A first analysis of the component reliability shows (see Table 1) that the use of spare parts is required for long duration missions, as otherwise the reliability of the systems at 1000 days is unacceptable. As mass is a key parameter in space systems, a methodology to find the right balance between reliability and mass of the system, i.e. answering how many spare parts should be taken for each part type, is required. The Multi-Objective Optimization Problem is presented for the proposed technologies. The equations to solve this problem have been linearized in order to find nondominated solutions. This methodology provides only a study at a component level but can be further used for other ECLSS components, in order to analyze for each mission, the reliability of the entire ECLSS.

The results obtained (see Table 3) show that for long duration missions the 4BMS can be discarded because the mass is much higher (3.5 times the mass of the EDC), even though the technology is more mature. SAWD is the most efficient technology since the maintenance needs fewer interventions, but its mass is around 2.5 times the EDC mass. The EDC will require oxygen and hydrogen, which will need to be considered in the design of the whole ECLSS for a specific mission. In conclusion, from the mass versus reliability analysis, and looking at potential interfaces, the EDC can offer the best performance, followed by the SAWD. Therefore, it is suggested to investigate and improve them further.

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APPENDIX

Table 4. 4BMS - Parts' mass and failure rate, adapted from Handford (2004); Jones (2011); RiAC (2015); Wieland (1998); Yakut (1972); Yakut and Barker (1968).

4-Bed Molecular Sieve				
i	Description	N	Failure rate (1/h)	Mass (kg)
1	Air check valve	2	6.00E-06	0.1
2	Humidity sensor	1	1.00E-06	0.1
3	Temperature sensor	15	1.00E-05	0.1
4	Sample Port	2	1.00E-05	0.1
5	P sensor	2	1.00E-05	0.2
6	Air Selector Valve	6	1.00E-05	2.6
7	Air Blower	1	8.00E-06	2.3
8	Pre-cooler	1	5.99E-06	2.7
9	Heat exchanger	2	5.99E-06	3.3
10	Pump	1	1.50E-05	9.5
11	Desiccant Bed	4	1.30E-05	17.3
12	Sorbent Bed	4	1.30E-05	23.6

Table 5. EDC - Parts' mass and failure rate, adapted from Handford (2004); Jones (2011); RiAC (2015); Wieland (1998); Yakut (1972); Yakut and Barker (1968).

Electrochemical Depolarized Concentrator				
i	Description	N	Failure rate (1/h)	Mass (kg)
1	Temperature sensor	2	1.00E-05	0.10
2	Combustible gas sensor	1	1.00E-05	0.20
3	Voltage sensor	7	2.33E-05	0.20
4	Current sensor	1	2.14E-06	0.20
5	Humidity sensor	2	1.00E-06	0.20
6	Pressure sensor	2	1.00E-05	0.20
7	Valve quick disconnect	7	1.00E-05	0.23
8	Valve selenoid liquid	1	1.00E-05	0.45
9	Heat exchanger	2	6.00E-06	0.80
10	Valve. electrical	1	1.00E-05	0.91
11	Accumulator	1	5.00E-07	0.91
12	Current controller	1	1.00E-06	0.91
13	Flow sensor	2	1.00E-05	1.00
14	Valve. electric	2	1.00E-05	1.36
15	Valve. relief	1	1.00E-05	1.36
16	Pressure regulator	1	1.00E-05	1.36
17	Valve 4-way	1	1.00E-05	2.00
18	Valve 3-way	1	1.00E-05	2.09
19	Filter	6	5.00E-06	2.09
20	Flow sensor controller	1	1.00E-05	5.90
21	Pressure controller	1	1.00E-05	6.00
22	Pump	1	1.50E-05	6.35
23	Cell	3	3.00E-06	6.80

Table 6. SAWD - Parts' mass and failure rate, adapted from Handford (2004); Jones (2011); RiAC (2015); Wieland (1998); Yakut (1972); Yakut and Barker (1968).

Solid Amine Water Desorption				
i	Description	N	Failure rate (1/h)	Mass (kg)
1	Temperature sensor	4	1.00E-05	0.1
2	Valve shut off, manual	4	1.00E-05	0.2
3	Pressure sensor	3	1.00E-05	0.2
4	Valve 3-way electrical	1	1.00E-05	0.3
5	Valve 3-way electrical	2	1.00E-05	0.9
6	Valve press control	1	1.00E-05	1.0
7	Valve shut off, manual	1	1.00E-05	1.1
8	Valve press relief	1	1.00E-05	1.1
9	Valve shut-off electrical	2	1.00E-05	1.2
10	Valve 3 way manual	1	1.00E-05	1.6
11	Heat exchanger	5	5.99E-06	1.8
12	Valve 4-way electrical	2	1.00E-05	2.0
13	3-way electrical	1	1.00E-05	2.1
14	Blower	1	8.00E-06	6.4
15	Solid desiccant	4	1.30E-05	30.0