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Axiomatic Design Based Analysis and Equivalent Mass Comparison of Alternate Air Revitalization Systems

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A proposed Photocatalytic Air Processor (PAP) would combine two atmosphere revitalization functions for a crewed spacecraft, carbon dioxide removal and oxygen provision. The axiomatic design method is used to develop the general requirements and alternate system designs that combine these two atmosphere revitalization functions. There are two current atmosphere revitalization approaches. Short missions such as the space shuttle use lithium hydroxide (LiOH) to remove carbon dioxide and tanks to provide oxygen. The ISS (International Space Station) uses the CDRA (Carbon Dioxide Removal Assembly) to remove carbon dioxide and a Sabatier reactor and OGA (Oxygen Generation Assembly) to provide oxygen. The PAP could replace either of these combined systems, LiOH and oxygen tanks or the CDRA, Sabatier, and OGA. Axiomatic design is used to investigate these alternate high level system designs for atmosphere revitalization. The axiomatic design approach develops the requirements and design together from higher to lower system level, using a back-and-forth and top-down process. One objective is to reduce the coupling between design elements, which is a measure of system complexity. The equivalent system mass of the alternate systems is compared.

Nomenclature

CDRA = Carbon Dioxide Removal Assembly
CH4 = methane
CM = crew member
CO2 = carbon dioxide
COPV = Composite Overwrapped Pressure Vessel
DP = Design Parameter
ESM = Equivalent System Mass
FR = Functional Requirement
H2 = hydrogen
H2O = water
ISS = International Space Station
LCC = Life Cycle Cost
LiOH = lithium hydroxide
OGA = Oxygen Generation Assembly
PAP = Photocatalytic Air Processor
SMAC = Spacecraft Maximum Allowable Concentrations

I. Introduction

THE proposed Photocatalytic Air Processor (PAP) provides two atmosphere revitalization functions, carbon dioxide removal and oxygen provision. The axiomatic design method is used to develop the general requirements and alternate system designs for atmosphere revitalization. The PAP could replace the current atmosphere revitalization designs. The space shuttle and other short human missions have used lithium hydroxide (LiOH) to remove carbon dioxide and tanks to provide oxygen. The ISS (International Space Station) uses a CDRA (Carbon Dioxide Removal Assembly) to remove carbon dioxide and a Sabatier reactor and OGA (Oxygen

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Generation Assembly) to recycle carbon dioxide to provide oxygen. A top level block diagram of the ISS air revitalization system is shown in Figure 1.

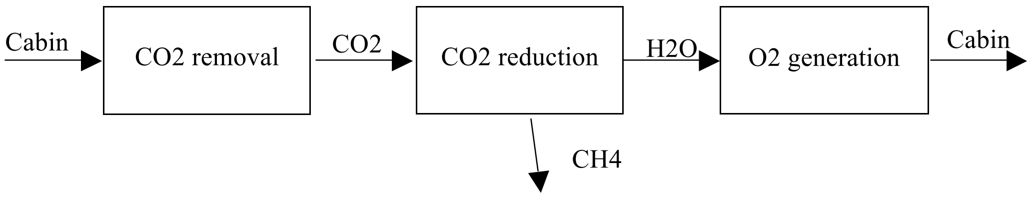

Figure 1. The ISS air revitalization system.

The PAP would use a photocatalytic reaction to directly convert atmospheric carbon dioxide and water to oxygen, methane, and other hydrocarbons. A top level block diagram of the PAP air revitalization system is shown in Figure 2.

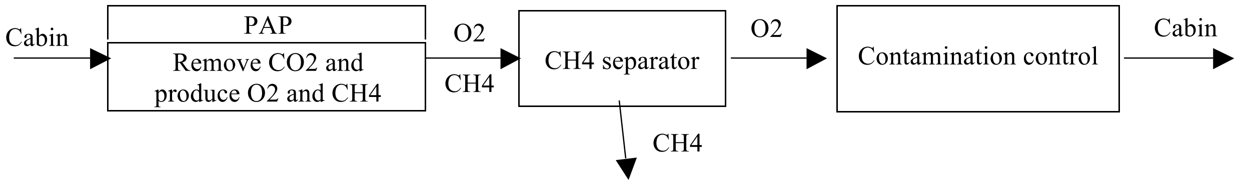

Figure 2. The PAP air revitalization system.

II. Axiomatic design and requirements decoupling

Axiomatic design is used to develop the requirements and alternate high level system designs for atmosphere revitalization. Axiomatic design uses a coupling matrix to control the relations between the requirements and system functions. The axiomatic design approach does not develop the full requirements before the design and independently of the design concept, but rather develops the requirements and design together in a top-down back-and-forth process. This contrasts with the usual approach of developing the complete detailed requirements before beginning the system design. Since it is conceptually difficult to develop requirements without having some design in mind, the usual approach often leads to a design concept that is produced without warning and accepted with little analysis. Axiomatic design is an attempt to formalize and rationalize the design process.

A. The axiomatic design approach

Axiomatic design theory was developed by Suh at MIT in 1990 and has been extended and republished. (Suh, 1990) (Suh, 2001) (Suh, 2005) Its use has been suggested for space life support. (Jones, 2016-82) The recently issued NASA reliability and maintainability standard uses a new approach similar to axiomatic design theory. (NASA-STD-8729.1A, 2017)

Axiomatic design uses a matrix to analyze the transformation of functional requirements (FRs) into design parameters (DPs). This is shown in Figure 3.

$$\begin{bmatrix} FR1 \\ FR2 \end{bmatrix} = \begin{bmatrix} A11 & A12 \\ A21 & A22 \end{bmatrix} \text{x} \begin{bmatrix} DP1 \\ DP2 \end{bmatrix}$$

Figure 3. Functional requirements (FRs), design parameters (DPs), and the design or coupling matrix A.

A functional requirement (FR) is what we want to achieve, what the system must perform. A design parameter (DP) defines how the FRs will be achieved, the key descriptors that characterize the design solution.

The two by two design matrix A indicates that the functional requirement FR1 is satisfied by a combination of design parameters DP1 and DP2. FR1 = A11 DP1 + A12 DP2, and similarly for FR2.

The two axioms of axiomatic design are formally stated as:

Axiom 1: The Independence Axiom. Maintain the independence of the functional requirements (FRs).

Axiom 2: The Information Axiom. Minimize the information content (complexity) of the design. (Suh, 2005)

Axiom 1 seems intuitively correct and very familiar. It is generally understood that reducing interconnections and dependencies can improve reliability and reduce integration and test problems. “(A) separation of a system into noninteracting subsystems is an extremely important technique known to all developed sciences – and to systems theorists as well.” (Weinberg, 1975) “In partitioning, choose the elements so that they are as independent as possible.” (Rechtin, 1991)

Axiom 2 is more difficult to understand and apply. Alternate designs produced using Axiom 1 should probably be compared using the standard systems engineering trade-off approach, considering mass, volume, power, performance, cost, reliability and other factors.

B. Top-down mapping of requirements to design concepts

In the Figure 3 matrix, the functional requirements (FRs) are related to design parameters (DPs) at a single level, but much of the power of axiomatic design is gained by mapping requirements to designs at successively lower levels. Figure 4 shows the FR decomposition process of developing detailed requirements and concepts by moving back and forth, zigzagging, between the functional (FR) and physical (DP) domains.

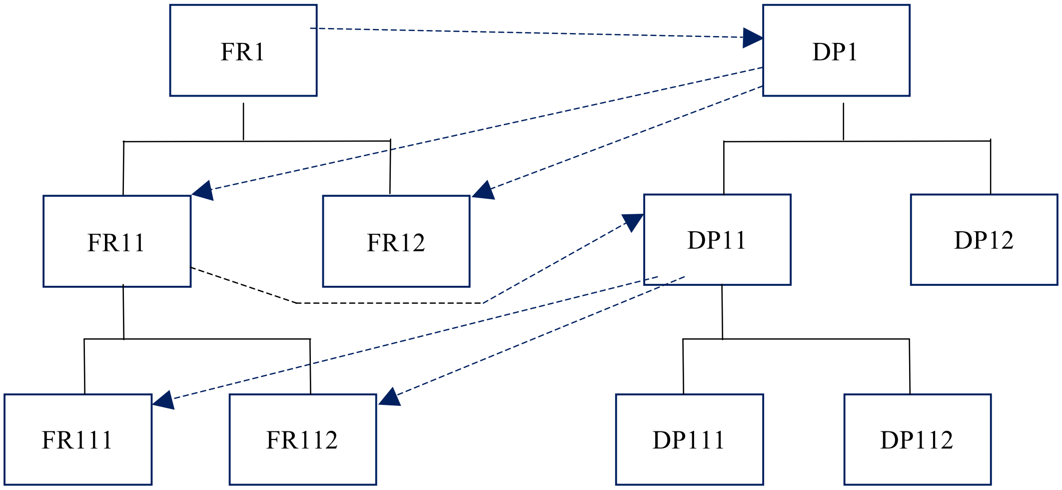

Figure 4. Decomposing FRs and DPs by zigzagging between successively lower system levels.

The axiomatic design process decomposes the highest-level design to develop lower level design details that can be implemented. To decompose the FR and DP one dimensional matrix vectors, we must zigzag between the requirements and design domains. This is illustrated in Figure 4. From FR1 in the functional domain, we go to the physical domain to conceptualize a design as DP1. Then the process comes back to the functional domain to create FR11 and FR12 at the next level down. Together FR11 and FR12 satisfy the highest level FR1. FR11 and FR12 are the decomposed FRs for the highest-level DP1. Then in the physical domain, DP11 is found to satisfy FR11. It in turn is used to create FR111 and FR112 at the third level. The process of decomposition is continued until the lowest-level FRs can be satisfied without further decomposition.

To analyze the design decision, the design equation FR = A x DP is examined at each level of decomposition. For example, in Figure 4, after FR1 and DP1 are decomposed into FR11, FR12 and DP11, DP12, the design equation describes the design concept at this level. At the higher levels of the process, the concept lacks detail, but the design matrix can be examined to see how well it satisfies the first axiom, independence. (Suh, 2005)

C. Design matrix coupling

A design is described as uncoupled, decoupled, or coupled, according to the pattern of zero and nonzero entries in the design matrix. According to the independence axiom, an uncoupled design is best and a decoupled design is not as good, while a coupled design is the least satisfactory. (Suh, 2005) Figure 5 shows the design matrix of an uncoupled design.

$$\begin{bmatrix} FR1 \\ FR2 \end{bmatrix} = \begin{bmatrix} X & O \\ O & X \end{bmatrix} \times \begin{bmatrix} DP1 \\ DP2 \end{bmatrix}$$

Figure 5. Uncoupled design.

An uncoupled design is described by a diagonal design matrix. Each of the FRs is satisfied by a single DP without being affected by any other DP. Figure 6 shows a decoupled design.

$$\begin{bmatrix} FR1 \\ FR2 \end{bmatrix} = \begin{bmatrix} X & O \\ X & X \end{bmatrix} \times \begin{bmatrix} DP1 \\ DP2 \end{bmatrix}$$

Figure 6. Decoupled design.

In this decoupled but not fully uncoupled design matrix, FR1 is satisfied by DP1, but FR2 is affected by DP1 even though it may be largely satisfied by DP2. In the design process, DP1 can be designed independently to satisfy FR1 and then DP2 can be designed to satisfy DP2 while also considering the effect of the existing DP1. Independence is desirable and coupling is to be avoided because with coupling, any change in the design or operation of DP1 will affect the performance of DP2. Also, any problems in designing or operating DP2 may force changes in DP1 that would make it less optimal in meeting FR1. Figure 7 shows a coupled design.

$$\begin{bmatrix} FR1 \\ FR2 \end{bmatrix} = \begin{bmatrix} X & X \\ X & X \end{bmatrix} \times \begin{bmatrix} DP1 \\ DP2 \end{bmatrix}$$

Figure 7. Coupled design.

The design in Figure 7 is fully coupled. Even though DP1 can be designed largely to meet FR1, and similarly for DP2 and FR2, both DPs affect both FRs and the design process must balance their interactions. In the extreme worst case of a fully coupled design matrix, any change in the design or operation of any of the DPs will affect all the FRs. Any later adjustments or failures will perturb the entire system. A fully independent design characterized by an entirely uncoupled design matrix would be best. Meeting the independence axiom requires maintaining the independence of the FRs. In the ideal case, the design matrix is square and the number of DPs equals the number of FRs. A good design must be either uncoupled or decoupled, and therefore, the intended design must have either a diagonal or a lower triangular pattern of entries. (Suh, 2005)

III. Atmosphere revitalization system requirements

The axiomatic design process will be used to consider the design of atmosphere revitalization systems, including the Photocatalytic Air Processor.

A. Level 1 and 2 atmosphere revitalization system requirements

The zigzag design process of Figure 4 is described using a table that shows the top-down process of expanding the level 1 requirement into level 2 requirements and the system design implementation of the different requirements. A table shows the process better than going between one tree for the requirements and another tree with identical structure for the systems as in Figure 4. Table 1 shows the two top levels of atmosphere revitalization requirements and systems. (The levels are indicated by the number of numerical digits in the FR or DP.)

Table 1. Atmosphere revitalization level 1 and 2 requirements and systems

Level 1	Requirement	FR1: Revitalize atmosphere in a space habitat		
	System	DP1: Atmosphere revitalization system		
Level 2	Requirement	FR11: Remove CO2	FR12: Provide O2	FR13: Do not contaminate cabin atmosphere
	System	DP11: CO2 removal system	DP12: O2 provision system	DP13: Contamination control system

There is one level 1 requirement, to revitalize the atmosphere in a space habitat. This requirement is allocated to one level 1 system, the atmosphere revitalization control system. The level 1 requirement is partitioned into three level 2 requirements, which are to remove CO2, provide oxygen, and not contaminate the cabin atmosphere. The three level 2 requirements are allocated to three level 2 systems, the CO2 removal, O2 provision, and contamination control systems. While it helps in clarifying requirements, the main purpose of going back and forth between requirements and systems in the axiomatic design approach is to ensure the maximum decoupling of each requirement from the systems implementing other requirements.

The precise requirements are important. The CO2 removal system may be required to reduce CO2 to about 3,000 ppm as now on the ISS, but much lower levels seem to be desirable. The basic CO2 removal system used on short missions, lithium hydroxide (LiOH), does not allow the recovery of oxygen and produces little contamination. The cabin trace contaminants must conform to the Spacecraft Maximum Allowable Concentrations (SMAC). It may or may not be permissible for the CO2 removal system to dump contaminants into the cabin to be removed by an existing independently designed trace contaminant removal system. If not, then the CO2 removal system must have its own contamination removal system.

B. The coupling of the level 2 atmosphere revitalization requirements and systems

The three atmosphere revitalization system requirements and the corresponding systems are represented by three by one matrices. They are related to each other by a three by three coupling matrix. This is shown in Figure 8.

FRs - requirements		Coupling matrix				DPs - systems
FR11: Remove CO2		X				DP11: CO2 removal system
FR12: Provide O2	=	Provides CO2	X		x	DP12: O2 provision system
FR13: Control contamination		Provides reduced CO2 atmosphere		X		DP13: Contamination control system

Figure 8. Level 2 atmosphere revitalization requirements, systems, and coupling matrix.

The purpose of DP11: CO2 removal system is to meet the CO2 removal requirement FR11, and similarly for the other two systems. These direct requirement-to-system relations are indicated by the X's on the main diagonal of the three by three coupling matrix. If the requirements and systems were completely uncoupled, as is the ideal case, the three-by-three matrix would have only the the diagonal X's and no other entries. As in matrix multiplication, the matrix entries indicate the effect on meeting the requirements, in the left three by one column, that is caused by the design and operation of the systems, in the right three by one column. An off-diagonal matrix entry indicates a coupling, where the design and operation of one system impacts meeting another system's requirement and affects the second system's design and operation. Coupling leads to iterations to refine the design and to complex cascade effects if operations are disturbed.

If oxygen is to be recovered from the carbon dioxide, the carbon dioxide must be provided to the oxygen provision system, shown in the first cell of row two of the coupling matrix. The reduced carbon dioxide atmosphere is provided to and processed by the contamination control system, shown in the first cell of row three. The level 2 atmosphere revitalization systems in Figure 8 are decoupled as in Figure 6, which indicates that they can be designed sequentially, at least in the first iteration. DP11: CO2 removal system is designed first. The compositions of its two output products, concentrated CO2 and cabin atmosphere with reduced CO2, set the requirements for the two downstream systems that process them. Changes may be made to DP11 to ease the design of DP12 and DP13, if the requirements FR12 and FR13 for providing oxygen and removing contamination are operative.

C. The level 3 carbon dioxide removal requirements and systems

Since the level 2 systems are decoupled, initially the level 3 requirements can be developed and the systems can be designed independently. Figure 9 shows the carbon dioxide removal requirements and systems. The system input is cabin atmosphere.

FRs - requirements		Coupling matrix						DPs - systems
FR111: Control intake humidity		X						DP111: Intake humidity control system
FR112: Remove CO2		Input air	X					DP112: CO2 removal system
FR113: Output cabin air	=		Output air	X			x	DP113: Cabin air output system
FR114: Output CO2			Output CO2		X			DP114: CO2 output system
FR115: Input/output H2O		Input/output H2O				X		DP115: H2O input/output system

Figure 9. Carbon dioxide removal requirements, systems, and coupling matrix.

An adsorption carbon dioxide removal system, such as the space station Carbon Dioxide Removal Assembly (CDRA), requires dry air which is produced within the CDRA before carbon dioxide removal. (Wieland, 1994, p. 198) A photocatalyst based system such as the proposed Photocatalytic Air Processor (PAP) system would control and balance the variable input humidity and carbon dioxide for optimum performance. The DP111: Intake humidity control system would require either water input or output. The core carbon dioxide removal process would output two streams, cabin air with reduced carbon dioxide and concentrated carbon dioxide. Here again the systems are decoupled with all interactions below the diagonal and so can be designed sequentially, at least initially.

D. The level 3 oxygen provision requirements and systems

Figure 10 shows the oxygen provision requirements and systems, assuming that oxygen is recovered from carbon dioxide extracted by the carbon dioxide removal system. The simplest from of oxygen provision is simply oxygen stored in tanks.

FRs - requirements								DPs - systems
FR121: Provide/recover H2		X	Provide CH4	Provide H2				DP121: H2 provision/recovery system
FR122: Reduce CO2 & H2 to H2O & C or CH4		Provide H2	X					DP122: CO2 reduction system
FR123: Generate O2 & H2 from H2O	=		Provide H2O	X			x	DP123: O2 generation system
FR124: Decontaminate output O2				Provide O2	X			DP124: O2 decontamination system
FR125: Dispose of C		Provide C	Provide C			X		DP125: C disposal system

Figure 10. The oxygen provision requirements, systems, and coupling matrix.

The current space station carbon dioxide reduction system is Sabatier (the alternate was Bosch). The Sabatier reduces carbon dioxide to water which is later disassociated into oxygen and hydrogen by an electrolysis-based Oxygen Generation Assembly (OGA). The Bosch directly produces water and solid carbon, but the Sabatier produces water and methane, CH4, so the hydrogen in methane must be recovered by pyrolysis for full closure. The carbon is ultimately derived from food and is disposed of. (Wieland, 1994, pp. 200-1) The proposed PAP is expected to produce hydrogen, methane, and other hydrocarbons. The large mass of carbon in the crew-produced carbon dioxide suggests that carbon disposal and perhaps hydrogen recovery will be needed.

The level 3 oxygen provision systems matrix is not decoupled, since there are entries above the diagonal. This reflects the closed loop nature of the combined Sabatier, electrolysis, and pyrolysis process. (Wieland, 1994, p. 200) If, as now on space station, the Sabatier-produced methane is vented into space, half the hydrogen in the water is lost and the other half recovered from electrolysis. If the Bosch process is used, no hydrogen recirculation is needed, and this produces a superior decoupled system architecture. The PAP will produce hydrogen, methane, and other hydrocarbons. Venting them all, not recovering their hydrogen, also produces a decoupled design. However, if hydrocarbons are vented, additional hydrogen must be provided to recover all the oxygen in the crew produced carbon dioxide. Not all the oxygen recovery requirements may apply on a particular mission.

E. The level 3 contamination control requirements and systems

Figure 11 shows the contamination control requirements and systems. The system input is cabin atmosphere after carbon dioxide has been removed.

FRs - requirements								DPs - systems
FR131: Filter particles		X						DP131: Filter system
FR132: Remove organics	=	Air flow	X				x	DP132: Carbon adsorption system
FR133: Remove H2 and CO			Air flow	X				DP133: H2 and CO converter

Figure 11. The contaminant control requirements and systems.

In a typical space station-like application, a trace contaminant control system can remove contaminants directly from unprocessed cabin atmosphere or from the output of the carbon dioxide reduction system. (Wieland, 1994, p. 36) The system can include filtration for particles, activated carbon for high molecular weight organics, and a catalytic converter to eliminate hydrogen and carbon monoxide. (Wieland, 1994, pp. 201-2) The system is sequential flow and decoupled.

The space station trace contaminant control system can remove, as the name implies, small or trace amounts of contaminants. Such a system can handle the output atmosphere from the carbon dioxide removal system but would be totally inadequate to remove the methane and other organic products of a carbon dioxide reduction system.

IV. Atmosphere revitalization requirements tree and system block diagrams

At this point, we have a three level requirements tree corresponding to a high level system block diagram.

A. Atmosphere revitalization requirements tree

Table 2 shows the carbon dioxide control functional requirements (FRs).

Table 2. Atmosphere revitalization functional requirements.

Level 1	FR1: Control CO2 in a space habitat		
Level 2	FR11: Remove CO2	FR12: Provide O2	FR13: Control contamination
Level 3	FR111: Control intake humidity	FR121: Provide/recover H2	FR131: Filter particles
	FR112: Remove CO2	FR122: Reduce CO2 & H2 to H2O & C or CH4	FR132: Remove organics
	FR113: Output cabin air	FR123: Generate O2 & H2 from H2O	FR133: Remove H2 and CO
	FR114: Output CO2	FR124: Decontaminate output O2	
	FR115: Input/output H2O	FR125: Dispose of C	

B. Atmosphere revitalization system block diagrams

The level 2 carbon dioxide control system block diagram with design parameters (DPs) is shown in Figure 12.

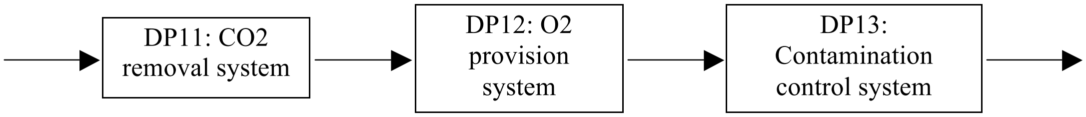

Figure 12. The level 2 carbon dioxide control system block diagram.

Each level 2 system satisfies one level 2 requirement and operates sequentially without feedback loops. The level 3 carbon dioxide removal system block diagram is shown in Figure 13.

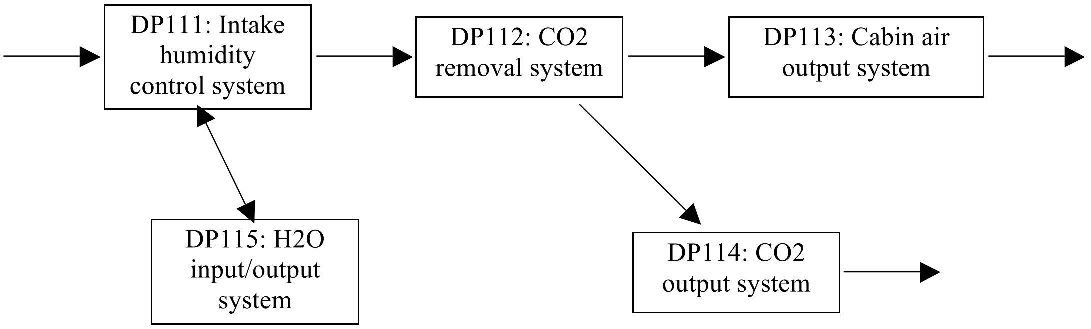

Figure 13. The level 3 carbon dioxide removal system block diagram.

The level 2 DP11 carbon dioxide control system is broken down into five level 3 systems. Each level 3 carbon dioxide control subsystem satisfies one level 3 requirement. All except the DP115: H2O input/output system operate sequentially without feedback or mutual adjustment. The level 3 oxygen recovery system block diagram is shown in Figure 14.

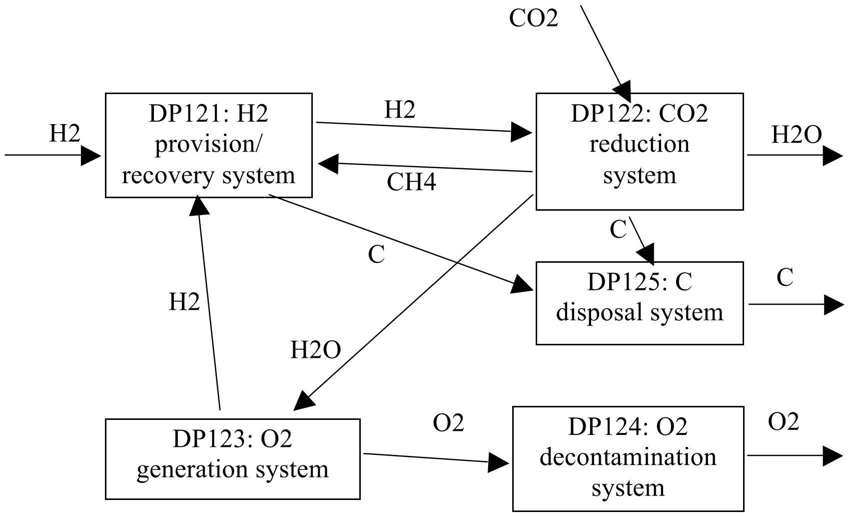

Figure 14. The level 3 oxygen recovery system block diagram.

The level 2 DP12: oxygen recovery system is broken down into five level 3 subsystems. There are multiple possible complex flows between the systems. A Sabatier carbon dioxide reduction system would produce methane that could be used for hydrogen recovery, while a Bosch system would avoid hydrogen recovery, instead directly producing carbon. The level 3 contaminant control system block diagram is shown in Figure 15.

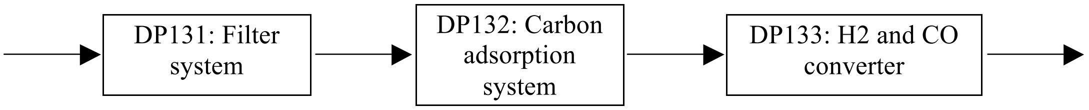

Figure 15. The level 3 contaminant control system block diagram.

In the level 3 contaminant control system, each level 3 subsystem satisfies one level 3 requirement and operates sequentially without feedback loops.

V. Revised Photocatalytic Air Processor (PAP) functional requirements and subsystems

The PAP converts carbon dioxide and water to oxygen and hydrocarbons within a flow of atmosphere, and the hydrocarbons must be separated before the atmosphere is returned to the cabin. The PAP system combines the level 2 functions of carbon dioxide removal and oxygen generation. The chemical coupling of carbon dioxide removal and oxygen generation by photocatalysis prevents decoupling these requirements. The PAP would replace both carbon dioxide removal and oxygen generation in the traditional systems architecture. This is a disadvantage, as it prevents partial or sequential upgrades. The requirements table and block diagram design elements differ from those for the other air revitalization systems.

A. PAP levels 1 and 2 requirements

The PAP requires water input and produces methane and twice the oxygen that is in the processed carbon dioxide. The PAP process works by first splitting water into H2 and O2. The H2 reacts with the CO2, producing CH4 and recovering the O2 in CO2, but another oxygen molecule is produced from 2 H2O. The PAP photocatalytic reaction is 2 H2O + CO2 = CH4 + 2 O2. If the PAP process removes all the crew-produced carbon dioxide, it will deplete humidity and produce more oxygen than the crew can consume.

Due to the different chemical reactions and the production of excess oxygen, the system performance requirements and block diagram change. The level 2 requirements must combine CO2 removal and O2 generation into one requirement served by one system, as shown in Table 3.

Table 3. PAP atmosphere revitalization level 1 and 2 requirements and systems

Level 1	Requirement	FR1: Revitalize atmosphere in a space habitat	
	System	DP1: Atmosphere revitalization system	
Level 2	Requirement	FR11: Remove CO2 and provide O2	FR12: Do not contaminate cabin atmosphere
	System	DP11: CO2 removal and O2 provision system	DP12: Contamination control system

There is one level 1 requirement, to revitalize atmosphere in a space habitat. The level 1 requirement is partitioned into two level 2 requirements, to remove CO2 and provide O2, and not contaminate the cabin atmosphere.

B. PAP level 3 requirements

The level 2 FR11 is broken down into level 3 FRs in Table 4.

Table 4. CO2 removal and O2 provision requirements.

Level 1	FR1: Revitalize atmosphere in a space habitat
Level 2	FR11: Remove CO2 and provide O2
Level 3	FR111: Intake atmosphere
	FR112: Control humidity
	FR113: Remove CO2 and provide O2
	FR114: Separate and vent CH4
	FR115: Remove and provide excess O2

The FRs have been modified to correspond to the functionality of the PAP system. The traditional recycling life support systems architecture includes three separate systems for carbon dioxide removal, carbon dioxide reduction and oxygen generation.

C. The PAP system block diagram

The PAP system combines carbon dioxide removal and oxygen generation. The DP systems corresponding to the FRs of Table 3 and 4 are shown in Figure 16, the PAP system block diagram.

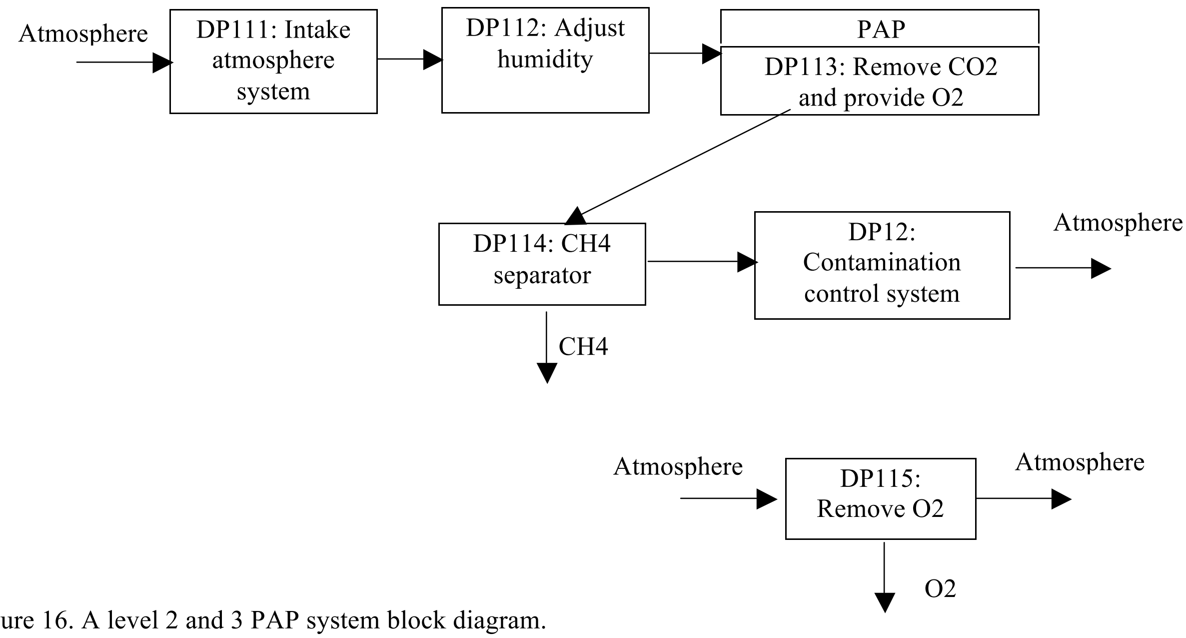

Figure 16. A level 2 and 3 PAP system block diagram.

The level 2 and 3 PAP block diagram indicates some overall system design considerations for the PAP. The PAP requires the correct mixture of carbon dioxide and water, provided by DP111 and DP 112. The PAP DP113 output is a cabin atmosphere stream with carbon dioxide and some water removed by conversion to oxygen and methane. The methane and perhaps other hydrocarbons must be removed from the atmosphere stream by DP114 before atmosphere is returned to the cabin. The atmosphere probably will require further contamination control by DP12. If the methane is vented, hydrogen will be depleted. Hydrogen could be provided either directly or by methane pyrolysis, CH4 = C + 2H2. An additional requirement and block would be needed.

The loss of hydrogen if methane is vented occurs on ISS and is a familiar problem. The current space station atmosphere revitalization approach includes carbon dioxide removal, Sabatier conversion of carbon dioxide and hydrogen to methane and water, and electrolysis generation of oxygen from water. The crew's metabolism of food, obtaining energy from hydrocarbons, produces water as well as carbon dioxide. Recovering all the breathed oxygen requires obtaining oxygen from the crew's exhaled or excreted water.

The most important and novel system design issue for the PAP is that, since it produces far too much oxygen, it does not even approximately reverse the human CO2 producing function. The oxygen the PAP produces includes all the oxygen in the carbon dioxide produced by crew respiration plus another equal amount derived from atmospheric humidity. Water electrolysis is not needed to recycle all the breathed oxygen, but nearly half of the oxygen produced must be recovered and somehow reused.

VI. Applying axiomatic design theory

Axiomatic design theory says to design in steps, top-down, but we already have candidate alternative system designs that have been used on past and current missions. These are:

1. Apollo - O2 tanks and LiOH
2. Skylab and ISS - CO2 removal beds
3. ISS - CO2 removal beds, Sabatier used or with future provision for, oxygen generator
4. ISS additions and alternates - pyrolysis, Bosch
5. Future – PAP and others

Axiomatic design can help track requirements, assumptions, and interfaces. Axiom 1 says to maintain independence of the functional requirements (FRs), but some designs have coupled requirements built-in. The PAP removes CO2 and H2O and produces O2 in a coupled chemical reaction, and a human does the reverse, using O2 to produce CO2 and H2O. The coupling is unavoidable and therefore creates system problems.

VII. Atmosphere revitalization systems Equivalent System Mass (ESM)

The Equivalent System Mass (ESM) is a metric developed to help select life support systems. ESM includes the mass of the system hardware, the mass of spares and supplies, the mass required to provide the structural volume containing the system, and the mass of the power and cooling systems needed to support it.

ESM = Mass of system (kg) + Mass of supplies (kg) + Volume of system (m^3) *
Mass equivalent of volume (kg/m^3) + Power of system (kW) *
Mass equivalent of power and cooling (kg/kW)

The mass equivalent of volume (kg/m^3) depends on habitat construction. 216 kg/m^3 is used for a Mars transit shielded volume. (BVAD, 2015, p. 23) The mass equivalent of power and cooling (kg/kW) depends on the mission location, power source, and cooling method. It is assumed that the power and cooling loads are equal, as is common. 83 kg/kW is used to include Mars transit power and cooling. (BVAD, 2015, p. 23) ESM is appropriate for rough, order-of-magnitude calculations for initial technology selection. Compared to using Life Cycle Cost (LCC) in technology comparisons, the mass or ESM is more favorable to recycling systems than storage systems. Recycling significantly reduces the launch mass on long missions, but recycling systems are much more expensive to develop than storage systems.

A. The ESM of standard air revitalization systems

Table 5 shows the ESM calculations for standard air revitalization components and system configurations.

Table 5. ESM of air revitalization components and systems

Component or system	Variable				Fixed			
	Mass, kg/d	Volume, m^3/d	Power, kW/d	Variable ESM, kg/CM-d	Mass, kg	Volume, m^3	Power, kW	Fixed ESM, kg/CM
Oxygen	0.84			0.84				
Oxygen tank, 0.36 * gas	0.30			0.30				
LiOH	1.75			1.75				
LiOH and oxygen storage				2.89				
Molecular sieve					29.30	0.11	0.18	68.00
Molecular sieve and oxygen storage				1.14				68.00
Oxygen generation					16.10	0.02	0.21	37.85
Molecular sieve and oxygen generation, free water								105.85
Sabatier CO2 reduction					4.50	0.02	0.01	9.65
Hydrogen supply	0.09			0.09				
Hydrogen tank, 0.36 * gas	0.03			0.03				
Molecular sieve, Sabatier, oxygen generation, and hydrogen supply				0.12				115.50
Bosch CO2 reduction					34.00	0.19	0.08	81.68
Molecular sieve, Bosch, and oxygen generation								187.53
Mass equivalents	1	216	83		1	216	83	
Units		kg/m^3	kg/kW			kg/m^3	kg/kW	

The lithium hydroxide (LiOH) and oxygen storage system is suitable for short missions. It includes LiOH canisters that absorb carbon dioxide and oxygen in tanks. Multiple LiOH canisters and oxygen tanks are required.

The mass flows are indicated in kg/crewmember-day, kg/CM-d. Each standard crewmember consumes 0.84 kg/CM-d of oxygen. (Weiland, 1994, p.6) About 2 kg of LiOH is required to remove the 1 kg/CM-d of carbon dioxide. (Eckart, 1996. P. 192) The shuttle LiOH canister weighed 7 kg and was rated at 4 crewmember-days, 1.75 kg/CM-d. The best existing Orbital AKT Composite Overwrapped Pressure Vessel (COPV) weighs 36% of the mass of gas it can contain. (Orbital DS436, 2016) The total LiOH and oxygen storage system mass is 2.89 kg/CM-d.

The ISS uses a four bed molecular sieve, the Carbon Dioxide Removal Assembly (CDRA). The mass, power, and volume data are from Eckart. (Eckart, 1996, p. 185) The molecular sieve can be combined with oxygen storage for atmosphere revitalization.

The four bed molecular sieve can be combined with oxygen generation from water rather than with oxygen provided in tanks. The ISS oxygen generation system uses Solid Polymer Water Electrolysis (SPWE). The system data is given by Carrasquillo et al. (Carrasquillo et al., 1997)

In computing the ESM, the water is assumed to be free. The ISS apparently has excess water, a positive water balance, due to the water provided in the food, 1.15 kg/CM-d, and the water produced by crew metabolism, 0.35 kg/CM-d. (Weiland, 1994, p. 6) Obtaining this water requires purifying the humidity condensate and urine with a water processing system. (Suppose that the water is not free but must be supplied from Earth. Providing 0.84 kg/CM-d of oxygen requires 0.95 kg/CM-d of water. A reasonable estimate is 0.2 kg of tanks per kg of water. (ILO, p. 99) The water plus tanks is then 0.95 + 0.95 * 0.2 = 1.14 kg/CM-d. Interestingly, the mass of oxygen plus oxygen tanks is exactly equal to the larger mass of water plus the smaller mass of water tanks, so it costs exactly the same mass to supply from Earth either the oxygen or the water to produce the oxygen. If all the water for crew oxygen must be supplied from Earth, there is no need for an oxygen generation system, since it is easier to launch the oxygen.)

In the full space station carbon dioxide removal and oxygen recovery system, the carbon dioxide is removed by a four bed molecular sieve, combined with hydrogen and converted to water and methane in the Sabatier carbon dioxide reduction system, and then the water converted to oxygen and hydrogen by electrolysis. The Sabatier mass, power, and volume data are from Eckart. (Eckart, 1996, p. 197) If the methane is vented as is now done, hydrogen must be supplied or the oxygen recovery will be limited.

Considering the hydrogen supply, the Sabatier reaction is CO2 + 4H2 = CH4 + 2H2O. If the methane is lost, 0.09 kg/CM-d of hydrogen must be supplied to completely process the 1.00 kg/CM-d of carbon dioxide. At 0.36 kg of tankage per 1 kg of gas, the tank mass is 0.03 kg/CM-d. Pyrolysis could be used to crack the methane and recover its hydrogen, but Bosch is a more direct and less massive approach to increased closure.

The Bosch reaction is CO2 + 2H2 = 2H2O + C. Water electrolysis then produces oxygen and recovers the input hydrogen. The Bosch mass, power, and volume data are from ARC and Eckart. (ARC, 1990) (Eckart, 1996, p. 195) The final traditional system consists of the four bed molecular sieve, the Bosch carbon dioxide reduction system, and the electrolysis oxygen generator.

The mass equivalents of volume and of power plus cooling are 216 kg/m^3 and 83 kg/kW for a Mars transit shielded volume. (BVAD, 2015, p. 23) It was assumed that the power and cooling loads are equal, although carbon dioxide reduction does produce significant heat.

B. ESM versus time of standard air revitalization systems

Figure 17 plots the ESM of the traditional air revitalization systems versus mission duration for the first 200 days.

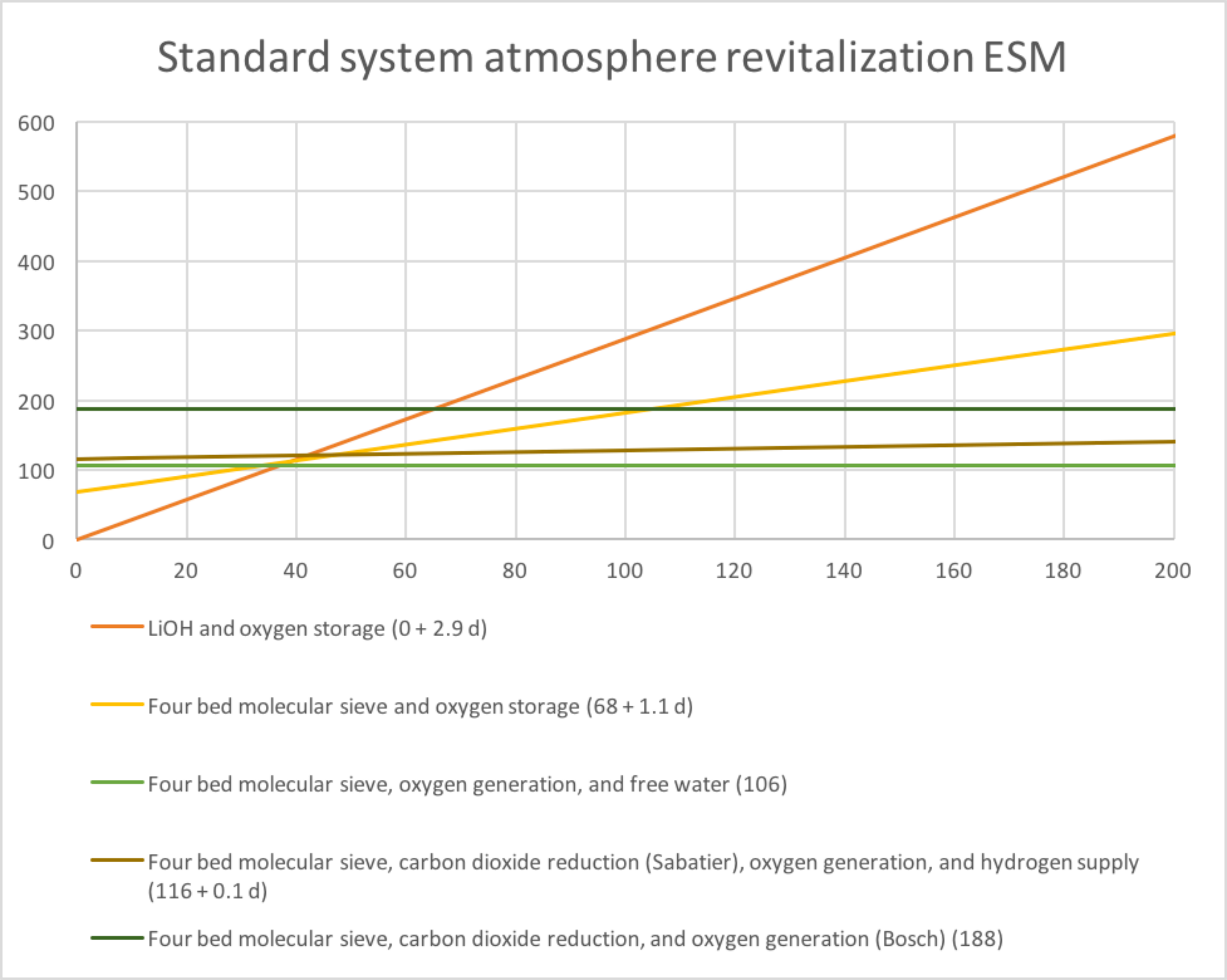

Figure 17. ESM of standard air revitalization systems.

Pure resupply, LiOH and oxygen, has the lowest ESM for missions shorter than 38 days. A four bed molecular sieve with oxygen generation and free water has the lowest ESM for longer missions. For short missions, the initial fixed ESM is the key discriminator between different approaches. For long missions, the daily resupply ESM becomes more important.

VIII. PAP external mass flows and balance

The PAP does CO2 reduction by first splitting H2O. Its external mass flows and balance are determined by its process equation, 2 H2O + CO2 = CH4 + 2 O2. One product O2 is from CO2, the other from H2O. The mass flows are shown in Table 6.

Table 6. PAP process external mass flows and balance.

Mass flow balance, kg/CM-d				
	O2	CO2	H2O	CH4
Crew	-0.84	1.00		
Water system			0.82	
PAP	1.45	-1.00	-0.82	0.36
Excess O2	-0.61			

The crew member oxygen and carbon dioxide mass flows are from Wieland. (Wieland, 1994, p. 6) The metabolic water was slightly adjusted based on oxygen mass balance. An intake humidity control is required to adjust the ratio of water vapor to carbon dioxide.

It is assumed that the water system provides free water. The total PAP oxygen output is 1.45 kg/CM-d, 173 percent of the crew need. It is assumed that the excess oxygen is a useful resource. The output methane is vented and its hydrogen lost.

IX. PAP mass, volume, power, and ESM

The mass, volume, power, and ESM of the PAP level 2 and 3 subsystems is shown in Table 7. This section derives the data for each of the DP's in Table 7.

Table 7. Mass, volume, power, and ESM of PAP subsystems.

	Mass, kg/CM	Volume, m^3/CM	Power, kW/CM	Fixed ESM, kg/CM
DP111: Intake atmosphere	0.5	0.00	0.02	2
DP112: Dry atmosphere	1.8	0.04	0.00	10
DP113: PAP	15.0	0.04	2.24	210
DP114: CH4 separator	16.0	0.09	0.08	42
DP12: Contamination control	50.0	0.15	0.075	89
DP115: Remove O2	4.1	0.01	0.12	16
Totals	87.4	0.33	2.53	369
Mass equivalents	1	216	83	
Mass equivalent units	kg/kg	kg/ m^3	kg/kW	

A. DP111: Intake atmosphere mass, volume, and power

The atmosphere intake mass flow must be sufficient to allow removal of the crew produced carbon dioxide, 1.00 kg/CM-d. At standard temperature and pressure, one mole of gas has a volume of 22.4 liters. Since the atomic weight of carbon dioxide is 44, one mole, 44 grams, occupies 22.4 liters. 1.00 kilogram, the daily crewmember output, occupies 509 liters or 18.0 cubic feet. Since the carbon dioxide is 0.4% of the spacecraft atmosphere, the 1.00 kilogram of carbon dioxide is contained in 4,495 cubic feet of atmosphere. 4,495 cubic feet per day is 3.12 cubic feet per minute per crewmember. A standard oversized blower with 35 cubic feet per minute would have 0.5 kg/CM mass, 0.001 m^3/CM volume, and use 18 W/CM of power, a negligible ESM cost.

B. DP112: Dry atmosphere mass, volume, and power

The water vapor in the air flow must be controlled to the level appropriate for the conversion of the water and carbon dioxide to oxygen and methane. The DP112: Dry atmosphere system will consist of an air dryer. A desiccant air dryer with 25 cubic feet per minute would have 1.8 kg/CM mass, 0.04 m^3/CM volume, and use no power, a negligible ESM cost.

C. DP113: PAP mass, volume, and power

The PAP contributes 210 kg of the total 369 kg ESM, 76 percent. DP113 PAP power ESM is 186 kg, 88% of the DP113 total and 50% of the overall total.

The crewmember production of carbon dioxide is 1.00 kg/CM-d or 21 L/CM/h. The catalyst surface removes carbon dioxide concentrated at 10% at the rate of 5.3 L/m^2-h. The required catalyst area is then 4.0 m^2/CM. The catalyst illumination was 14 mW/cm^2 or 140 W/m^2, pure ultra violet. The required power is then 0.56 kW/CM. The carbon dioxide concentration will be a constant 0.4% instead of 10% declining to 7%. This may reduce CO2 production by one half and increase power by 2. LEDs can be 50% efficient, increasing power by 2. With this fourfold increase, the required power is 2.24 kW/CM.

The PAP volume is a cube filled with small square channels, 1 cm by 1 cm, that are coated with catalyst and illuminated using fiber optics. Volume is estimated at 0.04 m^3/CM and mass as 15 kg/CM, and their ESM is negligible compared to the power ESM.

D. DP114: CH4 separator mass, volume, and power

The PAP air flow process converts a portion of the carbon dioxide at 0.4% of the spacecraft atmosphere to methane at a lower concentration. This low concentration of methane is not flammable and methane is odorless. Methane is usually removed by oxidation in catalytic converters or by pyrolysis, but this would simply convert it back to carbon dioxide, exactly reversing the process that PAP air revitalization implements. No suitable technology currently exists, but theoretical analysis suggests that molecular adsorption of methane is possible. The DP114: CH4 separator is assumed to be a two bed molecular sieve, with 16 kg/CM mass, 0.09 m^3/CM volume, and 0.08 kW/CM power. (Eckart, 1996, p. 185)

E. DP12: Contamination control mass, volume, and power

In addition to methane, the PAP will probably produce a variety of unknown contaminants. A trace contaminant control system can remove contaminants directly from unprocessed cabin atmosphere or from the output of the carbon dioxide reduction system. (Wieland, 1994, p. 36) The system can include filtration for particles, activated carbon for high molecular weight organics, and a catalytic converter to eliminate hydrogen and carbon monoxide. (Wieland, 1994, pp. 201-2). The DP12: Contamination is assumed to be a trace contaminant control system, with 50 kg/CM mass, 0.15 m^3/CM volume, and 0.075 kW/CM of power. (Eckart, 1996, p. 209) (ARC, 1991, p. 346)

F. DP115: Remove O2

The large excess oxygen produced by the PAP process must be removed from the atmosphere and stored for use. Atmospheric oxygen concentrators are common hospital and household items. DP115: Remove O2 can be similar to a commercial single person system, with 4.1 kg/CM mass, 0.011 m^3/CM volume, and 0.12 kW/CM of power. (Oxygen Concentrator Store, 2017)

G. ESM versus time of the PAP and some standard air revitalization systems

Figure 18 plots the ESM of the PAP and three traditional air revitalization systems versus mission duration for the first 200 days.

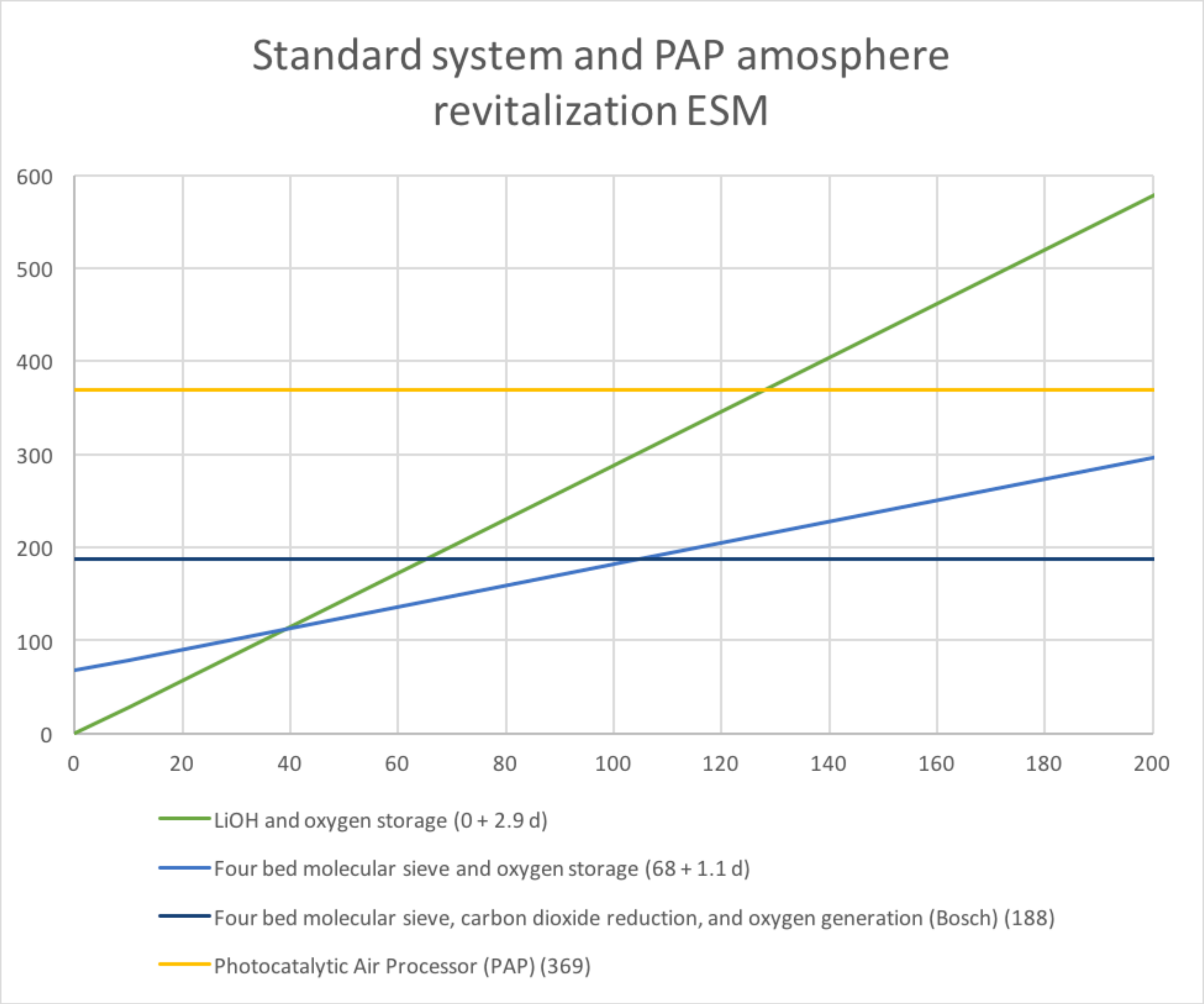

Figure 18. ESM of the PAP and traditional air revitalization systems versus mission duration.

While the PAP has lower ESM than LiOH and oxygen resupply after 127 days, its fixed ESM of 369 kg is higher than the fixed ESM of all the standard air revitalization systems. 186 kg of the PAP ESM is due to its 2.24 kW power and cooling requirement. Producing the light required for photocatalytic conversion requires high power, even with monochromatic LEDs and fiber optics. The ESM for the standard systems is based on early prototypes and is significantly lower than for flight systems. This was considered appropriate for comparison to the PAP, since the PAP is at an even earlier conceptual stage.

X. Conclusion

ESM is appropriate to compare technology at the conceptual or preliminary design stage. It provides only a rough order of magnitude indication of the relative mass and launch cost of systems. More detailed systems analysis and comparison should use life cycle cost, which includes development and operations costs as well as launch cost. With the recent dramatic reduction in launch cost, reducing system mass now has much lower priority.

ESM correctly and usefully indicated the problem of high initial ESM for the PAP and the reason for high ESM in the PAP use of significant electrical power. The photocatalytic conversion of water and carbon dioxide to oxygen and organics is energy inefficient. Improving the quantum efficiency is the main objective of current research in artificial photosysthesis.

The systems engineering analysis of the PAP used the requirements development and implementation process of axiomatic design. This showed that the photocatalytic reaction implemented by the PAP did not conform to the standard ISS life support architecture. The PAP would replace two standard subsystems, carbon dioxide removal and oxygen generation, and combine their functions in an inconvenient way. The PAP, by producing oxygen from both carbon dioxide and water, produces nearly twice the crew required oxygen. By replacing carbon dioxide by methane in the processed atmosphere flow, the PAP would require an innovative methane removal system using unexplored technology.

The PAP research suggests interesting opportunities. It has stimulated the investigation of more efficient photo catalysts which are needed to reduce power. The original system concept used sunlight directly, which would reduce cost and allow the use of less efficient catalysts. The PAP would have higher safety and lower temperature and pressure than standard systems and would have fewer parts and so probably require less maintenance.

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