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Reliability versus mass optimization of CO_2 extraction technologies for long duration missions

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Abstract

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

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

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Nomenclature

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
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

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