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Design Rules for Life Support Systems

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Abstract

This paper considers some of the common assumptions and engineering rules of thumb used in life support system design. One general design rule is that the longer the mission, the more the life support system should use recycling and regenerable technologies. A more specific rule is that, if the system grows more than half the food, the food plants will supply all the oxygen needed for the crew life support. There are many such design rules that help in planning the analysis of life support systems and in checking results. These rules are typically if-then statements describing the results of steady-state, "back of the envelope," mass flow calculations. They are useful in identifying plausible candidate life support system designs and in rough allocations between resupply and resource recovery. Life support system designers should always review the design rules and make quick steady state calculations before doing detailed design and dynamic simulation. This paper develops the basis for the different assumptions and design rules and discusses how they should be used. We start top-down, with the highest level requirement to sustain human beings in a closed environment off Earth. We consider the crew needs for air, water, and food. We then discuss atmosphere leakage and recycling losses. The needs to support the crew and to make up losses define the fundamental life support system requirements. We consider the trade-offs between resupplying and recycling oxygen, water, and food. The specific choices between resupply and recycling are determined by mission duration, presence of in-situ resources, etc., and are defining parameters of life support system design.

Design Rules for Space Life Support Systems

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ABSTRACT

This paper describes engineering rules of thumb for life support system design. One general design rule is that the longer the mission, the more the life support system should use regenerable technologies and recycling. A more specific rule is that, if plants supply more than about half the food, the plants will provide all the oxygen needed by the crew. There are many such design rules that can help in planning the analysis of life support systems or in assessing design concepts. These rules typically describe the results of steady state, "back of the envelope," trade-off calculations. They are useful in suggesting plausible candidate life support system designs or approaches. Life support system engineers should consider the basic design rules and make quick steady state calculations as a guide before doing detailed design.

INTRODUCTION

The life support system is constrained by the mission objectives and the requirement to sustain human beings in a closed environment off Earth. The need to provide the crew air, water, and food defines the most fundamental material flows in the life support system. The specific choices between resupply and recycling of oxygen, water, and food are determined by mission duration, presence of in-situ resources, etc., and are defining parameters in life support system design.

After considering general systems design rules and the usual life support systems architecture, this paper presents design rules for life support systems. Most rules will be familiar and obvious to experienced life support engineers and analysts and are stated briefly. Some rules, for instance that mass should be minimized for planetary missions but not for Earth orbit, are less familiar and require more explanation. These design rules were collected to help life support engineers and mission planners anticipate the results of deeper, more thorough analysis.

Human needs and mission objectives together determine the requirements of the life support system. The system design objective is to provide life support while optimizing performance, safety, risk, and cost. Technology and systems integration issues limit the system design options.

The design rules are presented under the following headings:

1. General systems design
2. Life support system design
3. Human metabolic needs
4. Hygiene water requirements
5. Atmosphere losses
6. Mission parameters
7. Systems integration and recycling
8. Hardware and technology

All the design rules are listed in an appendix.

GENERAL SYSTEMS DESIGN

There are important general rules governing the design of any system.

The fundamental system architecture is decided very early in any project. Mission definition and the high level trades conducted during or before phase A determine 70 to 90 percent of a project's system performance and cost. (Wertz and Larson, p. 230) (National Academy Press, App. C) In software development, all the big mistakes are made the first day (Rechtin, p. 48)

Start with a good system design.

How is it possible to start with a good design? The project should include experienced managers, systems engineers, life support designers, and analysts. Without the right experience, people ask the wrong questions and solve the wrong problems.

Include experienced people.

The proposed system architecture should be compared to previously flown systems and to alternative concepts. The designers should ask, "What is different and why?"

Understand earlier and alternate designs. Focus on differences and choices.

All design decisions must be orchestrated to advance a few key mission objectives. (Rechtin, p. 76) (Aslaksen, p. 145)

Design top down from the major mission objectives.

The sooner a problem is found, the easier and cheaper it is to fix. The cost of repair can increase an order of magnitude for problems found at the next higher system level or in the next later mission phase. (Rechtin, p. 148)

Review the system design frequently. Find the problems early.

Each life support engineer should consider the system-wide and mission level impacts of his or her design choices. We should all be aware of integration issues and respond to the needs of engineers designing interfacing subsystems.

Everyone should think like a systems engineer.

Managers of a single mission phase or engineers in charge of one particular subsystem might optimize only within their own limited area of responsibility. They may ignore externalities, push requirements across the interfaces into other areas, and hoard their own reserves and margins. They may not think like systems engineers. Suppose a manager is responsible for all life support system design and development, but not for launch and not for operations. This system development manager may not minimize mass to cut launch costs, or provide recycling to reduce resupply, or do integrated testing to prevent operational surprises. He may not have the knowledge, resources, or motivation to consider mission wide impacts. Mission management must define requirements, mandate testing, and allocate funds to ensure optimally attaining the mission objectives.

Mission management must ensure the mission objectives are achieved.

The life support system exists to provide the required performance, but it must do so with reasonable cost and risk. Cost, risk, system availability and safety analysis are necessary elements of systems design.

Design must consider cost, reliability, availability and safety.

The requirements are difficult, the environment is hostile, and success can not be guaranteed even by the most strenuous efforts. The design approach must focus on necessities to make success as likely as possible.

Costs will be high. Systems will fail. Lives will be at risk.

Life support design must be simple, practical, and austere.

Extreme requirements increase system complexity and cost. They should be challenged up front and even at later stages of design. (Rechtin, pp. 45-6)

Reduce requirements as much as possible.

Cost and failure rate both increase with parts count. (Rechtin, pp. 19, 127)

Simplify the design as much as possible.

The greatest performance leverage is at the interfaces. So is the greatest danger of error or failure. (Rechtin, pp. 29, 107, 89)

Focus on subsystem interfaces.

Automation is a powerful way to enhance system performance. It should be used to the extent it is cost effective.

Embed digital computers, communication, control, and human interfaces into the system.

Advanced information tools and methods make possible computer-aided concurrent systems development. We can track requirements, perform systems level engineering, do trade-offs, test interface specifications, and simulate integration and operations entirely by computer.

Use computer design tools.

System design requires making trade-offs between conflicting objectives involving performance, schedule, and cost. Every design has its drawbacks. Avoiding the worst potential problems may determine the final design choice. (Rechtin, pp. 57, 269, 272)

No one design can optimize all mission objectives.

Performance, schedule, and cost are interrelated. Any two bound the third.

Better, faster, cheaper? Pick two! (Rechtin, p. 139)

LIFE SUPPORT SYSTEM DESIGN

The life support system is designed to satisfy human requirements reliably and safely in the mission environment. We can think of the human, the life support system, and the mission environment as three expanding concentric circles, as shown in figure 1.

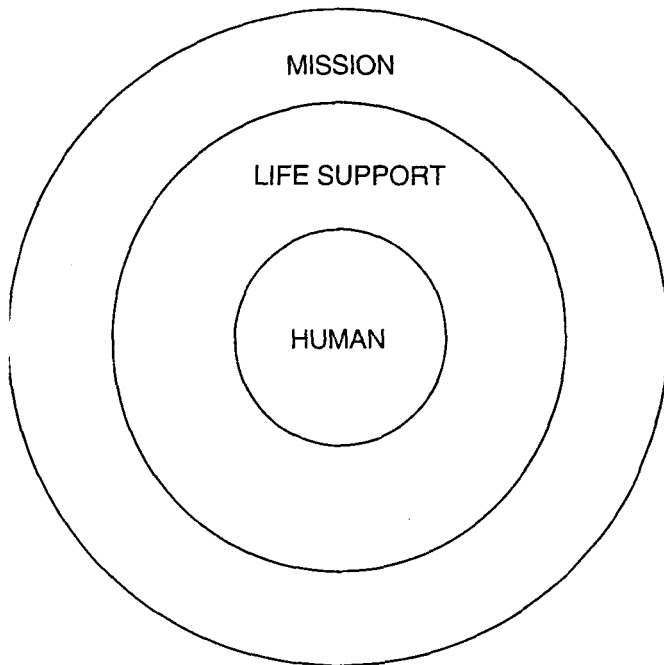


Figure 1. The human, the life support system, and the mission environment.

Between the human and the mission environment, we must provide the buffer of a life support system. The requirements of the life support system are determined by human metabolic needs and by the mission parameters. The optimum system design must accommodate human physiology in the hostile environment of the mission with the best balance of performance, safety, reliability, and cost.

The human requires air, water, food, an environment with proper temperature and pressure, waste removal, and hygiene facilities. Human biology constrains and interconnects the resulting mass and energy flows. Human metabolic needs define the major system requirements.

The mission objectives require humans in space and determine the environment in which they must be supported. The mission can be described in terms of its crew size, duration, destination, vehicle and base design, and planned operations. The mission destination determines transportation cost, travel time, resupply delay, operational environment, possible contamination, and *in situ* resources. The vehicle and base design determine the cost of system mass, power,

and volume and the atmosphere leakage. The planned operations determine the amount of Extra-Vehicular Activity (EVA). (Doll and Eckart, pp. 562-3) (Eckart, p. 83)

The human needs and mission objectives determine the life support system definition, including functions, architecture, subsystems, and interfaces. The design typically has functional subsystems to provide one particular human need (oxygen, water) or to treat one particular human waste (carbon dioxide, wash water).

The seven life support subsystems in the designed configuration of the US Orbital Segment of the International Space Station (ISS) are Atmosphere Control and Supply (ACS), Atmosphere Revitalization (AR), Fire Detection and Suppression (FDS), Temperature and Humidity Control (THC), Vacuum System (VS), Water Recovery and Management (WRM), and Waste Management (WM). The hardware components of these life support subsystems are listed in Table 1 below. (Carrasquillo, Reuter, and Philistine) Wastewater is recycled, but carbon dioxide is not. Excess water from the Space Shuttle is stored in the WRM and used to generate oxygen by electrolysis in the OGA.

Table 1. ISS life support subsystems and components

Subsystem component
Atmosphere Control & Supply (ACS)
Oxygen and Nitrogen Tanks
Pressure Control Panel (PCP)
Airlock Pump
Atmosphere Revitalization (AR)
Carbon Dioxide Removal Assembly (CDRA)
Trace Contaminant Control (TCC)
Major Constituent Analyzer (MCA)
Oxygen Generator Assembly (OGA)
Airlock Carbon Dioxide Removal Unit
Fire Detection & Suppression (FDS)
Portable Fire Extinguisher
Smoke Detector
Temperature and Humidity Control (THC)
Common Cabin Air Assembly (CCAA)
Intermodule Ventilation (IMV) Fan
Intermodule Ventilation (IMV) Valve
Filter Assembly
Avionics Air Assembly (AAA)
Vacuum System (VS)
Water Recovery and Management (WRM)
Water Processor Assembly (WPA)
Water Quality Monitor
Urine Processor
Condensate Tank
Fuel Cell Water Storage
Waste Management (WM)
Commode/Urinal

Life support subsystems are defined by function – oxygen generation, carbon dioxide removal, wastewater processing, etc.

These functional life support subsystems are used on ISS and similar subsystems were used in previous missions. (Wieland, pp. 2281-8)

The basic architecture of life support systems is stable.

It is difficult to change several parts of a complex system at once. Each intermediate stage of system design must be functional, reliable, and safe. (Rechtin, p. 91) A new fundamental design approach, such as replacing physico-chemical technologies with biological ones, will be easier to accomplish one subsystem and one function at a time.

Life support systems will probably evolve one subsystem or component at a time.

Human metabolic needs, hygiene water requirements, atmosphere losses, mission constraints, system integration and recycling, and technology all restrict life support system options and impose specific design rules. Next, we consider rules resulting from human physiology.

HUMAN METABOLIC NEEDS

The basic life support commodities in order of urgency of supply are oxygen, water, and food. Humans require these resources to support human metabolic needs. They produce waste outputs (carbon dioxide, urine, feces, etc.) which must be removed while maintaining environmental control.

The standard crewmember daily metabolic requirements for oxygen, food, and drinking water are shown in Table 2 below. (Wieland, p. 6) (Reed and Coulter, p. 122) Hygiene water is considered in the next section.

Table 2: Standard crewmember oxygen, food, and water needs.

Standard crewmember needs	kg
Oxygen	0.84
Food solids	0.62
Water in food	1.15
Food preparation water	0.76
Drinking water	1.62
Total oxygen, food, and water mass	4.99

The requirements of Table 2 are based on an average metabolic rate of 2,677 Calories (kcal) per person per day and a respiration quotient of 0.87.

A crewmember requires about 5 kg (11 lbs) of drinking water, hydrated food, and oxygen per day.

Water for drinking and food preparation dominates. The 5 kg is roughly 1/2 water, 1/3 hydrated food, and 1/6 oxygen.

Including the water in food, water is 71 percent of the mass. Oxygen is 17 percent and food solids are 12 percent.

Dehydrating food can reduce food resupply mass by 2/3.

Human physiology imposes a fixed relation between the oxygen and food consumed and energy production. One gram of carbohydrate yields 4 Calories, as does protein, while one gram of fat gives 9 Calories. A diet with 10 percent fats provides 4.5 calories per gram, and a diet of 30 percent fats provides 5.5 calories per gram.

Food solids provide about 5 Calories per gram.

Carbohydrate yields 3.8 Calories per gram of oxygen consumed, protein 2.6, and fat 3.1.

Respiration produces about 3.4 Calories per gram of oxygen consumed.

CALORIE NEEDS - The calorie requirement for an average adult American man weighing 79 kg is 3,402 Calories, and for an average adult woman weighing 63 kg is 2,547 Calories, based on the level of physical activity described below. (Jones) The male-female average calorie requirement is then 2,975 Calories. This is about 10 percent more than for the standard crewmember of Table 2, since the weight and physical activity assumed here are higher. The food solids and oxygen masses in Table 2 would be 10 percent higher for this higher number of Calories.

Average males need 3,400 and average females 2,550 Calories per day.

The average is 2,975 Calories per day.

Males need about 1/3 more Calories than females.

The gender effect is due to differences in average weight and percent body fat. (Jones)

Or, males need 1/7 more and females 1/7 less than the average Calories. (425 Calories)

It is as if males consume one day more life support allowance per week and females one day less.

Many calories are used to supply the energy needed to do physical work. Metabolic needs are usually estimated using three components: basal metabolic rate, physical activity, and diet induced thermogenesis. The basal metabolic rate is the energy used by a person who is awake but resting in a comfortable environment, and depends on lean body mass. Diet induced thermogenesis is the expenditure of energy in digesting, absorbing, distributing, and sometimes storing the nutrients in the diet, and is about 10 percent of the ingested calories. Basal metabolic rate and the associated diet induced thermogenesis are nearly constant for an individual over periods of years, while physical activity and its associated diet induced thermogenesis vary day-to-day. (Jones)

The above computation of calorie needs assumed that the crewmember spent 8 hours sleeping, 11 hours sitting, 2 hours standing, 2 hours walking, 1/2 hour in heavy work, and 1/2 hour in exercise. If the average 79 kg man merely slept and sat, his calorie expenditure (due to basal metabolic rate and diet induced thermogenesis) would be only 2,641 Calories. This is 760 less than the above 3,402 Calories which includes the described physical activity. If the 63 kg woman merely slept and sat, her calorie expenditure would be 1,940 Calories, 606 less than the above 2,547 Calories with the assumed physical activity. Much higher levels of physical activity are possible. If the number of calories expended in physical activity doubles, the total calories will increase 23 percent. (Jones) Because work and exercise induce perspiration, drinking water requirements also can be expected to increase with physical activity.

Minimum resting Calories are constant and equal to about 75% of the total.

Calories used in physical activity can easily double, increasing the total Calories by 25%. (750 Calories)

The resting calorie needs change due to individual weight variations. The average adult male weight of 79 kg has a standard deviation of 13.6 kg, corresponding to 310 Calories. The average adult female weight of 63 kg has a standard deviation of 15.2 kg, corresponding to 291 Calories. A range of plus or minus 1.645 standard deviations includes 90 percent of a normally distributed population. Approximating the male-female average standard deviation as 300 Calories, we would expect the calorie range of plus and minus $300 \times 1.645 = 494$ Calories to include 90 percent of crewmembers randomly selected from the American population. (Jones) Crewmembers would probably tend to be average size rather than extreme size.

Calorie needs vary 10 - 20% due to body weight variations. (300-500 Calories per day.)

The total mass of oxygen, food, and drinking water per day should vary roughly with Calorie need.

HYGIENE WATER REQUIREMENTS

Table 3 below lists the minimum, nominal, and maximum drinking and hygiene water requirements estimated for Space Station Freedom. (Wieland, pp. 6, 230) (Reed and Coulter, p. 125)

Table 3: Space station water needs

Water use (kg)	Minimum	Nominal	Maximum
Consumed			
Food preparation	0.40	0.76	0.91
Drinking	0.21	1.62	1.77
Consumed total	0.61	2.38	2.68
Hygiene			
Shower	1.82	2.73	2.73
Dishwash	3.63	5.45	5.45
Handwash	3.63	4.09	4.54
Urine flush	0.00	0.50	0.73
Clothes wash	0.00	12.50	12.50
Hygiene total	9.08	25.27	25.95
Grand total	9.69	27.65	28.63

Table 4 below is similar, but shows the drinking and food preparation water requirements from the Space Shuttle, with the hygiene total from Space Station Freedom used to compute the grand total. (Wieland, p. 230)

Table 4: Space Shuttle Water Usage Needs

Water Use (kg)	Minimum	Nominal	Maximum
Consumed			
Food preparation	0.73	0.89	1.22
Drinking	0.27	1.70	3.57
Consumed total	1.00	2.59	4.79
Station hygiene total	9.08	25.27	25.95
Grand total	10.08	27.86	30.74

The nominal hygiene water is 25.27 kg, while the oxygen, hydrated food, and the consumed water amount to 4.99 kg per day in Table 2.

The hygiene (washing) water is typically 25 kg/day, 5 times the 5 kg/day mass of oxygen, hydrated food, and food preparation and drinking water.

Including hygiene water, a crewmember requires about 30 kg of water, food, and oxygen per day.

Considering minimum, nominal, and maximum, the total consumed food preparation and drinking water is 7 to 11 percent of hygiene water total, except when it reaches 18 percent for the Orbiter maximum drinking water. This is based on drinking 3.57 kg of water, 0.94 gallons or fifteen 8 ounce glasses per day, which seems excessive. The consumed water (food preparation and drinking) typically equals only 10 percent of the hygiene (washing) water.

The hygiene (washing) water is typically 10 times the mass of the food preparation and drinking water.

Tables 3 and 4 show minimal water use much less than nominal.

The minimum consumed (food preparation and drinking) water is roughly 1/3 of nominal.

The minimum hygiene (washing) water is roughly 1/3 of nominal.

Two-thirds reduction in total water use, to 10 kg/day, is possible.

Reductions to 5-6 kg/day per person are possible under emergency conditions. (Reed and Coulter, p. 124)

ATMOSPHERE LOSSES

The leakage of the spacecraft structure and losses during airlock operation require resupply of atmosphere. The spacecraft atmosphere will very likely be Earth-normal, 80 percent nitrogen and 20 percent oxygen. The nitrogen is merely a buffer gas. It can not be generated or recovered by recycling. The nitrogen that could be obtained from waste derived from food solids is much smaller than typical leakage. Nitrogen resupply must be equal to leakage plus airlock loss.

Nitrogen resupply is needed to make up atmosphere leakage and airlock loss.

The leakage design parameter for Space Station Freedom was 0.23 kg/element per day. A typical laboratory or habitation element had volume of 106 m³. (Wieland, p. 213) Pressure was to be 14.7 psia, 1 atmosphere. (Wieland, p. 184) 106 m³ of air at 1 atmosphere pressure and 25 degrees Centigrade corresponds to about 125 kg of air per element. The 0.23 kg per day leakage rate per element is then 0.18 percent per day.

The Space Station Freedom equipment airlock had volume of 26 m³, was to be cycled about once per week, and was to lose 10 percent of the air per operation. (Wieland, p. 213) 2.6 m³ of air at 1 atmosphere pressure and 25 degrees Centigrade corresponds to about 3.1 kg of air. This amount was lost once per week, so the

equipment airlock air loss is 0.44 kg per day, larger than the leakage of one element.

If the space station has 10 elements, the total atmosphere loss from leakage and airlock recycling is 2.74 kg/day.

The daily atmosphere loss due to leakage and airlock operation can equal 2 - 3 kg/day.

The atmosphere is 20 percent oxygen, so 0.55 kg of oxygen is lost per day. The metabolic use of oxygen is 0.84 kg/day per crewmember, as shown in Table 2. Assuming a crew of six, total metabolic use is 5.04 kg.

Leakage and airlock loss of oxygen can equal 10% of the metabolic use of oxygen by the crew.

MISSION PARAMETERS

We consider each mission parameter and how it affects life support design. The top level mission parameters are crew size, duration, destination, vehicle and base design, and planned operations. Some of these have several subparameters we discuss specifically.

CREW SIZE - We first consider crew size.

The mass of oxygen, water, and food consumed increases directly with crew size.

The range of crew size is expected to be two to perhaps eight, with three to six most likely.

The size and cost of the life support system increase with crew size, but less than directly. Some economies of scale are possible.

Some supporting or underutilized system elements do not increase. (Wieland, p. 29)

DURATION - The next major mission parameter is duration. The ISS is designed to operate for many years, but the longest duration mission beyond low Earth orbit (LEO) has been two weeks for Apollo.

The mass of oxygen, water, and food consumed increases directly with duration.

The processing capacity of the life support system hardware does not increase with duration.

Longer duration missions require hardware with higher reliability, maintainability, and repairability, more spares, and longer life.

Mission cost can be reduced for longer duration missions by adding equipment to recycle material. The material

cost savings obtained by recycling increase with duration, but the cost of the recycling equipment remains constant. This justifies more recycling as duration increases. (Wieland, p. 3) (Doll and Eckardt, p. 563)

There is an optimum level of closure for each mission. Short missions tend to be open loop. Open loop systems are simple and reliable but their cost increases with mission distance, due to the launch and transportation cost, and with duration, due to the daily resupply requirement. Longer missions tend to be closed loop. Closed loop systems are complex and costly to develop. They save cost because they require lower total mass. They have operations costs for power and heat rejection, as well as the usual mass penalty. They have reliability and maintainability issues. (Doll and Eckart, pp. 539-40)

The optimum amount of recycling (of oxygen, water, and possibly food) increases as mission duration increases.

In expanding life support closure, the order should be water recycling, regenerative carbon dioxide absorption, oxygen recycling from carbon dioxide, and food production from human and plant waste. (Eckart, pp. 82-83, 110) (Doll and Eckart, pp. 563-4) (Wieland, p. 32)

For duration beyond a few weeks, regenerable technologies should be used to recycle water.

For duration beyond a few weeks, regenerable technologies rather than lithium hydroxide should be used to remove carbon dioxide.

For duration beyond a few weeks, oxygen regeneration should be used.

For duration of several years or permanent bases, food production might be considered.

The breakeven point for food production may not be reachable at any duration with currently anticipated technology. (Doll and Eckart, p. 566)

Longer duration missions require more waste processing for stabilization, storage, and sanitation.

This is in addition to greater need to recycle material. (Doll and Eckart, p. 549)

DESTINATION - The third mission parameter we consider is destination. The destination determines several lower level mission parameters: transportation cost, travel time, resupply delay, and operational environment. All human space missions have been in LEO except one, Apollo.

Transportation cost - The launch cost is usually the largest cost for a planetary mission. Launch cost is proportional to system mass and dominates planetary mission cost unless design efforts are made to reduce mass.

The cost of a Space Shuttle launch to low Earth orbit is roughly 25 \$/kg. Space hardware development typically costs 100 \$/kg, with a range of from 50 to 150 \$/kg. (Wertz and Larson, pp. 125, 254) For an Earth orbit mission, the hardware development cost is 2 to 6 times the launch cost. For a mission beyond Earth orbit, we must launch to Earth orbit both the life support system and the vehicles and propellant needed to place the life support system at the final mission location. The vehicles and propellant can weigh twenty to thirty times the payload itself. This means that the hardware emplacement cost can be 20 to 30 times 25 \$/kg, or 500 to 750 \$/kg. "The cost of a human-crewed mission to the Moon or Mars is typically millions of dollars per delivered kg." (Wertz and Larson, p. 254)

Planetary missions should be designed for significantly reduced mass.

But this is not true for Earth orbit missions. Launch cost to Earth orbit is only 25 \$/kg, which is small compared to typical development costs.

Earth orbit missions should not be designed for minimum mass.

Reducing system mass usually decreases performance and safety margins and increases risk and development cost. Because of the relatively low launch cost for Earth orbit missions, most authorities on spacecraft design strongly discourage mass minimization. For instance:

"A particularly strong example of the problem of optimization is trying to achieve minimum spacecraft weight. This is perhaps the *single most economically destructive force in spacecraft design*. Specifically, weight optimization leads to uniquely designed structures, minimal use of standard components, materials and processes unique to space, and inadequate margin in all elements." (Wertz and Larson, p. 37, italics added.)

This statement applies to Earth-orbiting spacecraft, where development cost is several times launch cost. For example, the ISS may ultimately cost \$30 billion for development and \$6 billion for launch. The launch cost is only 20 percent of development cost. Increasing development cost significantly to save mass would not be cost-effective. ISS was not designed for minimum mass. However, mass reduction is appropriate and necessary for missions beyond Earth orbit, where launch cost greatly exceeds development cost. Robotic

planetary missions are always designed for reduced mass.

Travel time - Travel time may be a large or small part of mission duration.

Long travel time requires closed loop life support in microgravity.

Travel time is the parameter of concern, not distance per se. Advanced nuclear propulsion may reduce travel time. Low cost ion propulsion may reduce emplacement cost but increase travel time.

Resupply delay - Resupply delay is caused by both travel time and operational considerations such as vehicle availability and turn around time.

Longer resupply delay requires increased storage and spares, and higher system maintainability and reliability at a remote base.

Operational environment - The operational environment always includes the vacuum of space and possibly a planetary environment. The planetary environment determines the mission destination subparameters of gravity, contamination, and *in situ* resources.

Life support systems must operate in microgravity and possibly in planetary gravity.

Planetary dust and atmosphere and soil chemistry must be considered.

***In situ* resources can be used to reduce resupply and recycling needs.**

VEHICLE AND BASE DESIGN - The fourth mission parameter we consider is vehicle and base design. The vehicle and base design determines the third level mission parameters of the cost of mass, power, and volume and the atmosphere loss and leakage.

Cost of mass, power, and volume - The relative cost of the mass, power, and volume of the life support system drive the system design trades as formalized in equivalent mass computations. (Doll and Eckart, p. 549) Expensive power favors open loop life support, cheap power favors recycling. The life support design should be optimized in the context of the total mission, vehicle, and base design.

Design cost analysis should consider the total mission cost, not only development or launch or operations cost.

Atmosphere loss and leakage - Atmosphere loss and leakage create unavoidable resupply costs, as discussed above.

Higher resupply cost justifies tighter atmosphere leakage and loss specifications.

PLANNED OPERATIONS - The fifth and last mission parameter is planned operations. Operations affect life support through the planned number of EVA's. EVA causes airlock atmosphere loss, cooling water loss, use of open loop life support consumables, etc.

EVA suits typically use nonregenerable life support. (Wieland, p. 30)

This imposes resupply requirements. The EVA consumables consist of LiOH canisters for carbon dioxide removal, oxygen, and water, as shown in Table 5. (Griffen, Spampinato, and Wilde, p. 723)

Table 5. Consumables per EVA

LiOH	2.9 kg
Oxygen	0.63 kg
Water	3.5 to 5.4 kg
Total	7.03 to 8.93 kg

One EVA in an open loop suit requires about 3 kg of LiOH and 5 kg of water.

ISS EVA uses regenerable carbon dioxide removal, eliminating the LiOH canisters. (Griffen, Spampinato, and Wilde, p. 724) A future system might capture the carbon dioxide and recycle it into oxygen, eliminating the oxygen resupply.

Water is the largest EVA consumable. Some is drunk, then respired or perspired, and finally captured as condensate. This condensate and the rest of the stored consumed water is used for suit heat rejection by ice sublimation. (Griffen, Spampinato, and Wilde, p. 726) Sublimation will not work in the Mars atmosphere and radiators may be used. (Griffen, Spampinato, and Wilde, p. 715)

SYSTEMS INTEGRATION AND RECYCLING

The major human wastes are carbon dioxide, respiration and perspiration water in the atmosphere, urine with urine flush water and urine solids, feces water and solids, personal wash water with sweat solids, and clothes wash water. Some food preparation water, personal wash water, and clothes wash water evaporates into the atmosphere.

The total mass of the wastes equals the total mass of the oxygen, water, and food consumed. Some of these wastes can be easily recycled, such as water condensed from the atmosphere. Recycling of all life support waste products is not economically feasible because of the law of diminishing returns.

Full closure is impossible. Some resupply is always necessary. Some regeneration and recycling is usually economic.

Life support commodities should be provided by a cost-effective combination of resupply and recycling.

Waste should be recycled only if we need the recovered resource. Otherwise, we should stabilize and store or dump the waste.

The portion of each life support consumable that is resupplied or recycled is a key life support system design parameter.

The air, water, food, and waste material flows are interconnected within the human metabolism. These flows are also interrelated in the life support system. An ideal plant based closed life support system would simply reverse the human metabolic process. Increased closure of the oxygen and water loops increases the coupling between the oxygen and water systems. (Wieland, p. 35)

The mass balances affect the kinds and amounts of material that should be recycled. External losses and gains, such as leakage, airlock and EVA losses, *in situ* resources, and incidental resupply such as the water in hydrated food, must be considered. (Doll and Eckart, pp. 563-4)

The cost-effective amount of water recovery depends on the water balance.

The Space Shuttle fuel cells provide water for the ISS. Such added water allows less efficient water recovery. (Wieland, p. 38)

Fuel cells or a hydrated food supply can provide significant water.

For the food solids and water in food, see Table 2 above or Table 6 below. The crew's metabolism of food solids using atmospheric oxygen will produce carbon dioxide and additional water. Accounting for the water originally in or metabolized from Earth grown food reduces the requirement to resupply or recycle water. Accounting for the oxygen contained in that water similarly reduces the need to resupply or recycle atmospheric oxygen.

We can generate oxygen by using electrolysis rather than by reducing carbon dioxide if excess water is available. (Doll and Eckart, pp. 563-4)

We should reduce carbon dioxide to recover oxygen if the system must recycle most of the water. (Doll and Eckart, pp. 563-4)

RESUPPLIED FOOD - The consumption of resupplied food produces waste products that can be recycled to provide oxygen and water. The standard crewmember daily metabolic inputs and outputs are shown in Table 6 below. (Wieland, p. 6) (Reed and Coulter, p. 122)

Table 6. Human metabolic inputs and outputs

Inputs	kg	Output	kg
Oxygen	0.84	Carbon dioxide	1.00
Food solids	0.62	Respiration & perspiration water	2.28
Water in food	1.15	Urine water	1.50
Food preparation water	0.76	Feces water	0.09
Drinking water	1.62	Sweat solids	0.02
		Urine solids	0.06
		Feces solids	0.03
(water subtotal)	3.53	(water subtotal)	3.87
Total mass	4.99		4.98

All the oxygen consumed is not converted to carbon dioxide. (The respiratory quotient, which is the ratio of carbon dioxide output to oxygen input in moles, is typically 0.8 or 0.9 and varies with diet - Eckart, p. 95.) As the molecular weight of carbon is 12 and oxygen is 16, carbon dioxide is 32/44 or 73 percent oxygen. The 1 kg of exhaled carbon dioxide shown in Table 6 contains only 0.73 kg of oxygen. The remaining oxygen is in water and other waste.

Only 80-90% of the crew oxygen can be recovered from the carbon dioxide.

Note that the output water subtotal in Table 6 is 0.34 kg more than the input water subtotal.

Metabolism of food produces about 1/3 kg/day/crewmember more water than consumed.

As the molecular weight of hydrogen is 1, 0.34 kg of water contains 0.34*(16/18) or 0.30 kg of oxygen. To provide the missing 15 percent of the 0.84 kg of oxygen per day per crewmember requirement, we need to process about 0.14 kg of water.

The missing 15% of the crew oxygen can be recovered from 0.14 kg of water. We still have about 0.2 kg/day/crewmember of excess water.

Most of the water required is hygiene water, about 25.27 kg per day per crewmember, as shown in Table 3. Total water need is 28.8 kg per day per crewmember.

If dehydrated food is supplied, the water recycling system can loose only 0.7% without resupply.

Hydrated food provides an additional 1.15 kg of water per day per crewmember. Supplying hydrated food reduces the total water needed to 27.65 kg per day per crewmember.

If hydrated food is supplied, the water recycling system can loose 5% without resupply.

GROWN FOOD - Whereas resupplying food provides waste material that can reduce the need for recycling water and oxygen, growing food is itself a way of recycling water and oxygen.

The harvest index of plants grown for food is roughly 50%. (Doll and Eckart p. 549) (Eckart, p. 280)

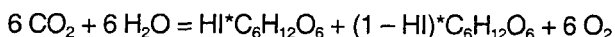
If we grow roughly half the food, plant growth will supply all the oxygen required by the crew and remove all the carbon dioxide generated by the crew. (Finn)

This is because, at a harvest index of 50 percent, we grow a mass of inedible material equal to the food. If we grow less than 50 percent of the food, additional oxygen must be supplied to the crew. If we grow more than 50 percent, some waste must be oxidized to provide carbon dioxide for the plants.

The key is the relation between the harvest index and the fraction of food grown.

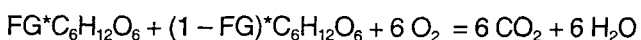
The fraction of the food that must be grown to provide all crew oxygen and absorb all crew carbon dioxide equals the harvest index.

To see this, consider the chemical equations for photosynthesis and respiration. Photosynthesis combines carbon dioxide and water to produce edible and inedible hydrocarbons and oxygen.



HI is the harvest index, $\text{HI} \cdot \text{C}_6\text{H}_{12}\text{O}_6$ is the edible biomass, and $(1 - \text{HI}) \cdot \text{C}_6\text{H}_{12}\text{O}_6$ is the inedible biomass.

Respiration is the reverse reaction.



FG is the fraction of food grown, $\text{FG} \cdot \text{C}_6\text{H}_{12}\text{O}_6$ is the mass of grown food, and $(1 - \text{FG}) \cdot \text{C}_6\text{H}_{12}\text{O}_6$ is the mass of supplied food.

No matter how many plants are grown, no matter how large the crew, photosynthesis and respiration involve equal numbers of carbon dioxide, water, glucose, and oxygen molecules. (Roughly, ignoring the respiration quotient.) If we want plant growth to supply all the oxygen required by the crew and to remove all the carbon dioxide generated by the crew, the total plant biomass must equal the total crew food mass. And there is a second equality. The edible biomass is identical to the food grown, so $\text{HI} = \text{FG}$. This shows the fraction of the food that must be grown to provide all crew oxygen and absorb all crew carbon dioxide equals the harvest index. Also, the inedible biomass is identical to the food supplied. The resupply of food is equal to the inedible biomass stored or dumped. The input and output masses balance and no physico-chemical oxygen and carbon dioxide recycling systems are needed.

If FG, the fraction of food grown, is less than HI, the harvest index, the edible biomass is still identical to the food grown, but the food supplied is greater than the inedible biomass, so the plants supply less oxygen than required by the crew and remove less carbon dioxide than generated by the crew. For example, if the harvest index is 50 percent and the fraction of food grown is only 25 percent, physico-chemical systems must supply half the crew oxygen and absorb half the carbon dioxide.

If FG is more than HI, the edible biomass is still identical to the food grown, but the food supplied is less than the inedible biomass, so the plants supply more oxygen than required by the crew and require more carbon dioxide than generated by the crew. The excess oxygen can be used to burn or decompose the inedible plant material or the human solid waste. This produces the carbon dioxide needed for further plant growth. For example, if the harvest index is 50 percent and the fraction of food grown is 100 percent, waste processing systems must use an amount of oxygen equal to the crew use to produce an amount of carbon dioxide equal to the crew output.

We need to oxidize solid waste to produce carbon dioxide if the plants produce more than roughly half (the harvest index) of the crew food. (Finn)

If the plants produce all the crew food, we need to oxidize all the waste.

HARDWARE AND TECHNOLOGY

The state of life support technology and the actual hardware that has been developed and flown define practical limits for future systems design.

It is likely that the life support systems for the next human mission will be similar in concept and technology to those developed for the International Space Station (ISS). (Wieland, p. 31)

They will be physico-chemical rather than bioregenerative.

Bioregenerative oxygen and water subsystems require more mass, volume, power, and crew time than physico-chemical subsystems. They are also much less developed for flight. They have lower technology readiness and higher risk. Processing equipment is much more likely to fail than stored supplies. (Doll and Eckart, pp. 551, 566-7)

Physico-chemical subsystems are unavoidable. Many requirements can be handled only by physico-chemical subsystems. These include atmosphere storage, temperature and pressure control, monitoring, and circulation; water storage and distribution; and plant growth atmosphere and water control. (Doll and Eckart, 552)

For planetary missions, ISS-like physico-chemical subsystems must be reengineered for minimum mass.

The launch cost per kilogram is much higher for planetary missions. Reducing mass is common for robotic planetary missions.

DISCUSSION

Providing human life support for the next human mission with adequate safety, reliability, performance and cost will not be easy. The life support is a major source of cost and risk.

It is worth considering what kind of mission would be easiest for provision of life support. What mission would allow the safest, most reliable, best performing, and least expensive life support system?

The mission that would have the safest life support is the one closest to Earth. Short travel time would allow quickly returning to Earth, sending human help, communicating information, or providing replacement equipment and supplies. The safest mission is in high Earth orbit, at a libration point, or in Moon orbit, only the next small step beyond LEO.

The mission that would have the most reliable life support is one using proven, flight tested equipment that has been demonstrated long term on the ISS. Such equipment would be suitable for high Earth orbit, a libration point, or Moon orbit without being reengineered for minimum mass, if it could be emplaced gradually and cheaply, using electronic propulsion, in advance of

human use. Some recycling equipment, such as a Sabatier to recover water from carbon dioxide, could be added without reducing reliability if water resupply was available as a backup. A life support system for the Moon or Mars surface could use ISS technology, but would need to be redesigned to reduce mass, to increase recycling, and to utilize *in situ* resources.

The mission that would have the best performing life support would be one making maximum use of *in situ* resources. The surfaces of Mars and the Moon can provide water, but have reduced sunlight (Mars, due to distance and dust) or poorly patterned sunlight (Moon, with a month long day). High Earth orbit or a libration point provide nearly continuous sunlight as a resource.

The mission that would have the least expensive life support would be one with low development cost, low emplacement cost, and low operations cost. Using ISS equipment designs would reduce development cost. Missions in orbits near Earth with slow pre-emplacment would have low transportation cost. Missions using *in situ* resources would have low operations costs. Missions with a small crew making brief visits would also have low operations costs. The task of the crew might be to modify or repair automated large array astronomical observing equipment or to use such equipment in a human guided research mode. The crew could make a human guided close reconnaissance of the Moon. Any experiments that can not be accommodated on ISS could be conducted

The ultimate life support is a closed bioregenerative system growing plants for food. What mission is most likely to first use such a system? Growing plants for food and oxygen might be cost-effective on a large permanent space station, far from Earth, with artificial gravity, using continuously available sunlight.

CONCLUSION

The usual way to consider life support system design is to make extensive assumptions about the mission and then work out the detailed design trade-offs. This gives an accurate and complete picture of a specific life support design for the assumed mission, but it obscures the essential requirements and the systems design drivers in the mass of detail. This paper is intended to present some common system design insights in the form of simple rules.

The design rules are intended to give some guidance before detailed analysis and provide a quick check of the results. The rules may be most useful to people who will never do an analysis or design, but who must consider life support systems in the context of proposing new technologies or mission concepts.

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APPENDIX - LIST OF DESIGN RULES

GENERAL SYSTEMS DESIGN

1. Start with a good system design.
2. Include experienced people.
3. Understand earlier and alternate designs. Focus on differences and choices.
4. Design top down from the major mission objectives.
5. Review the system design frequently. Find the problems early.
6. Everyone should think like a systems engineer.
7. Mission management must ensure the mission objectives are achieved.
8. Design must consider cost, reliability, availability, and safety.
9. Costs will be high. Systems will fail. Lives will be at risk.
10. Life support design must be simple, practical, and austere.
11. Reduce requirements as much as possible.
12. Simplify the design as much as possible.
13. Focus on subsystem interfaces.
14. Embed digital computers, communication, control, and human interfaces into the system.
15. Use computer design tools.
16. No one design can optimize all mission objectives.
17. Performance, schedule, and cost are interrelated. Any two determine the third.

LIFE SUPPORT SYSTEM DESIGN

1. Life support subsystems are defined by function – oxygen generation, carbon dioxide removal, wastewater processing, etc.
2. The basic architecture of life support systems is stable.
3. Life support systems will probably evolve one subsystem or component at a time.

HUMAN METABOLIC NEEDS

1. A crewmember requires about 5 kg (11 lbs) of drinking water, hydrated food, and oxygen per day.
2. Water for drinking and food preparation dominates. The 5 kg is roughly 1/2 water, 1/3 hydrated food, and 1/6 oxygen.
3. Dehydrating food can reduce food resupply mass by 2/3.
4. Food solids provide about 5 Calories per gram.
5. Respiration produces about 3.4 Calories per gram of oxygen consumed.

CALORIE NEEDS

1. Average males need 3,400 and average females 2,550 Calories per day.
2. The average is 2,975 Calories per day.
3. Males need about 1/3 more Calories than females.

4. Or, males need 1/7 more and females 1/7 less than the average Calories. (425 Calories)
5. Minimum resting Calories are constant and equal to about 75% of the total.
6. Calories used in physical activity can easily double, increasing the total Calories by 25%. (750 Calories)
7. Calorie needs vary 10 - 20% due to body weight variations. (300-500 Calories per day.)
8. The total mass of oxygen, food, and drinking water per day should vary roughly with Calorie need.
6. For duration beyond a few weeks, regenerable technologies rather than lithium hydroxide should be used to remove carbon dioxide.
7. For duration beyond a few weeks, oxygen regeneration should be used.
8. For duration of several years or permanent bases, food production might be considered.
9. Longer duration missions require more waste processing for stabilization, storage, and sanitation.

HYGIENE WATER REQUIREMENTS

1. The hygiene (washing) water is typically 25 kg/day, 5 times the 5 kg/day mass of oxygen, hydrated food, and food preparation and drinking water.
2. Including hygiene water, a crewmember requires about 30 kg of water, food, and oxygen per day.
3. The hygiene (washing) water is typically 10 times the mass of the food preparation and drinking water.
4. The minimum consumed (food preparation and drinking) water is roughly 1/3 of nominal.
5. The minimum hygiene (washing) water is roughly 1/3 of nominal.
6. Two-thirds reduction in total water use, to 10 kg/day, is possible.

ATMOSPHERE LOSSES

1. Nitrogen resupply is needed to make up atmosphere leakage and airlock loss.
2. The daily atmosphere loss due to leakage and airlock operation can equal 2 - 3 kg/day.
3. Leakage and airlock loss of oxygen can equal 10% of the metabolic use of oxygen by the crew.

MISSION PARAMETERS

CREW SIZE

1. The mass of oxygen, water, and food consumed increases directly with crew size.
2. The size and cost of the life support system increase with crew size, but less than directly. Some economies of scale are possible.

DURATION

1. The mass of oxygen, water, and food consumed increases directly with duration.
2. The processing capacity of the life support system hardware does not increase with duration.
3. Longer duration missions require hardware with higher reliability, maintainability, and repairability, more spares, and longer life.
4. The optimum amount of recycling (of oxygen, water, and possibly food) increases as mission duration increases.
5. For duration beyond a few weeks, regenerable technologies should be used to recycle water.

DESTINATION

1. Planetary missions should be designed for significantly reduced mass.
2. Earth orbit missions should not be designed for minimum mass.
3. Long travel time requires closed loop life support in microgravity.
4. Longer resupply delay requires increased storage and spares, and higher system maintainability and reliability at a remote base.
5. Life support systems must operate in microgravity and possibly in planetary gravity.
6. Planetary dust and atmosphere and soil chemistry must be considered.
7. *In situ* resources can be used to reduce resupply and recycling needs.
8. Design cost analysis should consider the total mission cost, not only development or launch or operations cost.
9. Higher resupply cost justifies tighter atmosphere leakage and loss specifications.

PLANNED OPERATIONS

1. EVA suits typically use nonregenerable life support.
2. One EVA in an open loop suit requires about 3 kg of LiOH and 5 kg of water.

SYSTEMS INTEGRATION AND RECYCLING

1. Full closure is impossible. Some resupply is always necessary. Some regeneration and recycling is usually economic.
2. Life support commodities should be provided by a cost-effective combination of resupply and recycling.
3. Waste should be recycled only if we need the recovered resource. Otherwise, we should stabilize and store or dump the waste.
4. The cost-effective amount of water recovery depends on the water balance.
5. Fuel cells or a hydrated food supply can provide significant water.
6. We can generate oxygen by using electrolysis rather than by reducing carbon dioxide if excess water is available.
7. We should reduce carbon dioxide to recover oxygen if the system must recycle most of the water.

8. Only 80-90% of the crew oxygen can be recovered from the carbon dioxide.
9. Metabolism of food produces about 1/3 kg/day/crewmember more water than consumed.
10. The missing 15% of the crew oxygen can be recovered from 0.14 kg of water. We still have about 0.2 kg/day/crewmember of excess water.
11. If dehydrated food is supplied, the water recycling system can lose only 0.7% without resupply.
12. If hydrated food is supplied, the water recycling system can lose 5% without resupply.
13. The harvest index of plants grown for food is roughly 50%.
14. If we grow roughly half the food, plant growth will supply all the oxygen required by the crew and remove all the carbon dioxide generated by the crew.
15. The fraction of the food that must be grown to provide all crew oxygen and absorb all crew carbon dioxide equals the harvest index.

16. We need to oxidize solid waste to produce carbon dioxide if the plants produce more than roughly half (the harvest index) of the crew food.
17. If the plants produce all the crew food, we need to oxidize all the waste.

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