2 BIO-Plex Pinch Analysis:

Development of Energy Content Data for a System with Partial Food Production and Partial Waste Recycling Under Steady-State Conditions

Julie Levri and Cory Finn, August 19, 1999

All suggestions and corrections welcome.
jlevri@mail.arc.nasa.gov, cfinn@mail.arc.nasa.gov

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1 Introduction

The systems modeling and analysis group at Ames Research Center is currently working on the first year tasks for the grant entitled "Advanced Life Support Power Reduction." The Advanced Life Support Power Reduction research involves developing approaches for reducing system power and energy usage in Advanced Life Support (ALS) regenerative systems suitable for exploring the Moon and Mars. The effects of system configuration and processor scheduling are being investigated, along with system energy integration and energy reuse techniques and advanced control methods for efficient distribution of power and thermal resources. Here we discuss progress to date on applying system energy integration and energy reuse techniques to the life support problem.

1.1 Approach

One of the main objectives of the power reduction research is to develop system designs that are more efficiently integrated from an energy standpoint, so that the equivalent system mass of future life support systems can be reduced. Hot and cold streams within the system can be matched and their energy exchanged in order to lower the external cooling and heating requirements. Some subsystem designers have taken advantage of energy integration within their subsystem design in order to minimize power usage. However, due to limitations on the number of available hot and cold streams within a given subsystem, only partial energy reuse is generally achievable. A system approach to energy integration will inevitably yield better results than the more common subsystem-by-subsystem power optimization approach. When the entire system is treated, there is much more flexibility in the design approach, and the potential for energy reuse is substantially greater.

In *A User Guide on Process Integration for the Efficient Use of Energy* by B. Linnhoff, energy integration techniques are discussed. Using the simple, practical method outlined in Linnhoff's book, referred to here as the “Pinch Technique”, system design options can be identified that lower the overall system energy usage. In the Pinch Technique, first, process streams and their thermal attributes (heat capacity flowrate, supply temperature and target temperature) are identified. The heat duty that is required to bring each stream from its supply temperature to its target temperature is calculated. Next, composite curves are constructed, first for the streams that require cooling (hot streams), then for the streams that require heating (cold streams). The hot composite curve contains the aggregate energy content information for all of the hot streams, and the cold composite curve contains all of the aggregate energy content information for all of the cold streams.

The hot and cold composite streams are plotted together in a heat content graph, and the minimum heating and cooling requirements for the system are identified. An energy cascade (a net enthalpy balance on the system) is performed to identify the locations where external heating and cooling must be supplied. Once the energy cascade has been completed, an optimal system heat exchange design can be developed by matching hot and cold streams such that heat exchanger loads are maximized, so that the total number of exchangers can be minimized. For a more detailed explanation of the Pinch Technique, please refer to the attached NRA proposal "Advanced Life Support Power Reduction".

1.2 Year One Goals and Tasks

The goal for year one of the energy integration work is to develop thermally-integrated system designs using the BIO-Plex as a baseline system. Specific tasks for the first year include:

1. Identify candidate technologies and designs for the BIO-Plex.
2. Identify potential hot and cold streams for candidate technologies.
3. Develop energy content data for each hot and cold stream using mass and energy flow models as needed to produce temperature, flow and composition data.
4. For various candidate designs, identify and quantify potential savings for power, heating and cooling, and make estimates on the increase in emplaced mass needed for energy exchange equipment.
5. Make recommendations on system designs that incorporate energy reuse.
6. Prepare a report and/or research paper to document the results listed above.

1.3 Current Status

To date, progress has been made on items 1, 2, 3 and 6 above. In "1 BIO-Plex Pinch Analysis", a spreadsheet containing information compiled from various sources on thermal flow characteristics of candidate BIO-Plex technologies was discussed. Work since the previous memorandum has involved selection of an example subsystem for application of the Pinch Technique, determination of steady-state flows through the system as well as development of temperature intervals, heat capacities and heat duties for flowrates of interest. In the current memorandum, progress on this work is detailed.

2 Description of the Example System

The Pinch Technique is typically applied to industrial designs that are already in existence or are substantially predefined. In this investigation, the BIO-Plex Phase I, 120-

day test with a crew of four persons is used as a starting point for an initial investigation of applying the Pinch Technique to bioregenerative life support systems. The Phase I test will entail 45% food production and 25% solids processing. Because the BIO-Plex is still in the design phase, assumptions on some technologies must be made in order to apply the technique. Data was collected on various technologies for atmosphere revitalization, solids processing, water recovery, biomass production, food processing and habitat provisions (see memo entitled 1-BIO-Plex Pinch Analysis and Pinch Data spreadsheet). In the following sections, technology and design choices are defined, based on information obtained in the data collection efforts. Technologies were selected based upon probable technologies specified by BIO-Plex personnel, the availability of data as well as the potential enthalpy demand or supply of a particular technology.

2.1 Biomass Production Chamber

The crops that will be grown in the biomass production chamber (BPC1) and possible growth parameters are listed in Table 1. It is assumed that 400W high-pressure sodium (HPS) lamps will be used throughout the chamber. It is also assumed that the lamp arrangement will be designed such that any crop may be grown in any tray and that crop-specific light intensities will be achieved by turning on a percentage of the available lamps. It is assumed that lamps will be air-cooled, with a teflon barrier at the bottom of each light box.

Table 1. Possible crop growth specifications for BPC1.[1, 2, 3]

Crop	Number of Trays	Area per Tray (m^2)	Growth Period (d)	Photoperiod (h)	PPF ($\mu mols/m^2$-s)
Wheat	1	14.17	74	24	1500
Wheat	2	3.35	74	24	1500
Soybean	3	14.17	90	12	1000
Potato	1	6.19	112	12	1000
Sweet Potato	1	6.19	120	12	1000
Tomato	1	3.35	85	16	1000
Salad Mix	1	3.35	45	16	350

2.2 Food Processing and Preparation System

Candidate processes in the food processing and preparation system (FPS) that are of most interest in terms of reusing waste heat in the Pinch Technique are the crop dryer and dishwasher.

The crop dryer will be used at harvest times to dry wheat berries and soybeans. Three to four uses per week during harvest is an initial guess on the frequency of use of the crop dryer[4]. However, for this document, it is assumed that the crop dryer feed and air flowrates are continuous and at steady-state.

It is assumed that a dishwasher is used once daily to clean utensils, pots, pans and dishes.

2.3 Solids Processing System

A system similar to that which was used in the LMLSTP Phase III Test Bed is assumed to treat 25% of solid wastes in the first BIO-Plex test. Packaging is not included in the treated wastes.

The solids processing system (SPS) system will consist of a fluidized combustion unit, followed by a particulate filter, a catalytic gas cleanup system, and an activated carbon

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[1] Castillo, Juan. Personal communication, June 1999.

[2] Henderson, Keith. Personal communication, June 1999.

[3] Barta, Daniel J; Castillo, Juan M; Fortson, Russ E. The Biomass Production System for the Bioregenerative Planetary Life Support Systems Test Complex: Preliminary Designs and Considerations, 29th International Conference on Environmental Systems, SAE #1999-01-2188.

[4] Peterson, Laurie, personal communication, June 1999.

trace contaminant cleanup system[5]. Atypically-small SPS processors will be assumed for this study for several reasons. Only 45% of the crew food is grown, which limits the amount of inedible biomass that is oxidized in the SPS. Only 25% of the solid waste that is generated (inedible biomass, wasted edible biomass and human wastes) is treated in the SPS system, which further limits the loading to the SPS. Also, this initial application of the Pinch Technique considers steady-state conditions, thus spreading out over time the SPS loading and reducing the overall size. Upon applying the Pinch Technique to systems with increased solid waste recycling, SPS processor sizes will increase. Dynamic variations in the processor loads will also cause SPS processor sizes to increase.

2.4 Atmosphere Revitalization System

For CO_2 recovery, a solid amine water desorption system is assumed. Steam-heated solid amine is used to adsorb CO_2 from the atmosphere. In the desorption process, steam is passed over the bed to release CO_2. A solid polymer water electrolysis system is used to generate O_2 and H_2 from water. Hydrogen gas is assumed to be vented.

The trace contaminant control system (TCCS) is assumed to be similar to that which was used in the LMLSTP Phase III Test Bed[6]. The first two units in the TCCS are an ammonia removal catalyst and an Englehard catalyst to oxidize hydrocarbons and oxygenates to CO_2 and H_2O. Ten percent of the air flow is then directed to another Englehard catalyst and heated to oxidize methane and halocarbons. The air is finally passed over a sorbent bed to remove hydrogen chloride and hydrogen fluoride formed during the oxidation of halocarbons.

2.5 Water Recovery System

The water recovery system (WRS) is assumed to consist of immobilized cell and trickling filter bioreactors, followed by an air evaporation system (AES), ammonia removal

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[5] Edeen, Marybeth; Pickering, Karen D. Biological and Physical-Chemical Life Support Systems Integration – Results of the Lunar Mars Life Support Phase III Test. 28th International Conference on Environmental Systems, SAE #981708, 1998.

[6] Brasseaux, Sandra F.; Graf, John C.; Lewis, John F.; Meyers, Karen E.; Rosenbaum, Melissa L.; Supra, Laura N. Performance of the Physicochemical Air Revitalization System During the Lunar-Mars Life Support Test Project Phase III Test. 28th International Conference on Environmental Systems, SAE #981703, 1998.

system and aqueous-phase catalytic oxidation system (APCOS). Such a system is similar to that used in the LMLSTP Phase III Test[7].

3 Determination of Steady-State Mass Flowrates

Steady-state flowrates of atmospheric gases, solid wastes, greywater, and edible biomass are estimated for the first planned BIO-Plex test. The estimates are made in order to determine the flow of streams that may require cooling and streams that may require heating for various technologies in the test bed.

In the first test, a crew of four will remain in the test bed for 120 days[8]. A "hot start" will be initiated, with plants at varying degrees of maturity in the first biomass production chamber. There will be stored agricultural products in bins ready for processing, biological water and waste processors fully inoculated at steady state and a steady-state heat load at the onset of the test. It is planned that 45% of the crew's diet will be grown in BPC1, and 25% of the solid waste will be recovered[9]. Separate plant/crew air loops will be incorporated. In such a configuration, air from the crew compartment is cycled to the atmosphere revitalization system (ARS) for CO_2 removal and O_2 and N_2 addition. Air is then returned to the crew compartment. CO_2 which is removed is stored in a buffer tank until it is needed by BPC1. Air from BPC1 is sent directly to the ARS for O_2 scrubbing and CO_2 and N_2 addition. O_2 which is removed is stored in a buffer tank until needed by the crew or SPS. Crop transpiration water is treated in the WRS and recycled to nutrient tubs. Crew waste water is treated in the WRS and recycled to the crew and ARS.

3.1 Biomass Production Chamber

The growth rates and compositions of edible and inedible biomass from BPC1 are required to determine rates of CO_2 consumption, H_2O consumption and O_2 production. The quantity of O_2 that is generated by the crops in BPC1 reduces the O_2 generation demand on the ARS. The quantity of edible biomass that is produced by the crops must be processed in the food processing system before being consumed by the crew. The

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[7] Pickering, Karen D; Edeen, Marybeth A. Lunar-Mars Life Support Test Project Phase III Water Recovery System Operation and Results. 28th International Conference on Environmental Systems, SAE #981707, 1998.

[8] Tri, Terry O. BIO-Plex Project Status. Presented at the Advanced Life Support Status Meeting/Teleconference, May 20, 1999.

[9] Advanced Life Support Program Plan, Rev A, CTSD-ADV-348, JSC 39168, Crew and Thermal Systems Division, Lyndon B. Johnson Space Center, NASA, 1998, Section 8.0.

inedible biomass and the wasted edible biomass produced by the crops must be sent to the SPS.

Table 3 shows typical edible crop compositions in terms of edible protein, fat, carbohydrate, fiber and water[10]. Table 4 shows the nominal production rates of wet and dry edible and inedible biomass, assuming nominal edible biomass growth rates and harvest indexes from the Baseline Values and Assumptions Document (BVAD). (Note that tomato edible growth rate is taken from Drysdale et al, 1997). The overall crop harvest index is 0.57 kilograms of edible crop per kilogram of total biomass. It is assumed that 25% of the inedible biomass is sent to the SPS, and the vaporized inedible crop water is eventually sent to the WRS, for a water load of 2.12 kg/d.

It is assumed that crop transpirate is condensed, collected and sent to the WRS for processing. Table 2 shows possible transpiration rates for each crop and resultant loading to the WRS.

Table 2. Possible Transpiration Rates and Resultant Loading to the WRS.

Crop	Area (m^2)	Transpiration Rate[11] (kg/m^2-d)	Loading to WRS (kg/d)
Wheat	20.87	5.55	115.8
Soybean	42.51	4.32	183.6
Potato	6.19	4.74	29.3
Sweet Potato	6.19	4.74	29.3
Tomato	3.35	1.58	5.3
Mix	3.35	1.58	5.3
Total			**368.7**

Table 3. Typical Wet Edible Biomass Compositions, Excluding Minerals.[12]

Crop	Protein Mass Percent	Carbohydrate Mass Percent	Fat Mass Percent	Fiber Mass Percent	Water Mass Percent
Wheat	11.9	62.1	2.0	10.5	13.4
Soybean	38.1	7.1	20.4	24.8	9.6

[10] For conventionally-grown (not hydroponically-grown) crops.

[11] Drysdale, Alan; Grysikiewicz, Mike; Musgrove, Velda. Life Sciences Project Annual Report, 1996

[12] Scherz, Heimo; Senser, Friedrich. Food composition and Nutrition Tables, 5th edition, Scientific Publishers, Stuttgart, 1994.

Potato	2.1	15.3	0.1	2.1	80.4
Sweet Potato	1.7	24.4	0.6	3.2	70.2
Tomato	1.0	2.6	0.2	1.0	95.2
Mix[13]	1.3	1.1	0.2	1.5	96.0

Table 4. Quantities of Edible and Inedible Biomass Grown.

Crop	**Dry Edible Crop Growth Rate (kg/m^2d)[14]**	**Harvest Index[14]**	**Inedible Biomass Water Mass Percent[15]**	**Wet Edible Crop Grown (kg/d)**	**Wet Inedible Biomass Grown (kg/d)**	**Dry Edible Crop Grown (kg/d)**	**Dry Inedible Biomass Grown (kg/d)**
Wheat	0.0177	0.40	91	0.427	6.157	0.369	0.554
Soybean	0.0057	0.40	86	0.268	2.596	0.242	0.363
Potato	0.035	0.70	85	1.103	0.619	0.217	0.093
Sweet Potato	0.012	0.82	85	0.249	0.109	0.074	0.016
Tomato	0.0098[16]	0.48	95	0.690	0.711	0.033	0.036
Mix	0.0083[17]	0.92	95	0.390	0.054	0.028	0.003
Total				3.126	10.246	0.963	1.065
Total per Person per Day				**0.781**	**2.561**	**0.241**	**0.266**

If it is assumed that 1.62 kg of wet, edible biomass (calculated from the BVAD, Table 3.6.5) is required to be consumed per person per day and that edible biomass is processed with an overall efficiency of 93% by mass (see Table 5), then BPC1 will be able to account for 45% of the required mass of hydrated food. However, if one assumes that 11,820 kJ of energy from food are required per crew member per day[18], then only

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[13] Represented as lettuce.

[14] Drysdale, Alan; Hanford, Anthony. Advanced Life Support Systems Modeling and Analysis Project Baseline Values and Assumptions Document, CTSA-ADV-371, JSC 39317, June 18, 1999. Table 3.11.1.

[15] Drysdale, Alan; Grysikiewicz, Mike; Musgrove, Velda. Life Sciences Project Annual Report, 1996, Table 5.1-2.

[16] Drysdale, Alan; Beavers, Dan; Posada, Velda. KSC Life Sciences Project Annual Report, 1997, Table 3.1.

[17] Average edible growth rate for equal masses of lettuce, carrot and cabbage.

[18] Lange, K.E.; Lin, C.H. Advanced Life Support Program Requirements Definition and Design Considerations, CTSD-ADV-245 (Rev A), JSC 38571, January 1998, section 4.1.4.1.

29% of the crew energy requirement is satisfied from BPC1 on average (see Table 6). Thus, a quantity of packaged food must be supplied to the crew. The composition of the packaged food will affect the products of human metabolism.

If it is assumed that any packaged food that must be supplied to the crew is 40% water[19] and 5% fiber by mass, and that dry food energy percentages for protein, carbohydrate, and fat are 15%, 50% and 35%, respectively[20], then each crew member requires 0.73 kg of packaged food per day (see Table 7 and Table 8). Each crew member would then consume 0.73 kg of packaged food and 0.73 kg of wet, edible crop per day, for a total of 1.46 kg of food per day. This quantity is less than 1.62 kg/d because of the energy-dense packaged food.

Food mass and energy percentages supplied by BPC1 in the first test could be increased by scheduling planting and harvests strategically for the BPC1 hot start. The number of moles of protein, carbohydrate and fat given in the rightmost column of Table 8 is of interest for human metabolism stoichiometry (see section 3.3).

Table 5. Processing Efficiencies and Quantities of Crops Available for Consumption.

Crop	Processing Efficiency[21] (%)	Wet Edible Crop Grown (kg/d)	Wet Edible Crop Wasted (kg/d)	Wet Edible Crop Eaten (kg/d)
Wheat	90	0.427	0.043	0.384
Soybean	80	0.268	0.054	0.214
Potato	95	1.103	0.055	1.047
Sweet Potato	95	0.249	0.012	0.236
Tomato	95	0.690	0.034	0.655
Mix	95	0.390	0.019	0.370
Total		3.126	0.218	2.908
Total per Person per Day[22]		**0.781**	**0.054**	**0.727**

[19] Drysdale, Alan; Hanford, Anthony. Advanced Life Support Systems Modeling and Analysis Project Baseline Values and Assumptions Document, CTSA-ADV-371, JSC 39317, June 18, 1999. Footnote 32.

[20] Lange, K.E.; Lin, C.H. Advanced Life Support Program Requirements Definition and Design Considerations, CTSD-ADV-245 (Rev A), JSC 38571, January 1998, Figure 7, Diet 'A'.

[21] Drysdale, Alan; Grysikiewicz, Mike; Musgrove, Velda. Life Sciences Project Annual Report, 1996, Table 5.1-2.

[22] Not considering food processing wastes/plate wastes.

Table 6. Energy Content of Edible Biomass Grown in Test Time Frame[23].

Crop	Energy from Protein (kJ/d)	Energy from Carbohydrate (kJ/d)	Energy from Fat (kJ/d)	Total Energy from Edible Crop (kJ/d)
Wheat	853	4434	327	5615
Soybean	1708	318	2062	4089
Potato	389	2821	46	3256
Sweet Potato	69	1017	57	1142
Tomato	111	304	55	469
Mix	80	203	31	313
Total Grown	3210	9097	2577	14,884
Total Eaten	2986	8463	2398	13,847
Total Eaten per Person	**747**	**2116**	**599**	**3462**

Table 7. Composition of Packaged Food, Excluding Minerals.

Compound	Energy Content (%)	Mass (%)	Energy Content per Mass of Packaged Food (kJ/kg)
Protein	15	10	1714
Carbohydrate	50	34	5713
Fat	30	11	3999
Water	0	40	0
Fiber	0	5	0
Total (kJ/kg)			11426
Required Energy from Packaged Food (kJ/per-d)			11820 - 3462 = 8358
Required Mass of Packaged Food per Person per Day[24] (kg/per-d)			**8358 kJ/per-d ÷ 11426 kJ/kg = 0.73kg/per-d**

Table 8. Composition of Food Eaten, Excluding Minerals.

Compound	Mass Eaten from Crops	Mass Eaten from Resupply (kg/d)	Total Mass Eaten (kg/d)	Total Moles Eaten

[23] Assuming 4 kCal/g protein (16.74 kJ/g protein), 4 kCal/g carbohydrate (16.74 kJ/g carbohydrate), and 9 kCal/g fat (37.66 kJ/g fat).

[24] This is the mass of food that must be consumed. To calculate the total mass of food that must be resupplied, divide by the packaged food processing efficiency (assumed to be 93% for this study).

	(kg/d)			(mol/d)
Protein	0.178	0.300	0.478	5.760
Carbohydrate	0.506	0.999	1.505	8.358
Fat	0.064	0.311	0.374	1.463
Water	2.012	1.170	3.182	176.8
Fiber	0.148	0.146	0.295	1.818
Total	2.908	2.926	5.834	194.2
Total per Person	**0.727**	**0.731**	**1.458**	**48.55**

Given the production rates and compositions of the crops in BPC1, one can calculate the CO_2, H_2O, and HNO_3 usage rate as well as the O_2 production rate for BPC1. Stoichiometry for crop production of protein, carbohydrate, fat, fiber and lignin is taken from Volk and Rummel, 1987. Table 9 shows the compositions of reactants CO_2, H_2O, and HNO_3 and products edible protein, carbohydrate, fat, and O_2 from Volk and Rummel's paper.

Table 9. Chemical Compositions of Reactants and Products of Plant Growth.

Reactant or Product	Chemical Formula	Molecular Weight (g/mol)
Carbon Dioxide	CO_2	83
Water	H_2O	180
Nitric Acid	HNO_3	256
Protein (edible or inedible)	C_4H_5ON	32
Carbohydrate	$C_6H_{12}O_6$	90
Fat	$C_{16}H_{32}O_2$	851
Fiber	$C_6H_{10}O_5$	420
Lignin	$C_{10}H_{11}O_2$	44
Oxygen	O_2	18

Table 10 lists reactants and products in terms of moles and mass for crop growth of 45% of the required food (by mass) for the overall reaction of edible and inedible biomass growth.

Table 10. Reactants and Products in Crop Growth with Production of 45% of Required Food (by mass).

Compound	Quantity Reacted or Produced (mol/d)	Quantity Reacted or Produced (kg/d)
Carbon Dioxide	79.21	3.485
Water	57.88	1.042

Nitric Acid	6.808	0.429
Protein (edible)	2.313	0.192
Carbohydrate	3.023	0.544
Fat	0.268	0.069
Protein (inedible)	4.495	0.373
Fiber	3.290	0.533
Lignin	0.981	0.160
Oxygen	96.41	3.085

The overall reaction of crop growth for growth of 45% of the required food mass in the BIO-Plex is:

$79.21\ CO_2 + 57.88\ H_2O + 6.808\ HNO_3$ ◊ $2.313\ C_4H_5ON + 3.023\ C_6H_{12}O_6 + 0.268\ C_{16}H_{32}O_2 + 4.495\ C_6H_{10}O_5 + 3.290\ C_{10}H_{11}O_2 + 96.41\ O_2$

The nutrient solution which flows through the nutrient delivery system for hydroponic growth of crops will require a small amount of cooling to maintain temperatures slightly below ambient by discarding heat collected from the BPC1 atmosphere. It is assumed that 5.7 L/m^2- min of hydroponic solution are used for BPC1, which is equivalent to the flowrate that was used in the LMLSTP III 90-day test bed[25]. This amounts to 677,981 kg/d of hydroponic solution flow to consider for cooling requirements. It is assumed that crop transpirate is condensed and sent to the WRS.

3.2 Food Processing and Preparation System

The production rate of edible material by BPC1 is required to determine food processing heating and cooling requirements in the BIO-Plex. Primary food processing units of interest for the Pinch Technique that require heating of inflow streams are the crop dryer and the dishwasher. It is assumed that water from crop drying is eventually condensed and sent to the WRS. Unvaporized dishwasher water is sent directly to the WRS, and vaporized dishwasher water is assumed be condensed in the HVAC and also sent to the WRS for treatment.

[25] Barta, Daniel J.; Henderson, Keith. Performance of Wheat for Air Revitalization and Food Production During the Lunar-Mars Life Support Test Project Phase III Test. 28th International Conference on Environmental Systems, SAE #981704, 1998.

It is assumed that 24% of the water in wheat is lost upon drying and that 77% of the water in soybean is lost upon drying[26]. Thus, if 100% of the grown edible wheat is dried and 50%[27] of the grown edible soybean is dried, a total of 0.024 kg/d of water must be released to the air passing over the crops in the crop dryer. Assuming a constant wet bulb temperature, if the inflow temperature of air to the crop dryer is 303 K (86 ºF; 30 ºC)[28], the humidity ratio of crew air is 0.01, and it's desired to have an outflow air temperature of 295 K, then 6.32 kg of air from the crew loop is required to pass though the crop dryer per day for steady-state conditions. Such an air flow will result in an outflow humidity ratio of 0.0138. A crop dryer sized to pass only 6.32 kg of air per day is unconventionally small[29]. However, such a crop dryer is assumed here, for the purposes of considering truly steady-state conditions. It is assumed that water from dried crops is eventually condensed and treated in the WRS.

An estimate for the daily water requirements for dish washing is 21.76 kg/d[30]. It is assumed that 99.45% of the spent water (21.64 kg/d) is sent to the WRS directly and that 0.55% (0.12 kg/d) of the spent water is released as water vapor, collected, condensed and sent to the WRS from the HVAC system.

It is assumed that edible crop that is wasted during food processing is sent to the SPS, where crop water is vaporized and transferred to the atmosphere to be eventually condensed and sent to the WRS. Food processing efficiencies are listed in Table 5. Loading to the WRS from wasted crop and packaged food (overall 7% by mass wasted) amounts to 0.238 kg/d. Food preparation water loading to the WRS is estimated at 2.8 kg/d[31].

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[26] Wheat loses approximately 24% of its water upon conversion to flour, and that soybean loses approximately 77% of its water upon roasting (determined from data from http://www.nal.usda.gov/fnic/cgi-bin/nut_search.pl

[27] 100% of what is dried and 50% of soybean is dried is a guess.

[28] Temperature of air for drying wheat should not be higher than 343 K, but the temperature of air for drying soybean should not be higher then 303 K. Thus a temperature of 303 K is assumed for all drying.

[29] Gregg Weaver's BIO-Plex power requirements list gives 130 W for the crop dryer. Based on web site http://www.peerlessmfg.cc/products/dryer1.html, which gives 5 hp for air flow rate of 11,300 cfm, an estimate for the BIO-Plex crop dryer is scaled at 397 cfm (11.24 m^3/min).

[30] Drysdale, Alan; Hanford, Anthony. Advanced Life Support Systems Modeling and Analysis Project Baseline Values and Assumptions Document, CTSD-ADV-371, JSC 39317, June 18, 1999, Table 15, 5.44 kg/per-d.

[31] Pickering, Karen D; Edeen, Marybeth A. Lunar-Mars Life Support Test Project Phase III Water Recovery System Operation and Results, 28th International Conference on Environmental Systems, SAE # 981707, 1998, Table 1.

3.3 Human Metabolism and Hygiene

Information on the steady-state flows of reactants and products of human metabolism is required in order to determine loading to the ARS, WRS and SPS. The quantity and composition of food consumed by the crew affects the quantity and composition of the waste products of human metabolism. Oxygen requirements for the crew impact oxygen generation rates in the ARS. Carbon dioxide production by the crew contributes to the quantity of CO_2 that must be removed in the ARS. Wastewater from human metabolism contributes to loading to the WRS, and waste quantity and composition affects loading and stoichiometry in the SPS.

Stoichiometry for human metabolism of protein, carbohydrate and fat is taken from Volk and Rummel, 1987. Table 11 shows the compositions of reactants protein, carbohydrate, fat, and oxygen and products urine solids, feces solids, sweat solids, carbon dioxide and water from Volk and Rummel's paper.

Table 11. Chemical Compositions of Reactants and Products of Human Metabolism.

Reactant or Product	Chemical Formula	Molecular Weight (g/mol)
Protein	C_4H_5ON	83
Carbohydrate	$C_6H_{12}O_6$	180
Fat	$C_{16}H_{32}O_2$	256
Oxygen	O_2	32
Urine Solids	$C_2H_6O_2N_2$	90
Feces Solids	$C_{42}H_{69}O_{13}N_5$	851
Sweat Solids	$C_{13}H_{28}O_{13}N_2$	420
Carbon Dioxide	CO_2	44
Water	H_2O	18

Given the consumption rate of protein, carbohydrate and fat and the assumption that human waste is 79.7% urine solids, 17.4% feces solids and 2.9% sweat solids (mole percents)[32], O_2 consumption as well as CO_2 and H_2O production rates can be calculated.

Table 12 lists reactants and products in terms of moles and mass for human metabolism based upon the diet discussed in section 3.1 of this document for a crew of four persons. It is assumed that ingested fiber is not metabolized by the crew, and that its chemical composition is not changed before passing to the solids processing system.

[32] Finn, Cory K. Steady-State System Mass Balance for the BIO-Plex. 28th International Conference on Environmental Systems, SAE #981747, 1998. (From the ALS Requirements Document Table 13).

Table 12. Reactants and Products in Human Metabolism with Production of 45% of Required Food (by mass).

Compound	Quantity Reacted or Produced (mol/d)	Quantity Reacted or Produced (kg/d)
Protein	5.760	0.478
Carbohydrate	8.358	1.505
Fat	1.463	0.374
Oxygen	84.74	2.712
Urine Solids	1.820	0.164
Feces Solids	0.397	0.633
Sweat Solids	0.066	0.028
Carbon Dioxide	75.40	3.318
Water	67.85	1.221

The overall reaction of human metabolism of food with growth of 45% of the required food mass is:

$5.760\ C_4H_5ON + 8.358\ C_6H_{12}O_6 + 1.463\ C_{16}H_{32}O_2 + 84.74\ O_2$ ◊ $1.820\ C_2H_6O_2N_2 +$
$0.397\ C_{42}H_{69}O_{13}N_5 + 0.066\ C_{13}H_{28}O_{13}N_2 + 75.40\ CO_2 + 67.85\ H_2O$

The amount of water generated metabolically by the crew, plus the amount of water ingested by the crew in the form of food water, drink water and food preparation water is equal to the quantity of water excreted by the crew in the form of water in urine, water in feces, water vapor produced while sweating and water vapor in respired air. If it is assumed that each crew member requires 3.52 kg of drinking, food preparation and food-ingested water per day[33] then the total outflow of water from the crew will be (3.52 kg/per-d X 4 persons) + 1.221 kg/d = 15.30 kg/d. It is assumed that 58.9% of this total (9.012 kg) is excreted as water vapor from sweat and respired air, 2.3% (0.352 kg) is excreted as water in feces, and 38.8% (5.937 kg) is excreted as water in urine[34]. It is assumed that all excreted water vapor from sweat and respired air is condensed in the HVAC and sent to the WRS. Loadings to the WRS from a four-person crew are assumed to be the same every day as listed in Table 13.

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[33] Lange, K.E.; Lin, C.H. Advanced Life Support Program Requirements Definition and Design Considerations, CTSD-ADV-245 (Rev A), JSC 38571, January 1998, Table 13, Nominal Physiological Loads.

[34] Lange, K.E.; Lin, C.H. Advanced Life Support Program Requirements Definition and Design Considerations, CTSD-ADV-245 (Rev A), JSC 38571, January 1998, Table 13, Nominal Physiological Loads.

Table 13. Loading to the WRS from the Crew.

Source	Loading (kg/d)
Oral Hygiene	1.44[35]
Flush Water	1.96[36]
Water from Sweat and Respired Air	9.01
Water in Urine	5.94
Water in Feces	0.35
Hand/Face Wash Water	16.32[37]
Shower Water	25.6[38]
Clothes Wash Water	49.88[39]
Total	**110.50**

It is assumed that 99.45% of shower water, hand/face wash water and clothes wash water (91.29 kg/d) are sent to the WRS directly, and that 0.55% (0.505 kg/d) is evaporated and eventually condensed and sent to the WRS. For the purposes of water supply to the crew and the FPS, it is assumed that only one hot water user may access heated potable water at a time (i.e. the dishwasher will not be run while a crew member is taking a shower, etc). Thus, all crew and FPS water streams that require heating (shower water, face/hand wash water, clothes wash water, and dish washing water) are lumped into one overall steady-state flowrate of 113.56 kg/d.

It is assumed that one average sized load of laundry is done per day and that 228 m^3/d (294.1 kg/d) of air is allotted for clothes drying[40].

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[35] Drysdale, Alan; Hanford, Anthony. Advanced Life Support Systems Modeling and Analysis Project Baseline Values and Assumptions Document, CTSD-ADV-371, JSC 39317, June 18, 1999, Table 15, 0.36 kg/per-d.

[36] Drysdale, Alan; Hanford, Anthony. Advanced Life Support Systems Modeling and Analysis Project Baseline Values and Assumptions Document, CTSD-ADV-371, JSC 39317, June 18, 1999, Table 15, 0.49 kg/per-d.

[37] Drysdale, Alan; Hanford, Anthony. Advanced Life Support Systems Modeling and Analysis Project Baseline Values and Assumptions Document, CTSD-ADV-371, JSC 39317, June 18, 1999, Table 15, 4.08 kg/per-d.

[38] Pickering, Karen D.; Edeen, Marybeth A. Lunar-Mars Life Support Test Project Phase III Water Recovery System Operation and Results. 28th International Conference on Environmental Systems, SAE #981707, 1998.

[39] Drysdale, Alan; Hanford, Anthony. Advanced Life Support Systems Modeling and Analysis Project Baseline Values and Assumptions Document, CTSD-ADV-371, JSC 39317, June 18, 1999, Table 15, 12.47 kg/per-d.

3.4 Solids Processing System

Steady-state flowrates of reactants and products to and from the SPS are required to determine impacts on the rest of the system. The amount and composition of solid waste sent to the SPS affects the flowrate and composition of the products of solid waste oxidation. Oxygen consumed by the SPS affects the amount of oxygen generation that the ARS must perform. Carbon dioxide produced by the SPS impacts the amount of CO_2 removal that the ARS must do. The amount of nitrogen gas that is produced by the SPS reduces the amount of leakage makeup gas that must be supplied to the system. The amount of water that is produced by the SPS affects the loading to the WRS.

For the 120-day BIO-Plex test, 25% of the solid products of human metabolism, inedible biomass and wasted edible biomass are oxidized in the solids processing system. Table 14 shows the compositions of reactants urine solids, feces solids, sweat solids, protein, carbohydrate, fat, fiber, lignin and oxygen as well as products carbon dioxide, water and nitrogen gas. Chemical compositions of reactants and products are taken from Volk and Rummel, 1987. Total wet solids mass loading to the SPS is 3.334 kg/d. The wet solids are 84.2% water by mass, thus dry solids used in the stoichiometric calculation below are 0.526 kg/d. It is assumed that water delivered to the SPS outflow air is eventually condensed and sent to the WRS.

Such a small amount of waste is not typically incinerated on a continuous basis. For instance, in the LMLSTP Phase III Test Bed, approximately 3840 mL of 50% fecal/water slurry were collected and burned every 4 days for approximately 3.2 hours at a rate of 20mL/min. However, consideration of steady-state conditions with 45% of food grown in the BIO-Plex and 25% of solid waste treatment necessitates the assumption of use of an atypically-small incinerator vessel. Startup conditions (specifically startup power requirements) are ignored, and it is assumed that a steady-state temperature is maintained within the incineration vessel, with continuous feed and air flow through the system.

Table 14. Chemical Compositions of Reactants and Products of Solid Waste Oxidation.

Reactant or Product	Chemical Formula	Molecular Weight (g/mol)
Urine Solids	$C_2H_6O_2N_2$	90
Feces Solids	$C_{42}H_{69}O_{13}N_5$	851
Sweat Solids	$C_{13}H_{28}O_{13}N_2$	420
Protein	C_4H_5ON	83

[40] This is 200cfm air flow. This is from www.doityourselfparts.com/images/APPLIANCES/LAUNDRY/SPEC_DRYERS.jpg

Carbohydrate	$C_6H_{12}O_6$	180
Fat	$C_{16}H_{32}O_2$	256
Fiber	$C_6H_{10}O_5$	162
Lignin	$C_{10}H_{11}O_2$	163
Oxygen	O_2	32
Carbon Dioxide	CO_2	44
Water	H_2O	18
Nitrogen Gas	N_2	28

Table 15 lists reactants and products in terms of moles and mass for solid waste oxidation based upon the diet discussed in section 3.1 of this document, with 45% of the required food mass provided by crops and treatment of 25% of the solid wastes.

Table 15. Reactants and Products in Solid Waste Oxidation with Production of 45% of Required Food and Treatment of 25% of Solid Wastes (by mass).

Compound	Quantity Reacted or Produced (mol/d)	Quantity Reacted or Produced (kg/d)
Urine Solids	0.455	0.041
Feces Solids	0.186	0.158
Sweat Solids	0.017	0.007
Protein (edible and inedible)	1.164	0.097
Carbohydrates	0.053	0.010
Fat	0.005	0.001
Fiber	1.068	0.173
Lignin	0.245	0.040
Oxygen	26.41	0.845
Carbon Dioxide	22.84	1.005
Water	18.00	0.324
Nitrogen Gas	1.518	0.043

The overall reaction of solid waste oxidation with growth of 45% of the required food mass and treatment of 25% of the solid wastes is:

$0.455\ C_2H_6O_2N_2 + 0.186\ C_{42}H_{69}O_{13}N_5 + 0.017\ C_{13}H_{28}O_{13}N_2 + 1.164\ C_4H_5ON + 0.053\ C_6H_{12}O_6 + 0.005\ C_{16}H_{32}O_2 + 1.068\ C_6H_{10}O_5 + 0.245\ C_{10}H_{11}O_2 + 26.41\ O_2$ ◊ $22.84\ CO_2 + 18.00\ H_2O + 1.518\ N_2$

If it is assumed that 50% of the O_2 in the inlet air to the SPS is utilized in oxidation, then the required air flowrate through the SPS is 7.344 kg/d air. This flowrate is based upon oxidation stoichiometry and the composition of the air (20.6% O_2 by volume) in the crew air loop (see Table 17 below).

3.5 Atmosphere Revitalization System

Steady-state mass flows of atmospheric gases must be adjusted for leakage that occurs from the BIO-Plex chamber. During the 120-day test, the BIO-Plex configuration will consist of a Biomass Production Chamber, Life Support Chamber, Habitation Chamber, Interconnecting Tunnel, and Airlock, all of cylindrical geometry[41]. A Utilities Distribution Module will be included in the BIO-Plex, but it will be separated atmospherically from the rest of the chambers[42]. Table 16 shows the volume of the BIO-Plex during the 120-day test, disregarding the Utilities Distribution Module.

Table 16. Volumes of the BIO-Plex in the 120-day Test, Excluding the Utilities Distribution Module[43].

Component	Diameter (m)	Length (m)	Volume (m^3)
BPC1	4.60	11.30	187.79
Life Support Chamber	4.60	11.30	187.79
Habitation Chamber	4.60	11.30	187.79
Interconnecting Tunnel	3.70	19.20	206.44
Airlock	3.70	4.60	49.46
Total			**819.28**

As previously mentioned, separate plant/crew air loops will be incorporated for the 120-day test. Table 17 shows the estimated daily gas leakage rates for the air loop involving the Life Support Chamber, Habitation Chamber, Interconnecting Tunnel and Airlock, assuming an Earth-normal atmospheric composition, temperature of 20 ºC, humidity ratio of 0.01, and a leakage rate of 1% by volume per day. Table 18 shows the estimated daily gas leakage rates for the air loop for BPC1 assuming a BPC-specific atmospheric composition, temperature of 20 ºC, humidity ratio of 0.011, and a leakage rate of 1% by volume per day. Table 19 shows total leakage rates of gases from the BIO-Plex.

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[41] Tri, Terry O. Bioregenerative Planetary Life Support Systems Test Complex (BIO-Plex): Test Mission Objectives and Facility Development. 29th International Conference on Environmental Systems, SAE #1999-01-2186, 1999.

[42] Tri, Terry. Personal communication dated 7/22/99.

[43] Kirby, Gina M. Bioregenerative Planetary Life Support Systems Test Complex: Facility Description and Testing Objectives. 27th International Conference on Environmental Systems, SAE #972342, 1999.

Table 17. Gas Leakage Rates from the Habitation Chamber, Life Support Chamber, Interconnecting Tunnel and Airlock of the BIO-Plex for the 120-day Test.

Gas	Partial Pressure (atm)	Volume in BIO-Plex (m^3)	Leakage (m^3/d)	Leakage (mol/d)	Leakage (kg/d)
Nitrogen	0.778	491.0	4.910	204.2	5.716
Oxygen	0.206	130.2	1.302	54.15	1.733
Carbon Dioxide	0.0004	0.249	0.003	0.104	0.005
Water Vapor	0.016	9.970	0.100	4.145	0.075
Total	**1.000**	**631.5**	**6.315**	**262.6**	**7.528**

Table 18. Gas Leakage Rates from BPC1 of the BIO-Plex for the 120-day Test.

Gas	Partial Pressure (atm)	Volume in BIO-Plex (m^3)	Leakage (m^3/d)	Leakage (mol/d)	Leakage (kg/d)
Nitrogen	0.778	146.03	1.460	60.72	1.700
Oxygen	0.203	38.17	0.382	15.87	0.508
Carbon Dioxide	0.0012[44]	0.222	0.002	0.092	0.004
Water Vapor	0.018	3.380	0.034	1.405	0.025
Total	**1.000**	**187.8**	**1.878**	**78.08**	**2.237**

Table 19. Total Leakage Rate from the BIO-Plex for the 120-day Test.

Gas	Leakage Rate (kg/d)
Nitrogen	7.416
Oxygen	2.241
Carbon Dioxide	0.009
Water Vapor	0.100
Total	**9.765**

The flows of gases to/from the atmosphere are based on stoichiometric calculations for flows to/from the Crew, BPC1 and SPS. Appropriate partial pressures and atmospheric compositions must be maintained through atmosphere revitalization and addition of makeup gases. Physical/chemical atmosphere revitalization techniques considered for this study that may require heating or cooling of mass flows include CO_2 removal, O_2 generation and trace contaminant control.

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[44] Drysdale, Alan; Hanford, Anthony. Advanced Life Support Systems Modeling and Analysis Project Baseline Values and Assumptions Document, CTSD-ADV-371, JSC 39317, June 18, 1999. Table 3.2.1.

The required rate of CO_2 removal for the crew air loop for steady-state conditions can be calculated by accounting for CO_2 output by humans, CO_2 output by the SPS, and the loss of CO_2 from the atmosphere through leakage. The required rate of O_2 removal for the BPC1 air loop for steady-state conditions can be calculated by accounting for O_2 production by the crops and the loss of O_2 from the atmosphere through leakage.

Table 20 shows the removal and makeup requirements of CO_2 and O_2 for the crew and BPC1 air loops. Positive values indicate a removal requirement for a particular gas, and negative values indicate a makeup requirement for a particular gas. In order to maintain the desired air composition of the crew and BPC1 air loops as defined in Table 17 and Table 18, the air flowrate from the crew air loop to the CO_2 removal unit should be 7129 kg/d (4.318 kg/d CO_2). Net O_2 deficits in the system (2.713 kg/d) will require electrolysis of water at a rate of 3.051 kg/d, which is supplied from WRS potable water. Electrolysis of 3.051 kg/d of water produces 0.339 kg/d of H_2, which is vented.

Also, in order to maintain the desired air composition of the crew and BPC1 air loops as defined in Table 17 and Table 18, the air flowrate from the BPC1 air loop to the O_2 removal unit should be 11.35 kg/d. Net CO_2 deficits in the BPC1 chamber will require supply of CO_2 from the CO_2 removal unit at a rate of 3.489 kg/d. Table 21 summarizes mass flows in the ARS.

Table 20. Net Gains/Losses of Gases from the Crew Air Loop.

Gas	Crew Removal/Makeup Requirements[45, 46] (kg/d)	BPC1 Removal/Makeup Requirements[47] (kg/d)
CO_2	+4.318	-3.489
O_2	-5.290	+2.577

Air flow rates to the trace contaminant control system (TCCS) are assumed to be identical to those in the LMLSTP Phase III 90-day Test Bed at 1579 kg/d (850 L/min).

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[45] See Table 12. Reactants and Products in Human Metabolism with Production of 45% of Required Food (by mass). and Table 17. Gas Leakage Rates from the Habitation Chamber, Life Support Chamber, Interconnecting Tunnel and Airlock of the BIO-Plex for the 120-day Test.

[46] See Table 15. Reactants and Products in Solid Waste Oxidation with Production of 45% of Required Food and Treatment of 25% of Solid Wastes (by mass). and Table 17. Gas Leakage Rates from the Habitation Chamber, Life Support Chamber, Interconnecting Tunnel and Airlock of the BIO-Plex for the 120-day Test.

[47] See Table 10. Reactants and Products in Crop Growth with Production of 45% of Required Food (by mass). and Table 18. Gas Leakage Rates from BPC1 of the BIO-Plex for the 120-day Test.

Table 21. Summary of Mass Flows in the ARS at Steady-State.

Compound	Flowrate (kg/d)	Origin	Destination
CO_2	4.318	Crew Atmosphere	CO_2 Scrubber
O_2	2.577	BPC1 Atmosphere	O_2 Scrubber
H_2O	3.051	WRS	O_2 Generation Unit
CO_2	3.489	CO_2 Scrubber	BPC1 Atmosphere
O_2	5.290	O_2 Scrubber	Crew Atmosphere
O_2	2.713	O_2 Generation Unit	Crew Atmosphere
H_2	0.339	O_2 Generation Unit	Vent

3.6 Water Recovery System

Water flows to the WRS have been discussed previously and include those listed in Table 22.

Table 22. Daily greywater flows to the WRS for the Example System.

Subsystem	Source	Steady-State Flowrate (kg/d)
BPC1	Inedible Biomass Water[48]	9.181
	Crop Transpirate	368.7
FPS[49]	Dried Crop Water	0.024
	Dish Washing Water	21.76
	Wasted Edible Crop Water	0.239
	Food Preparation Water	2.800
Crew	Oral Hygiene Water	1.440
	Flush Water	1.960
	Sweat and Respired Water	9.013
	Urine Water	5.937
	Feces Water	0.352
	Hand/Face Washing Water	16.32
	Shower Water	25.60
	Clothes Washing Water	49.90
SPS	SPS Product Water[50]	0.324
Total		**513.6**

Air flow rates through the air evaporation system in the LMLSTP Phase III test were approximately 40 cfm (2104 kg/d) for treating a greywater flowrate of 16.2 kg/d (15% of the greywater loading). Thus, it will be assumed that a similar arrangement in the BIO-Plex that treats 513.6 kg/d of greywater would have an air flowrate of 66,703 kg/d.

3.7 Summary of Flowrates

Table 23 summarizes the steady-state flowrates that require heating or cooling in the example system in which 45% of the crew food is grown and 25% of the solid wastes are treated. Mass flows consist of either water or air, and they have been categorized so in Table 23.

[48] See section 3.1

[49] See section 3.2.

[50] See Table 15. Reactants and Products in Solid Waste Oxidation with Production of 45% of Required Food and Treatment of 25% of Solid Wastes (by mass).

Table 23. Steady-State Mass Flowrates of Interest for the Pinch Technique in the Example System.

Stream	Location	Steady-State Flowrate
Water	Hydroponic solution	677,981 kg/d
	Crew/FPS (hygiene water)	113.6 kg/d
	WRS (greywater)	513.6 kg/d
Air	Crop dryer	6.320 kg/d
	Clothes dryer	294.1 kg/d
	SPS	5.508 kg/d
	CO_2 removal unit	7129 kg/d
	TCCS	1579 kg/d
	AES	66,703 kg/d

4 Determining Flow Characteristics for Application of the Pinch Technique

In order to apply the Pinch Technique, mass flows that require heating or cooling must be assessed for their heat duty, considering the mass flowrate, supply and target temperatures, and heat of vaporization and/or reaction.

In order to have maximal flexibility in application of the Pinch Technique to hot and cold streams in the example system, typically-applied heat exchangers within a unit are disregarded. Excluding unit-contained heat exchangers from the example design allows for trading of waste heat from any hot stream to any cold stream within the BIO-Plex.

Water flows that require heating or cooling in the example system are hydroponic solution water, hygiene/clotheswasher/dishwasher water (collectively referred to as hygiene water), greywater to the APCOS, and solid amine water desorption steam. The supply and target temperatures for these water flows are fixed and will not be considered for alteration in reusing waste heat.

Air flows that require heating or cooling in the example system are fluidized combustion unit air, catalytic gas cleanup air, TCCS air (Englehard catalyst#1 and #2), crop dryer air, clothes dryer air, and air through the AES. The first three of these air streams have fixed flowrates as well as fixed supply and target temperatures. The latter three of these air streams (crop dryer air, clothes dryer air and AES air) have flexible temperatures and/or flowrates, which vary with air relative humidity.

The large waste heat load from BPC1 lamps may be represented with an air-cooling flow stream, having a flexible flowrate as well as flexible supply and target temperatures.

In the following sections, each possible hot and cold stream is discussed, along with any degree of flexibility with respective flowrates and temperatures.

4.1 Hydroponic Solution Water

It was mentioned in section 3.1 that 677,981 kg/d of hydroponic solution flow must be considered for cooling. The hydroponic solution must be cooled from ambient temperature in the BPC (approximately 298 K; 77 ºF; 25 ºC) to approximately 294K (70 ºF; 21 ºC). Water has a heat capacity of 4.179 kJ/kg-K at BPC1 ambient temperature of approximately 298 K.

4.2 Hygiene Water

All crew and FPS water streams that require heating (shower water, face/hand wash water, clothes wash water, and dish washing water) are lumped into one overall steady-state inflow of 113.56 kg/d as discussed in section 3.3. A target temperature of 341 K (154 ºF; 68 ºC) is assumed for all hygiene water loads. The heat capacity of water at 295 K (ambient temperature) is 4.178 kJ/kg-K.

Outflow greywater must be cooled to ambient temperature. Since 0.55% of the heated water is assumed to evaporate, the outflow of greywater is 112.92 kg/d. The heat capacity of water at 341 K is 4.188 kJ/kg-K.

4.3 APCOS Water

The Aqueous Phase Catalytic Oxidation System requires that 513.6 kg/d greywater be heated to 422K (300 ºF; 149 ºC). It is assumed that waste heat from the AES is not used in a regenerative heat exchanger to heat water entering the APCOS (as was done in the LMLSTP Phase III test bed), so that the APCOS water must be heated from ambient temperature (water heat capacity of 4.178 kJ/kg-K). APCOS outflow water must then be cooled to ambient temperature from a temperature of 422 K, at which the heat capacity of water is 4.307 kJ/kg-K.

4.4 Solid Amine Water Desorption Steam

The solid amine water desorption CO_2 removal system requires steam to be passed over the bed during the CO_2 desorption phase. In a study by Heppner and Schubert[51] on solid amine water desorption, 14.4 kg water was required to be converted to steam in the

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[51] Happner, D.B. and Schubert, F.H. Electrochemical and Steam-Desorbed Amine CO_2 Concentration: Subsystem Comparison. SAE 831120.

desorption phase for removal of 4 kg/d of CO_2 from a saturated bed. Thus, it is assumed that 15.545 kg/d of water are required for desorption via steam for removal of 4.318 kg/d CO_2[52]. The heat capacity of steam (373 K) is 4.187 kJ/kg-K.

4.5 Fluidized Combustion Unit Air

The air flowrate to the fluidized bed combustion unit was shown in section 3.4 to be 7.344 kg/d. The target temperature for the inflow air will be assumed to be 1033 K (1400 ºF; 760 ºC), which is the same as that for the LMLSTP Phase III test bed for treating a 50% feces solids slurry. Inflow air must be heated from ambient temperature (295 K), at which air has a heat capacity of 1.004 kJ/kg-K. Outflow air from the fluidized bed is sent directly to the catalytic gas cleanup system.

4.6 Catalytic Gas Cleanup Air

Air flow to the catalytic gas cleanup system is identical to that of the fluidized bed combustion unit (5.508 kg/d). Air to the catalytic gas cleanup system is assumed to be heated to 1073 K (1472 ºF; 800 ºC), as was done in the LMLSTP Phase III test bed. The temperature of the air flowing into the catalytic gas cleanup system is 1033 K (1400 ºF; 760 ºC), for which the heat capacity is 1.136 kJ/kg-K.

Outflow air from the catalytic gas cleanup system must be cooled down to ambient temperature from the outflow temperature of 1073 K, at which the heat capacity of air is 1.143 kJ/kg-K.

4.7 TCCS Air

Inflow air to the TCCS was described in section 3.5 as 1579 kg/d. The first unit in the TCCS (ammonia removal catalyst) requires that air be heated to 474 K (394 ºF; 201 ºC) from ambient temperature (295 K) at which the heat capacity of air is 1.004 kJ/kg-K. It is also required that air passing through the second Englehard catalyst (10% of the total airflow) be heated to 674 K (754 ºF; 401 ºC) from 474 K, at which the heat capacity of air is 1.014 kJ/kg-K.

In the LMLSTP Phase III Test Bed, the TCCS incorporated a high efficiency counterflow plate/fin air-to-air heat exchanger which traded waste heat from the outflow stream of the second Englehard catalyst to the inflow air to the headworks of the TCCS. However, a unit-contained heat exchanger will not be included in the assumptions for this study. Thus, the 10% of the total air that exits the second Englehard catalyst must be cooled to

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[52] See section 3.5

295 K from a temperature of 674 K, at which the heat capacity of air is 1.059 kJ/kg-K. The remaining 90% of the total air exiting the first Englehard catalyst must be cooled to 295 K from 474 K, at which the heat capacity of air is 1.014 kJ/kg-K, before entering the final sorbent bed.

4.8 Crop Dryer Air

The crop dryer air flowrate and air temperatures for the example system were described in section 3.2(6.32 kg/d inflow at 303 K). The heat capacity of air at ambient temperature (assumed to be 295 K here) is 1.004 kJ/kg-K. The heat of vaporization of crop water reduces the outflow air to ambient temperature, thus the outflow air does not require cooling.

The incoming air temperature is flexible but should not exceed 303 K, which is the maximum recommended drying temperature for soybeans. However, a temperature less than 303 K may be used to dry the crops. Saturated air cannot be used for drying purposes, hence the inflow air temperature is limited by the humidity ratio of the crew air loop. However, it is not expected that air with a temperature lower than the ambient temperature will be used for drying, so the crew air ambient temperature may be taken as the lower limit for inlet air. If air from a source other then the crew air loop is used as inlet air, then the lower temperature limit may change, depending on the relative humidity of the inlet air.

4.9 Clothes Dryer Air

The clothes dryer air flowrate was mentioned in section 3.3 as 294.1 kg/d. It is assumed that the air inflow temperature for clothes dryer air is 333 K (140 ºF; 60 ºC). If the dryer is required to vaporize 0.274 kg of water (0.55% of 49.88 kg; see Table 13), and the inflow humidity ratio is 0.01, then the outflow temperature of the air will be 331.5 K (137 ºF; 58.3 ºC).

The incoming air temperature should not exceed 333 K for safety reasons, but the temperature may be reduced. As with the crop dryer air, saturated air cannot be used for drying purposes. The inflow air temperature is limited by the humidity ratio of the crew air loop. Again, it is not expected that air with a temperature lower than the ambient temperature will be used for drying, so the crew air ambient temperature may be taken as the lower limit for inlet air. If air from a source other then the crew air loop is used as inlet air, then the lower temperature limit may change, depending on the relative humidity of the inlet air.

4.10 Air Evaporation System Air

The WRS has to treat approximately 513.6 kg/d greywater, of which 100% passes through the AES in the example system. It was shown in section 3.6 that air flowrates through the AES will be 66,703 kg/d.

It will be assumed that the AES requires heated air to 338 K (149 ºF; 65 ºC), which was the air inflow temperature in the LMLSTP Phase III test bed air evaporation system. It is assumed that the air must be heated from ambient temperature (295 K), at which the heat capacity of air is 1.004 kJ/kg-K.

Outflow air must be cooled to ambient temperature (295 K). If an air flowrate of 66,703 kg/d at 338 K (149 ºF; 65 ºC) and a humidity ratio of 0.1 is used to vaporize 513.6 kg/d of water, the outflow temperature of the air will be 321 K (118 ºF; 47.8 ºC). At 321 K, the heat capacity of air is 1.006 kJ/kg-K.

Similarly to the crop dryer and clothes dryer specifications, AES flowrates and temperatures are flexible. The upper air temperature limit is determined by safety considerations and the maximum temperature that AES equipment can withstand. An upper temperature limit of 333 K (140 ºF; 60 ºC) will be assumed, based on consideration for avoidance of skin burns.

As with the crop dryer and clothes dryer, saturated air cannot be used for drying purposes. The inflow air temperature is limited by the humidity ratio of the crew air loop. Again, it is not expected that air with a temperature lower than the ambient temperature will be used for drying, so the crew air ambient temperature may be taken as the lower limit for inlet air. If air from a source other then the crew air loop is used as inlet air, then the lower temperature limit may change, depending on the relative humidity of the inlet air.

4.11 Lamp-Cooling Air

Heat-collecting air through the lamps has limits in terms of flowrate and temperatures which are determined by the maximum temperature that can be experienced by HPS lamps and the minimum air temperature that can flow through the light box without occurrence of condensation on the lamps.

Cooling requirements for the light box will depend upon the power load to the BPC1 lamps. In order to determine what percentage of the total available lighting will be used, a plant lighting delivery efficiency must be determined. Plant lighting delivery efficiency is defined as the amount of light delivered for a given amount of energy giong into the lighting system. It is assumed here that the BPC1 lighting system is sized based on wheat, since wheat requires the highest photosynthetic photon flux (PPF). Therefore, the wheat tray with the lowest lighting intensity per unit area (2704 W/m^2) is used as the basis for determining the lighting delivery efficiency from which the lighting use percentages for the other trays can be calculated. Using 96 lamps at 400 W each for the 14.17 m^2 wheat crop tray in order to achieve a PPF of 1500 µmols/m^{2}s corresponds to a plant energy delivery efficiency of 0.55 µmols /J. This is consistent with the BVAD, which specifies a range of 1.98 to 5.56 lamps per square meter area to give 1000 µmols/m^{2}s[53]. The percentage of available lighting that is actually used in each tray, as shown in Table 24, enables determination of lamp heat loads for each light box of HPS 400 W lamps.

Table 24. BPC1 Lighting Intensities, Percentage of Available Lighting Used and Resultant Heat Loads.

Crop	PPF Required (µmols/m^2-s)	Lamps per Tray[54]	Tray Area (m^2)	Light Intensity[55] (W/m^2)	Available Lighting Used (%)	Number of Trays	Power Load (kW)
Wheat	1500	96	14.17	2710	100	1	38.40
Wheat	1500	30	3.35	3582	75.7	2	18.17
Soybean	1000	96	14.17	2710	66.7	3	76.84
Potato	1000	60	6.19	3877	46.6	1	11.18
Sweet Potato	1000	60	6.19	3877	46.6	1	11.18
Tomato	1000	30	3.35	3582	50.4	1	6.048
Salad Mix	350	30	3.35	3582	17.7	1	2.124
Total							**163.9**

If it is assumed that 66% of the power load must be removed as heat directly from the light boxes[56] (the other 34% must be removed from the growing area), then the required heat load to remove from the light boxes is 108.2 kW. It will be assumed that the maximum allowable air temperature in the light boxes is 473 K (392 ºF; 200 ºC). The minimum inflow temperature is that at which 0.011 (BPC1 air humidity ratio) is the dew point temperature, which is the temperature below which undesirable condensation would occur in the light box. At a humidity ratio of 0.011, the dew point temperature of air is

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[53] Drysdale, Alan; Hanford, Anthony. Advanced Life Support Systems Modeling and Analysis Project Baseline Values and Assumptions Document, CTSD-ADV-371, JSC 39317, June 18, 1999, Table 3.10.2.

[54] Castillo, Juan. Personal communication, June 1999.

[55] Ballast power of 60 W per lamp is not included.

[56] Ewert, Mike. Unpublished data, personal communication, June 1999.

approximately 289 K (60 ºF; 15.6 ºC). If an air stream with a humidity ratio other than that of the BPC1 air was used, then the minimum air inflow temperature would change accordingly.

The air flowrate that is required to cool the light boxes depends upon the inflow and outflow air temperatures, according to the equation:

$$Q = mC_p(T_{out} - T_{in})$$

where Q = heat load to be removed; 108.2 kW in this example system,

m = mass flowrate of air in kg/d,

C_p = heat capacity of air at the inflow temperature (kJ/kg-K),

T_{in} = light box inlet air temperature (K),

T_{out} = light box outlet air temperature (K).

The above equation shows that the mass flowrate of air may be strategically chosen so as to maximize the usefulness of inlet and outlet air streams in applying the Pinch Technique.

4.12 Summary

Sections 4.1 through 4.11 describe characteristics of flowrates to consider in application of the Pinch Technique to the example system described in this document. For such a system, in order to achieve the highest possible power savings, the traditional Pinch Technique must be retailored to account for streams with a range of possible temperatures and flowrates.

5 Future Work

The next step in applying a modified version of the Pinch Technique is to develop temperature interval analysis charts for combinations of fixed and flexible streams in terms of their temperature and flow characteristics. Temperature interval analyses will lead to determination of the best temperature and flow choices (for streams with flexible characteristics) as well as the maximum possible amount of power reduction that will result from reusing waste heat.

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7 Acronyms and Abbreviations

AES	Air Evaporation System
ALS	Advanced Life Support
APCOS	Aqueous-Phase Catalytic Oxidation System
ARC	Ames Research Center
ARS	Atmosphere Revitalization System
BIO-Plex	Bioregenerative Planetary Life Support Systems Test Complex
BPC1	Biomass Production Chamber #1
BVAD	Baseline Values and Assumptions Document
CO_2	Carbon Dioxide Gas
CTSD	Crew and Thermal Systems Division
$C_2H_6O_2N_2$	Urine solids
C_4H_5ON	Protein (edible or inedible)
$C_6H_{12}O_6$	Carbohydrate
$C_6H_{10}O_5$	Fiber
$C_{10}H_{11}O_2$	Lignin
$C_{13}H_{28}O_{13}N_2$	Sweat solids
$C_{16}H_{32}O_2$	Fat
$C_{42}H_{69}O_{13}N_5$	Feces solids
FPS	Food Processing System
HNO_3	Nitric Acid
HPS	High-Pressure Sodium
HVAC	Heating, Ventilation and Air Conditioning
H_2	Hydrogen Gas
H_2O	Water
ICES	International Conference on Environmental Systems
JSC	Johnson Space Center
KSC	Kennedy Space Center
LMLSTP	Lunar-Mars Life Support Test Project

NASA	National Aeronautics and Space Administration
N_2	Nitrogen Gas
O_2	Oxygen Gas
PPF	Photosynthetic Photon Flux
SAE	Society of Automotive Engineers
SMAP	Systems Modeling and Analysis Project
SPS	Solids Processing System
TCCS	Trace Contaminant Control System
WRS	Water Recovery System