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Project Title	Multiobjective Optimization of Hybrid Regenerative Life Support Technologies(Topic D: Technology Assessment)
Principal Investigator	Vasilios Manousiouthakis, Associate Professor

5531-J Boelter Hall
Department of Chemical Engineering
University of California, Los Angeles
Los Angeles, CA 90095
(310)825-9385

1 Introduction

In the first year of this project we developed simple mathematical models for many of the technologies constituting the water reclamation system in a space station. These models were employed for subsystem optimization and for the evaluation of the performance of individual water reclamation technologies, by quantifying their operational "cost" as a linear function of weight, volume, and power consumption. Then we performed preliminary investigations on the performance improvements attainable by simple hybrid systems involving parallel combinations of technologies.

In the second year of the project, we are developing a software tool for synthesizing a hybrid water recovery system (WRS) for long term space missions. As conceptual framework, we are employing the state space approach [1]. Given a number of available technologies and the mission specifications, the state space approach would help design flowsheets featuring optimal process configurations, including those that feature stream connections in parallel, series, or recycles.

We visualize this software tool to function as follows: given the mission duration, the crew size, water quality specifications, and the cost coefficients, the software will synthesize a water recovery system for the space station. It should require minimal user intervention. Its overall structure is shown in Figure 1. The following tasks need to be solved for achieving this goal:

- Formulate a problem statement that will be used to evaluate the advantages of a hybrid WRS over a single technology WRS.
- Model several WRS technologies that can be employed in the space station.
- Propose a recycling network design methodology. Since the WRS synthesis task is a recycling network design problem, it is essential to employ a systematic method in synthesizing this network.

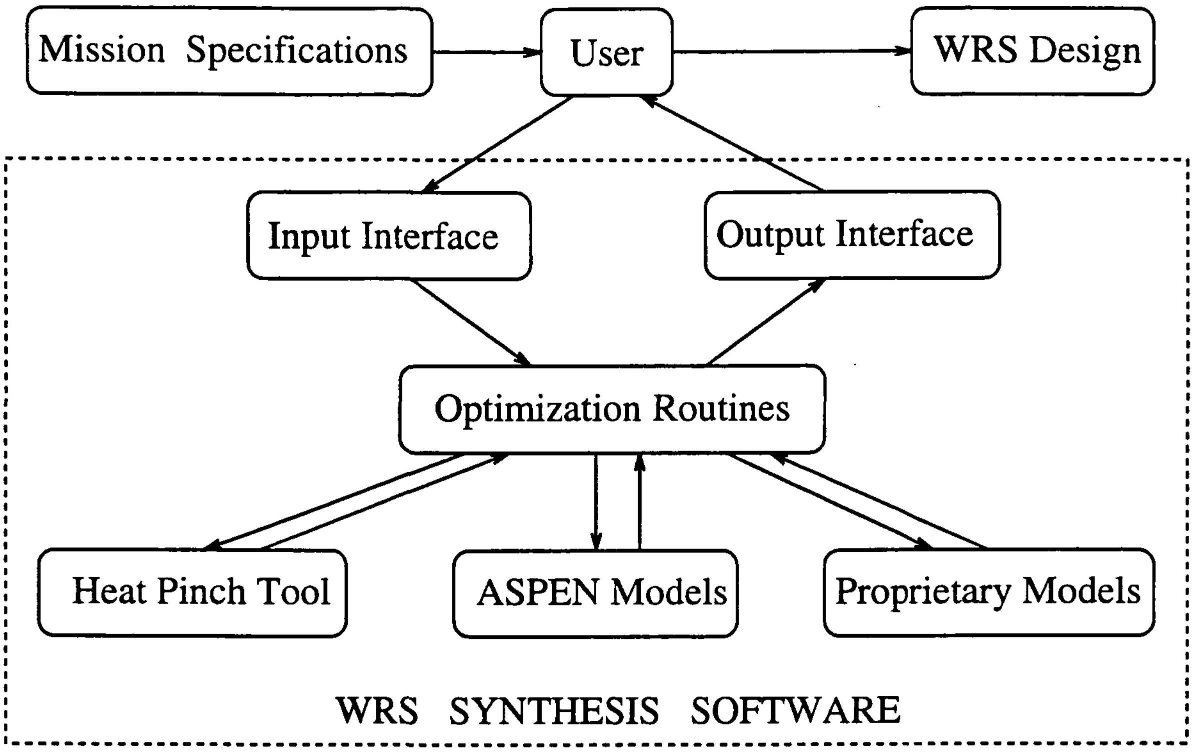

Figure 1: Structure of the proposed water reclamation system design software.

- Develop a software implementation for this design methodology. Design a hybrid system using this software and compare the resulting WRS with a base-case WRS.
- Create a user-friendly interface for this software tool.

Our efforts towards addressing these tasks are outlined below.

2 Problem Definition

The associated recycling network design task is:

> Given a set of feed streams that need to be recycled, with known flowrates, and inlet compositions and enthalpies; a set of product streams with known specifications on outlet compositions and enthalpies; a set of water reclamation technologies to be considered; and a set of auxiliary feed streams (e.g., air); determine the minimum "cost" system that delivers the product specifications.

The "cost" is a known linear function of weight, volume, and power consumption.

This problem statement is shown in Figure 2. The solution obtained to the above optimization task is the required WRS configuration that is indicated as a box in the figure.

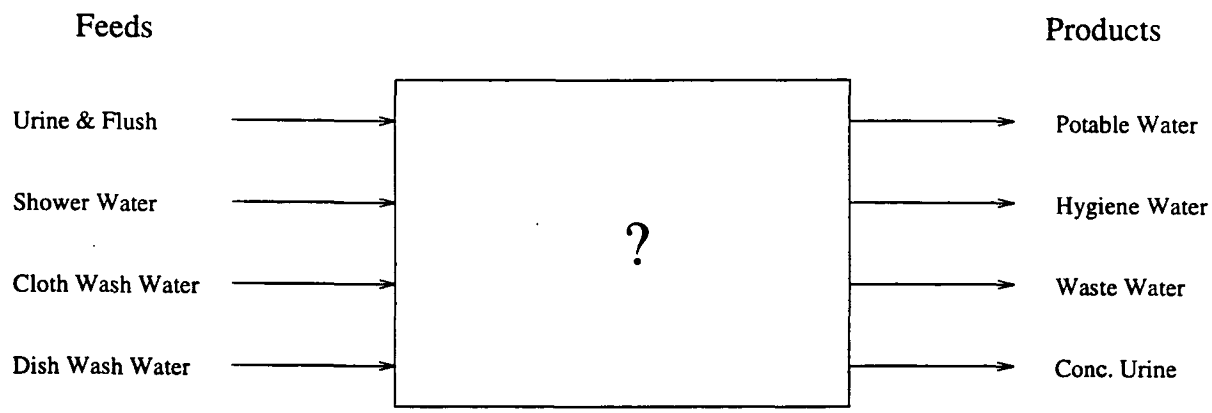

Figure 2: Input-Output diagram for a water recovery system. The physical properties of each stream are shown in Tables 1 and 2.

2.1 Technical Specifications

To proceed towards solution of this recycling network design task, we must first determine the inlet conditions of our feed streams and the outlet specifications on our product streams.

As feed streams, we consider four water streams: urine and flush, shower water, cloth wash water, dish wash water; their inlet compositions are given in Table 1. In reality, the space station wastewaters contain over 150 components. Most of these components are present in trace amounts. However, in Table 1, we neglect most of these trace components, and focus primarily on the components considered in our previous report [5]. The exact inlet compositions for each component are based on the data in [4], but some chemical species have been consolidated into one representative chemical of the same category. Though there are other waste water streams in the space mission, only the above four have significant flowrates to be reusable.

The water recovery system must deliver two purified water streams with different specifications: potable water and hygiene water. Specifications on these streams are shown in Table 2. These specifications have been derived from [3]. There are two waste effluents from the purification process: effluent water and concentrated urine. Part of the effluent water stream could be recycled back into the process.

In the entire process, we have restricted the water streams to contain only 11 components. This simplified representation yields optimization problems that are easier to solve. The components considered in the streams are: urea, creatinine, H_2O, NaCl, phenol, soap, and NH_3. Besides these species, O_2, N_2, N_2O, CO_2 are also considered, since they are present in the two reactors of the VPCAR subsystem.

The heat loss or gain to the environment from the system is modeled by considering the environment air as the heating or cooling medium [4].

The above feed and product streams constitute the typical input-output specifications for a water recovery system. The proposed software tool will use these specifications. However, the user can alter them to match the needs of a particular mission.

	Urine & Flush	Shower Water	Cloth Wash Water	Dish Wash Water
Temp(K)	297.26	360.00	360.00	360.00
Pres(Pa)	94400.00	2.0137E5	2.0137E5	1.0137E5
Flow Rate(kg/day)	1.8962E-3	6.1818E-4	1.3763E-3	6.2847E-4
Urea	1.0024E-2	9.2045E-4	6.9047E-4	0.0
Creatinine	5.0651E-3	1.7008E-3	1.3009E-3	0.0
H_2O	9.7717E-1	9.9099E-1	9.9611E-1	9.9490E-1
NaCl	7.2132E-3	6.7813E-4	4.7736E-4	0.0
Phenol	5.2698E-4	0.0	0.0	0.0
Soap	0.0	5.7031E-3	1.4010E-3	5.1000E-3
NH_3	0.0	6.4706E-6	1.9981E-5	0.0
CO_2	0.0	0.0	0.0	0.0
O_2	0.0	0.0	0.0	0.0
N_2	0.0	0.0	0.0	0.0
N_2O	0.0	0.0	0.0	0.0

Table 1: Feed stream properties. The composition of each species is given as its mass fraction.

Mass Frac.	Hygiene Water	Potable Water
Temp(K)	297.26	297.26
Pres(Pa)	2.0137E5	1.0137E5
Urine and Creatinine	1.100E-5	6.000E-7
NaCl	3.751E-4	3.751E-4
Phenol	1.000E-9	1.000E-9
Soap	5.0E-7	5.0E-7
NH_3	5.0E-7	5.0E-7
CO_2	1.5E-5	1.5E-5
O_2	1.0E-5	1.5E-5
N_2	1.0E-5	1.5E-5
N_2O	1.0E-6	1.5E-6

Table 2: Water quality requirements adapted from Carrasquillo (1992), stated as maximum allowable impurity mass fractions.

3 WRS Technologies: Model Development

Several technologies have been developed to recycle the wastewater streams into potable and hygiene streams detailed above. These include: thermoelectric integrated membrane evaporation subsystem (TIMES), vapor compression distillation (VCD) subsystem, vapor phase catalytic ammonia removal (VPCAR) subsystem, and the closed cycle air evaporator(AE) subsystem. The proposed WRS synthesis tool will employ these four technologies as constituents of the recycling network. Additional technologies can also be incorporated if desired.

For TIMES and AE, modeling equations detailed in our previous report [5, TM8–15 and AE13–15] are employed. For VCD and VPCAR, we have developed a simplified ASPEN model (explained below) which is based on [4]. These models quantify the operational "cost" of each technology as a linear function of weight, volume, and power consumption.

4 Recycling Network Design Through The State Space Approach

Solution to the recycling task stated above will yield the optimal configuration of technologies to be employed in the space station WRS. This configuration is selected as optimal among several configurations captured by the state-space description of the WRS.

As an example of the state space representation for the recycle design task, consider one possible configuration for a WRS shown in Figure 3. It employs two technologies: vapor compression distillation (VCD) and vapor phase catalytic ammonia reduction (VPCAR). It employs four vapor-liquid separators, two reactors and several pumps and heat exchangers. There are four feed streams and four product streams, as stated above.

The state space representation for this WRS is shown in Figure 4, and consists of a distribution network (DN), a heat exchange operator (HEO), and a process operator (PO). This state space approach can be employed to represent any flow configuration in this water recovery system. Any feed stream that enters the DN can leave the DN either as a product stream or as a stream entering the heat exchange operator. Streams leaving the two operators return to the DN. These, in turn, either exit the DN as a product stream or mix with the streams entering the heat exchange operator. Thus, the DN consists of inlet or splitting junctions, exit or mixing junctions, and all possible streams connecting these junctions. For example, a stream (LEXP) from the HEO returns to the DN, where it splits into a product stream (BTM) and a recycle stream (VXR2) to the HEO. In a general DN, this stream can split into as many streams as there are mixing (exit) junctions in the DN. Within the DN, each mixing or splitting junction must satisfy the overall and component mass balances, and the energy balance.

Pressure changes, namely, compression and expansion, are also represented within the DN. For example, the vapor product (50) from the flash separator in the vapor compression distillation (VCD) subsystem, may be compressed and heat a feed (VXEV) for a reactor (RXR1) in the VPCAR. However, such pressure changes increase the power consumption of the system, and contribute to the objective function. Note that mixture streams can be neither compressed nor expanded.

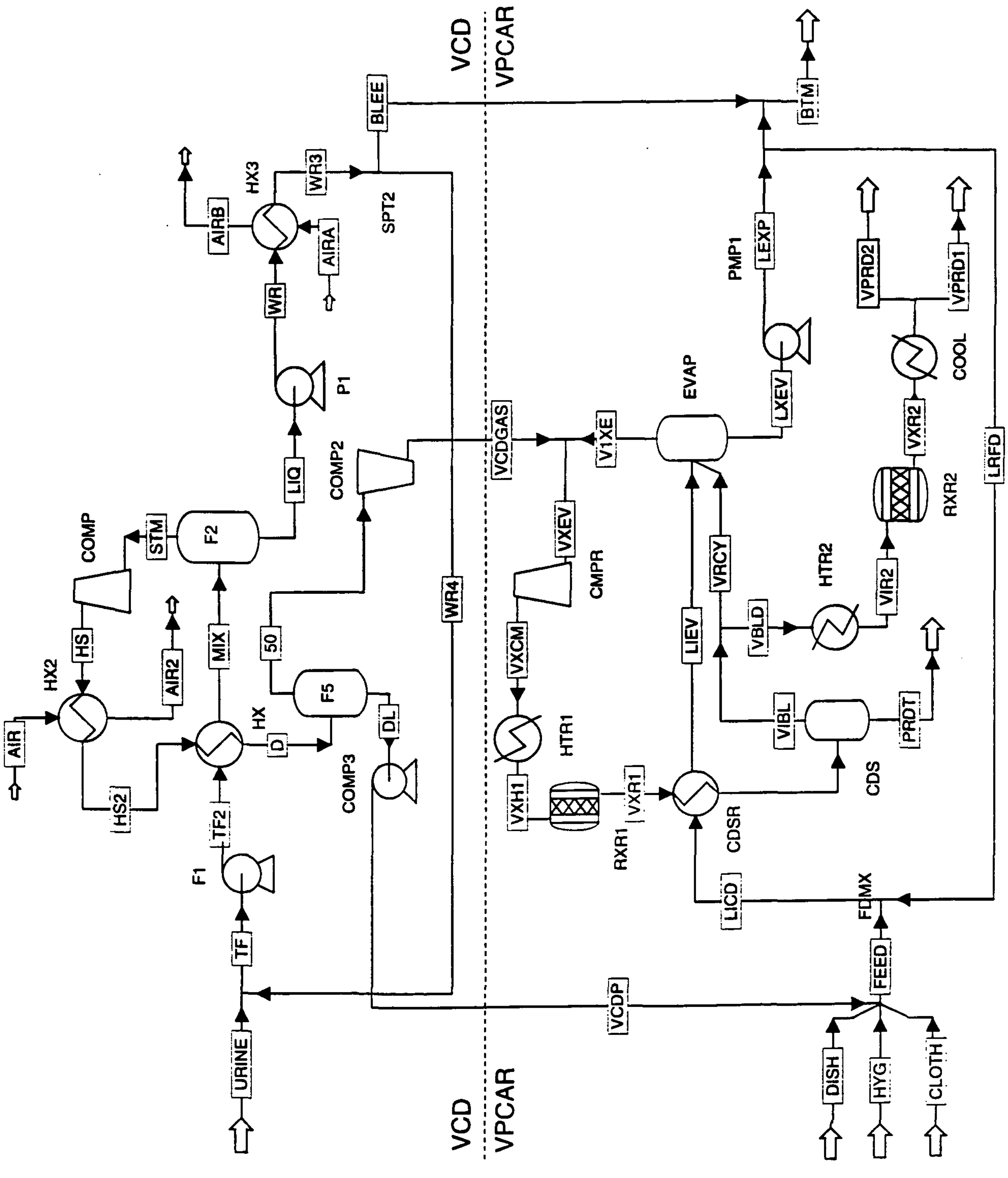

Figure 3: A water recovery subsystem configuration employing vapor compression distillation (VCD) and vapor phase catalytic ammonia reduction (VPCAR) technologies.

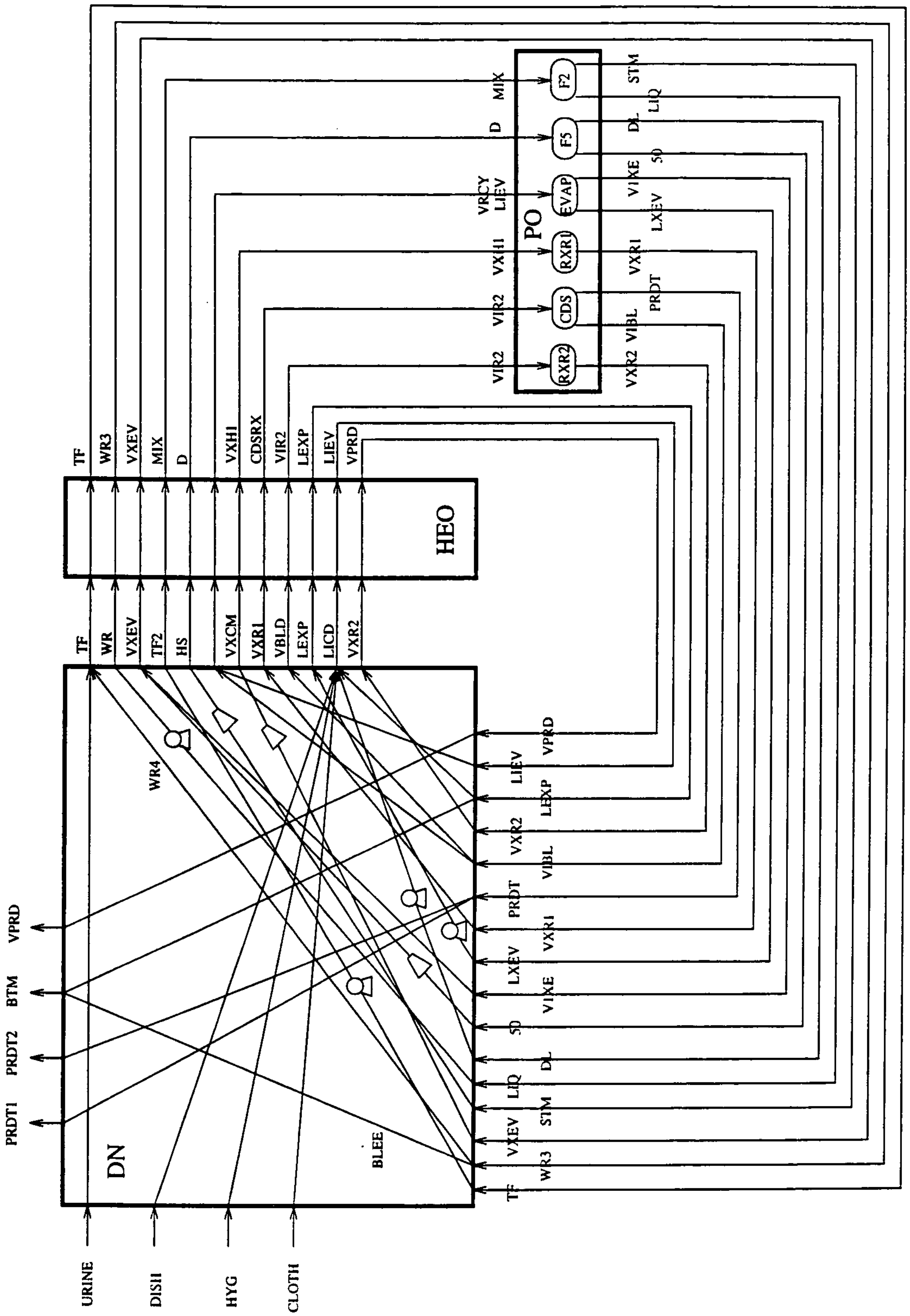

Figure 4: The state space representation of a water recovery subsystem employing VCD and VP-CAR.

All streams leaving the DN, except the product streams, enter the heat exchange operator. In the heat exchange operator, the streams are either heated or cooled to the desired exit temperatures. The minimum hot and cold utility required to accomplish this task is calculated by employing the pinch methodology. Given a set of streams that need to be either heated or cooled, a set of hot and cold utilities, and a driving force for heat transfer, the HEO identifies the minimum utility consumption. The calculation of this minimum utility is based on the satisfaction of the first and second laws of thermodynamics. This calculation procedure has been automated in our "pinch" calculation tool.

Streams leaving the heat exchange operator either return to the DN or enter the process operator. The streams entering the PO undergo a transformation due to unit operations of the several available water reclamation technologies (TIMES, AE, VCD, or VPCAR). The unit operations are modeled in simulator routines that employ either our own models, or those in commercial simulators such as ASPEN. Finally the streams return to the DN as inlet streams.

Note that any stream entering the DN can split into several stream, each of which can mix with a stream leaving the DN. Thus, while the DN can represent all possible flow configurations between these splitting and mixing junctions, it creates an overwhelming decision task for the system designer. Instead, the state space formulation leads to an optimization program to determine the flow configuration that achieves the product specifications at the least cost, from these options.

5 State Space Optimization Software

To solve this WRS design problem, the resulting optimization problem will be embedded in the software tool. This requires the automatic generation of constraints that define the DN, the HEO and the PO; the simulation routines for each technology to be employed once they are specified; and the objective function, given the cost coefficients.

A nonlinear optimization package is employed for the solution of the resluting optimization problem. We have written FORTRAN subprograms that define the constraints for the DN, the HEO, and the cost function. We are also developing ASPEN-Plus simulation models for some of the technologies. An interface that combines the ASPEN-Plus unit operation models with the nonlinear optimizer has been developed. This interface, for example, given the inlet and operating conditions for a flash separation in the VCD by the optimization routine, simulates the flash through ASPEN, and then returns the calculated flash outlet conditions to the optimization routine.

We have also acquired and installed new versions of ASPEN-Plus (Release 9.1.3) to help develop the software tool. This installation led to compatibility problems in running the IWRS flowsheet provided in [4].

As a starting point for the optimization program, we have decided to simulate the IWRS-1 flowsheet [4] with only two technologies: VCD and VPCAR. Our simulation results for this flowsheet are detailed in Appendix A, and the problems encountered in this simulation are outlined below.

6 Problems

- We assumed that the dishwashing wastewater is composed of water and soap only. This follows a similar assumption in [4]. However, this wastewater should have other organic components, primarily oils and food debris. We would like to obtain a detailed composition of this stream compatible with the 11 component representation we currently employ.

- We are missing accurate data for the feed and product compositions. Though the development of our simulation method does not depend on the exact inlet/outlet composition specifications, the results obtained from the program do. Hence, we would like at least one set of complete, representative stream data for a typical water recovery system. These specifications should contain:

  - The detailed inlet compositions with respect to the component list we have considered.
  - The outlet specifications (MCL) for the same list of components, that is based on the requirements in [3].
  - Representative temperature and pressure conditions for the inlet and outlet streams.

- Base case simulation. In order to determine the detailed product specification table, we simulated ASPEN flowsheets available from NASA Ames Research Center [4]. The results of this simulation are attached in Appendix A. The resulting product compositions are shown in Table 3.

  However, these simulation results do not meet the specifications in Table 2. We would like to reconcile our flowsheet and simulation with these specifications.

7 Future Plans

In the work thus far on this project, we have made significant progress towards formulating and programming the optimization problem for the synthesis of a WRS. In the remaining project period, we have scheduled the following activities:

- Water quality specifications, given in Table 2, have been adapted from [3]. For instance, urea and creatinine have been combined to meet the maximum allowable total organic content limit in the product water streams. A literature search for more detailed water quality requirements will be pursued.

- Develop a MINOS-ASPEN-Plus interface to determine the stream thermodynamics for calculating the temperature, pressure, or enthalpy conditions at any junction in the state space representation.

- Improve the ASPEN-Plus model for the VCD and VPCAR subsystems.

- Combine the modules of the code to create the WRS synthesis tool.

- Perform a water reclamation system synthesis case study.

8 Conference Presentations

Our paper titled "Multiobjective Optimization of Hybrid Regenerative Life Support Technologies," has been accepted for the 25th International Conference Environmental Systems. It will be presented in July, 1995. A draft of this paper is attached.

References

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A ASPEN-PLUS Simulation

ASPEN-PLUS is a commercial chemical process simulator. We have available to us the ASPEN-Plus simulation for one possible water recovery system configuration. This simulation was developed at the NASA Ames research center as part of a life support subsystem evaluation tool [4]. The flowsheet for the water recovery system consists of three subsystems: VCD, VPCAR, and supercritical water oxidation (SCWO). The NASA-Ames code simulates the separation tasks in each of these technologies with a combination of flash columns, heat exchangers, mixers and splitters. This approach allows one to simulate the novel technologies of IWRS on a commercial process simulator. The NASA-Ames model involves over 30 components or chemical species, including trace electrolytes and solids, in the flowsheet. Several of these components for which detailed thermodynamic properties are unavailable, were modeled with the same thermodynamics as those of water.

Even though human urine is composed of over 150 constituents, this model simulated 26 components for urine. These reduced components were first proposed in [6]. The compositions of shower wastewater, cloth washing wastewater and dishwashing wastewater are based on [9]. The flow rates of these streams are adapted from [2].

The WRS flowsheet has been simulated on a new release of ASPEN-Plus. Unfortunately, the NASA-Ames code, written for an earlier release of ASPEN, is not compatible with this release. Therefore, we have recreated an ASPEN model for VCD and VPCAR technologies, to simulate WRS configurations derived from the state space program. This simulator serves two other purposes: it provides feasible starting points for the optimization program, and parts of the simulator can be employed in the state space optimization.

The simulation of the VCD/VPCAR flowsheet involved several modifications in the original simulator. First, we extracted VCD and VPCAR information from the NASA-Ames flowsheet. Then, the following changes were made:

- The electrolyte and solid components were neglected to simplify the problem.
- We reduced the 30+ components in this flowsheet to 11, to make our optimization problem more tractable.
- Three flash columns in the VCD were deleted because they were adjusting electrolyte equilibrium temperature differences, that were no longer required.
- FORTRAN program units that controlled flow rates in the splitters were deleted.
- A reactor employed for urea hydrolysis reaction was removed because it produced low conversions, and led to convergence errors during program execution.
- The area of a heat exchanger in the VCD was increased to make it feasible.
- Feed O_2 required for an oxidation reaction was deleted. Instead, it was assumed that enough O_2 for this reaction is always available.

	Potable Water	Hygiene Water	Waste Water	Conc. Urine
Temp(K)	373.1950	373.1950	300.0000	345.5683
Pres(Pa)	1.0134E5	1.0134E5	1.0134E5	94400.00
Flow Rate(kg/day)	7.6926E-4	2.3078E-3	1.8324-03	1.0010E-5
Urea	2.9433E-10	2.9433E-10	0.0	4.1504E-2
Creatinine	5.5045E-10	5.5045E-10	0.0	7.7545E-2
H_2O	9.9999E-1	9.9999E-1	9.9970E-1	6.2037E-1
NaCl	0.0	0.0	0.0	2.3742-02
Phenol	1.1055E-6	1.1055E-6	6.4957E-8	6.0838E-4
Soap	8.0179E-8	8.0179E-8	0.0	0.2362
NH_3	5.4971E-9	5.4971E-9	3.3459E-7	5.3826E-8
CO_2	1.0074E-6	1.0074E-6	2.6246E-4	0.0
O_2	0.0	0.0	3.9272E-6	0.0
N_2	3.6817E-9	3.6817E-9	1.3798E-5	0.0
N_2O	4.8429E-8	4.8429E-8	0.0	0.0

Table 3: Product stream properties from the ASPEN-Plus simulation of a VCD-VPCAR configuration. The composition of each species is stated as its mass fraction.

- One of two consecutive separators in VPCAR was removed to improve flowsheet convergence.

This modified flowsheet is illustrated in Figure 3 and the simulation results are shown in Table 3. It should be noted that the output compositions of these streams does not satisfy all the water quality requirements. We are currently investigating flowsheet modifications that will allow all water quality requirements to be met.

SIMULATION OF AN INTEGRATED WATER RECLAMATION SUBSYSTEM, IWRS-1																	
Stream ID		AIR	AIR2	AIRA	AIRB	BLEE	BTM	CDSRX	CLOTH	D	DISH	DL	DV	FEED	HS	HS2	HYG
Temperature	K	297.0	297.0	295.0	295.0	299.0	345.6	406.8	360.0	305.1	360.0	305.1	305.1	344.7	376.8	362.7	360.0
Pressure	N/SQM	101300.0	101300.0	101300.0	101300.0	94400.0	94400.0	300000.0	201370.0	4801.3	101370.0	4801.3	4801.3	101370.0	4801.3	4801.3	201370.0
Vapor Frac		1.000	1.000	1.000	1.000	0.000	0.000	0.094	0.000	0.149	0.000	0.000	1.000	0.000	1.000	1.000	0.000
Mole Flow	KMOL/SEC	0.028	0.028	0.155	0.155	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
Mass Flow	KG/SEC	0.805	0.805	4.484	4.484	< 0.001	< 0.001	0.004	0.001	0.001	0.001	0.001	< 0.001	0.004	0.001	0.001	0.001
Volume Flow	CUM/SEC	0.678	0.678	3.751	3.751	< 0.001	< 0.001	< 0.001	< 0.001	0.005	< 0.001	< 0.001	0.005	< 0.001	0.045	0.043	< 0.001
Enthalpy	MMBTU/HR	-0.003	-0.003	-0.048	-0.048	> -0.001	> -0.001	-0.199	-0.073	-0.065	-0.033	-0.057	-0.008	-0.196	-0.056	-0.056	-0.033
Mass Frac																	
UREA						0.050	0.042	trace	690 PPM					414 PPM			920 PPM
PCREAT1						0.023	0.078	trace	0.001					774 PPM			0.002
H2O						0.893	0.620	1.000	0.996	1.000	0.995	1.000	1.000	0.996	1.000	1.000	0.991
AIR		1.000	1.000	1.000	1.000												
NACL						0.032	0.024		477 PPM					293 PPM			678 PPM
PHENOL						0.002	322 PPM	468 PPB		74 PPM		87 PPM	3 PPM	25 PPM	74 PPM	74 PPM	
PSMCT							0.236	65 PPB	0.001		0.005			0.002			0.006
H3N							54 PPB	164 PPB	20 PPM					9 PPM			6 PPM
CO2								64 PPM									
O2																	
N2								3 PPM									
N2O								5 PPM									
Mole Flow	KMOL/SEC																
UREA						trace	trace	trace	trace					trace			trace
PCREAT1						trace	trace	trace	trace					trace			trace
H2O						trace	trace	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
AIR		0.028	0.028	0.155	0.155												
NACL						trace	trace		trace					trace			trace
PHENOL						trace	trace	trace		trace		trace	trace	trace	trace	trace	
PSMCT							trace	trace	trace		trace			trace			trace
H3N							trace	trace	trace					trace			trace
CO2								trace									
O2																	
N2								trace									
N2O								trace									

SIMULATION OF AN INTEGRATED WATER RECLAMATION SUBSYSTEM, IWRS-1																	
Stream ID		AIR	AIR2	AIRA	AIRB	BLEE	BTM	CDSRX	CLOTH	D	DISH	DL	DV	FEED	HS	HS2	HYG
Temperature	K	297.0	297.0	295.0	295.0	299.0	345.6	406.8	360.0	305.1	360.0	305.1	305.1	344.7	376.8	362.7	360.0
Pressure	N/SQM	101300.0	101300.0	101300.0	101300.0	94400.0	94400.0	300000.0	201370.0	4801.3	101370.0	4801.3	4801.3	101370.0	4801.3	4801.3	201370.0
Vapor Frac		1.000	1.000	1.000	1.000	0.000	0.000	0.094	0.000	0.149	0.000	0.000	1.000	0.000	1.000	1.000	0.000
Mole Flow	KMOL/SEC	0.028	0.028	0.155	0.155	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
Mass Flow	KG/SEC	0.805	0.805	4.484	4.484	< 0.001	< 0.001	0.004	0.001	0.001	0.001	0.001	< 0.001	0.004	0.001	0.001	0.001
Volume Flow	CUM/SEC	0.678	0.678	3.751	3.751	< 0.001	< 0.001	< 0.001	< 0.001	0.005	< 0.001	< 0.001	0.005	< 0.001	0.045	0.043	< 0.001
Enthalpy	MMBTU/HR	-0.003	-0.003	-0.048	-0.048	> -0.001	> -0.001	-0.199	-0.073	-0.065	-0.033	-0.057	-0.008	-0.196	-0.056	-0.056	-0.033
Mass Frac																	
UREA						0.050	0.042	trace	690 PPM					414 PPM			920 PPM
PCREAT1						0.023	0.078	trace	0.001					774 PPM			0.002
H2O						0.893	0.620	1.000	0.996	1.000	0.995	1.000	1.000	0.996	1.000	1.000	0.991
AIR		1.000	1.000	1.000	1.000												
NACL						0.032	0.024		477 PPM					293 PPM			678 PPM
PHENOL						0.002	322 PPM	468 PPB		74 PPM		87 PPM	3 PPM	25 PPM	74 PPM	74 PPM	
PSMCT							0.236	65 PPB	0.001		0.005			0.002			0.006
H3N							54 PPB	164 PPB	20 PPM					9 PPM			6 PPM
CO2								64 PPM									
O2																	
N2								3 PPM									
N2O								5 PPM									
Mole Flow	KMOL/SEC																
UREA						trace	trace	trace	trace					trace			trace
PCREAT1						trace	trace	trace	trace					trace			trace
H2O						trace	trace	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
AIR		0.028	0.028	0.155	0.155												
NACL						trace	trace		trace					trace			trace
PHENOL						trace	trace	trace		trace		trace	trace	trace	trace	trace	
PSMCT							trace	trace	trace		trace			trace			trace
H3N							trace	trace	trace					trace			trace
CO2								trace									
O2																	
N2								trace									
N2O								trace									

SIMULATION OF AN INTEGRATED WATER RECLAMATION SUBSYSTEM, IWRS-1																
Stream ID		VBLD	VCDGAS	VCDP	VIBL	VIR2	VPRD	VRCY	VXCM	VXEV	VXH1	VXR1	VXR2	WR	WR3	WR4
Temperature	K	373.2	735.3	305.1	373.2	723.0	300.0	373.2	722.3	365.1	523.0	523.0	723.0	299.0	299.0	299.0
Pressure	N/SQM	101335.0	200000.0	201370.0	101335.0	101335.0	101335.0	101335.0	300000.0	32315.7	300000.0	300000.0	101335.0	94400.0	94400.0	94400.0
Vapor Frac		1.000	1.000	0.000	1.000	1.000	0.000	1.000	1.000	1.000	1.000	1.000	1.000	0.000	0.000	0.000
Mole Flow	KMOL/SEC	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	0.038	0.038	0.038
Mass Flow	KG/SEC	0.001	< 0.001	0.001	0.001	0.001	0.001	< 0.001	0.004	0.004	0.004	0.004	0.001	0.749	0.749	0.748
Volume Flow	CUM/SEC	0.001	< 0.001	< 0.001	0.001	0.002	< 0.001	< 0.001	0.004	0.020	0.003	0.003	0.002	0.001	0.001	0.001
Enthalpy	MMBTU/HR	-0.028	-0.008	-0.057	-0.028	-0.026	-0.033	> -0.001	-0.165	-0.174	-0.170	-0.170	-0.026	-36.815	-36.815	-36.781
Mass Frac																
UREA									trace	trace	trace	trace		0.050	0.050	0.050
PCREAT1									trace	trace	trace	trace		0.023	0.023	0.023
H2O		1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.893	0.893	0.893
AIR																
NACL														0.032	0.032	0.032
PHENOL		32 PPB	3 PPM	87 PPM	32 PPB	32 PPB	32 PPB	32 PPB	23 PPM	23 PPM	23 PPM	468 PPB	32 PPB	0.002	0.002	0.002
PSMCT									65 PPB	65 PPB	65 PPB	65 PPB				
H3N		952 PPB			952 PPB	952 PPB	952 PPB	952 PPB	8 PPM	8 PPM	8 PPM	164 PPB	952 PPB			
CO2		398 PPM			398 PPM	398 PPM	398 PPM	398 PPM	trace	trace	trace	64 PPM	398 PPM			
O2							12 PPM						12 PPM			
N2		21 PPM			21 PPM	21 PPM	41 PPM	21 PPM				3 PPM	41 PPM			
N2O		32 PPM			32 PPM	32 PPM		32 PPM				5 PPM				
Mole Flow	KMOL/SEC															
UREA									trace	trace	trace	trace		0.001	0.001	0.001
PCREAT1									trace	trace	trace	trace		< 0.001	< 0.001	< 0.001
H2O		< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	trace	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	0.037	0.037	0.037
AIR																
NACL														< 0.001	< 0.001	< 0.001
PHENOL		trace	trace	trace	trace	trace	trace	trace	trace	trace	trace	trace	trace	< 0.001	< 0.001	< 0.001
PSMCT									trace	trace	trace	trace				
H3N		trace			trace	trace	trace	trace	trace	trace	trace	trace	trace			
CO2		trace			trace	trace	trace	trace	trace	trace	trace	trace	trace			
O2							trace						trace			
N2		trace			trace	trace	trace	trace				trace	trace			
N2O		trace			trace	trace		trace				trace				

Multiobjective Optimization of Hybrid Regenerative Life Support Technologies

V. Manousiouthakis, D. Sourlas, M. Wilcoxson, J. Choi, S. Han, and H. Kim
Department of Chemical Engineering
University of California, Los Angeles
Los Angeles, CA 90095

ABSTRACT

This paper presents a methodology to design optimal water reclamation systems for long-duration space missions. These systems employ, *separately*, numerous technologies and are required to satisfy multiple goals. However, each of the available technologies may not meet these goals by itself. Instead, it is proposed to evaluate the optimal design of such systems employing, *simultaneously*, several technologies. First, mathematical models for each technology considered are developed. These models are employed to optimize two of these technologies, demonstrating that significant "cost" reductions are possible. Finally, hybrid systems with multiple technologies are designed and optimized to meet multiple objectives. The obtained results show that these systems outperform single technology based water reclamation systems.

INTRODUCTION

To reduce payload requirements that would make long-term space missions feasible, a closed-loop life support system for the mission crew is essential. This environmental control and life support system (ECLSS) is comprised of water reclamation, air revitalization, and waste management. Since water needs constitute 94% of the payload of the expendables [1], research has been focussed on water reclamation.

For a long-duration mission, water is required for drinking and food preparation for the crew. It is needed for hygiene purposes: shower, laundry, flush and dishwashing. Laboratory experiments that the crew carry out during a mission also may require water for cleaning and reagent use. Water is excreted in the sweat, urine, and breath of the crew. Water vapor is also produced from the hygiene systems. The purity requirements for potable, hygiene and laboratory water are different. Similarly, the composition of water from these sources varies. The aim of the water management unit is to convert the excreted or effluent water streams into streams that meet the quality specifications for drinking, hygiene, or laboratory. The water can then be recycled.

The different water requirements pose the problem of designing a water reclamation system that accomplishes the recycling of the different waste water streams. This problem can be stated as follows:

> Given a space flight mission, the specifications on the potable, hygiene and miscellaneous water streams, and the compositions of the waste streams from these functions, synthesize a network of separation processes, material-handling units and energy-recovery devices that removes, in a micro-gravity environment, the undesirables and converts each of the waste streams to recyclable product streams with maximum reliability and safety, and minimal volume, mass, new expendables and power requirements.

One technology alone cannot efficiently handle these requirements. For instance, if flash distillation is the chief unit operation, adsorption and ion-exchange may be a part of the system for pre/post-treatment. Given these multi-objectives and multi-technology options for the ECLSS, a method is required that would evaluate and choose the optimum technology combination and design a system that meets the various objectives at hand.

Ongoing research in this area has led to the development of several devices and regeneration schemes that utilize them. Next, we briefly review these technologies.

WATER RECLAMATION TECHNOLOGIES

We consider six subsystems: thermoelectric integrated membrane evaporation subsystem (TIMES), multifiltration (MF), vapor compression distillation (VCD), vapor phase catalytic ammonia removal (VPCAR), reverse osmosis (RO), and air evaporation (AE). Below, these subsystems are discussed briefly.

TIMES - In this process [3, 8, 20, 21], contaminated water is heated and evaporated in a hollow fiber membrane (HFM) evaporator which functions as a pervaporation unit. In this unit, water diffuses through the membrane and evaporates as soon as it reaches the outside surface of the tubes which is kept at low pressure by means of a vacuum pump. The vapor from the pervaporation unit is condensed on a porous plate connected to the cold junctions of the thermoelectric elements and its latent heat is recovered through a thermoelectric heat pump. This heat, combined with the Joule heat generated because of the inefficiency of the thermoelectric elements, is used in the heater that precedes the HFM evaporator.

MF - In this subsystem [15, 16], contaminated water is purified by directing it through a series of columns, each consisting of several different adsorbents. Each bed material adsorbs different components of the feed stream. This is a reliable and simple technology which requires no micro-gravity phase separation since the solid is stationary. It could serve as an extremely competitive technique in tandem with other technologies that require some pre- or post-treatment of the waste feed.

VCD - Vapor compression distillation is a phase-change separation procedure designed to recover water from its solutions (such as urine). The product from this process is hygiene water that can be subsequently processed by a multifiltration or a reverse osmosis unit. An evaporator and a mechanical compressor constitute the main components of a VCD system. The vapor produced in the evaporator is compressed so that its latent heat vaporizes the waste water stream entering the evaporator. In this system effective heat integration has been employed to reduce the overall power requirements. However, when VCD is considered as part of a water reclamation system that involves several technologies, it is not obvious whether this type of integration remains optimal.

VPCAR - The wastewater stream is vaporized in a hollow fiber evaporator and then treated to remove ammonia and light hydrocarbons. The treatment is a two step catalytic oxidation/decomposition of these compounds. The chief advantages of this process is that it does not require post and pre-treatment of water, delivers high quality water, and involves a small number of moving parts. However it requires large specific energy because of the high temperature reactions.

RO - Reverse osmosis (hyperfiltration) has been studied for wash water purification. In this process, an applied pressure counters the osmotic pressure to force flow across the membrane from the high solute concentration side to the low solute concentration side. The concentration difference across the membrane arises from the preferential permeability of water compared to contaminants (solutes) such as salt, soap, and urea. The hollow fiber RO module minimizes weight and maximizes resistance to fouling [17].

AE - Warm dry air is blown through a wick to evaporate the contaminated water. The warm moist air leaving the evaporator is then cooled to recover the water. The cooling takes place in two steps. The first heat exchanger (recuperator) is included to reduce the duty for both the heater and the condenser. The cold saturated air from the condenser is sent through the recuperator and then the heater to regenerate warm dry air. It would be more efficient to have multiple wick stages, rather than one stage as in the tested configuration. A multistage design would also require new heat integration schemes.

The optimization and technology assessment of a water reclamation system requires simple and reliable mathematical models for each subsystem. We have developed such models for the above subsystems. These models are derived from first principles and are sufficiently detailed to allow prediction of several quantities of interest (e.g. power, weight and volume) while still remaining tractable for use in large scale optimization studies. These models and equations are described in [9].

Next, these models are employed to optimize two subsystems.

SUBSYSTEM OPTIMIZATION

Subsystem performance can be optimized by appropriate choice of operating condition values. Next, we illustrate this approach using two particular subsystems (wick evaporator and vapor compression distillation) and we demonstrate how optimization can lead to performance improvements. In order to evaluate a system's performance, one should consider various characteristics such as weight, power consumption, volume, etc. In our work, we employ a single performance measure that simultaneously takes into account these contributions and quantifies the system's performance in terms of the total equivalent of the system as:

$$f_{obj} = C_w W_T + C_p P_T T_m + C_v V_T T_m \qquad (1)$$

All symbols are explained in the notation section at the end of the paper and cost coefficients C_w, C_p, and C_v are taken from [19]. Then, (1) becomes the objective function in a minimization problem that is solved using standard optimization software, for example MINOS. Since (1) emcompasses various contributions to the cost of the system, the proposed optimization approach is inherently multiobjective. Overall process model was used to relate operating conditions to weight, power and volume requirements. These equations were constraints in the optimization problem.

AE SUBSYSTEM OPTIMIZATION - Air evaporation water recovery has proven successful for urine processing [11, 13, 14]. The design of such a system requires that operating condition such as air flow rate, condenser temperature and wick inlet temperature be specified. In our work these values are such that the equivalent cost of the AE system is minimized.

The system was assumed to process 10 kg/day of urine flush (3-man crew) and the mission time was specified as 1 year. The results are tabulated in Table 1. For Case 1 condensation is permitted in the recuperative heat exchanger, while for Case 2 no phase change is allowed. The optimal designs for Case 1 and Case 2 differ in their temperatures and flow rates (the condenser temperature changes from 10°C to 28.3°C), but the objective function is nearly unchanged. Either optimal design resulted in a decrease in the objective function of nearly 30% as compared to the original design proposed in [11]. This reduction was due to the reduced heating and cooling requirements (Q_H and Q_C) in the heater, recuperator and condensor, and the reduction in the volume and mass of the air evaporator due to a decrease in its length (L).

Table 1: Wick Comparision

Variable*	Morasko et. al.	Case 1	Case 2
F(mole/s)	0.49	0.41	0.51
X_{wo}	0.025	0.028	0.051
X_{wi}	0.012	0.012	0.038
X_{wos}	0.052	0.086	0.110
T_{wi}(C)	54.4	65.0	65.0
T_{wis}(C)	10.0	10.0	28.3
T_{wo}(C)	33.9	43.7	47.4
T_{wos}(C)	21.1	23.0	33.3
T_{ci}(C)	22.8	20.5	33.3
$L(cm)$	40.0	23.3	21.8
T_{fi}(C)	21.1	38.0	42.4
X_{ho}	0.025	0.024	0.051
Q_C(W)	463	321	335
Q_H(W)	435	288	294
f_{obj}($\$ \times 10^6$)	1.78	1.29	1.33

* all symbols explained in the notation section.

VCD SUBSYSTEM OPTIMIZATION - The performance of the VCD unit for different values of the pressure ratio across its compressor (P_2/P_1) is quantified. Again, the system's performance is measured through the, so called, equivalent cost of the system (1). In this way, the different contributions to the cost of a mission are appropriately weighted and their sum yields the equivalent cost.

Three contributions to the cost of the mission will be considered in this study of VCD: weight (of rotating drums and their cylindrical covers), volume (due to the cylindrical covers) and work (compression work). The corresponding cost coefficients are the same as the ones used in (1). Changes in the pressure ratio do not significantly affect devices in the VCD flowsheet, other than the rotating drum assembly. The contribution of such devices to the overall cost can be assumed to be constant, and will not be considered in the subsequent calculations. In this way, optimal pressure ratio values can be identified, and the sensitivity of the cost value to changes in the pressure ratio can be established.

The following additional system parameters are fixed in this calculation [12]:

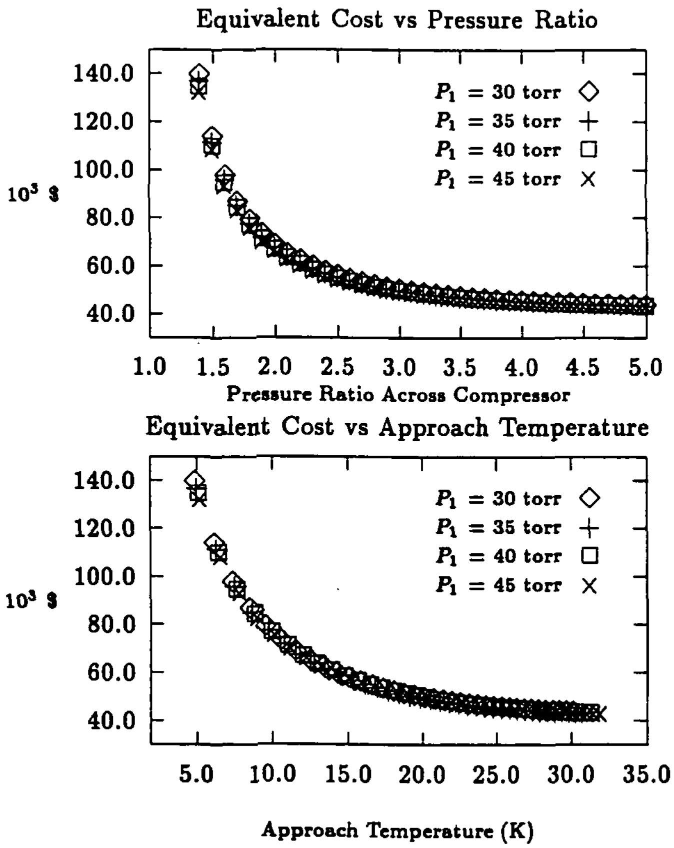

Figure 1: Optimal Pressure Ratio and Approach Temperature for VCD drum

Material: Aluminum (density 2.64 g/cm^3)
Metal Thickness: 1 mm
Small side of Inner Drum: radius 20 cm
Taper Angle: 5°
Clearances: 0.2 times the radius of the nearest drum side.

The results of this study are summarized in Figures 1 and 2. Low pressure ratios lead to small energy consumption at the compressor. They also lead to small differences in evaporation temperatures, i.e. small approach temperature values at the VCD drum. In this case, to achieve the desired heat exchange, large drum areas are required. As a result, volume and weight are expected to be the dominant contributions in the equivalent cost. This is supported by Figure 1 which establishes that operating a VCD unit with a pressure ratio value close to 1 is not an optimal policy.

The curves in Figure 1 reach a minimum which is located outside the pressure ratio range shown in this figure. The location of this minimum depends

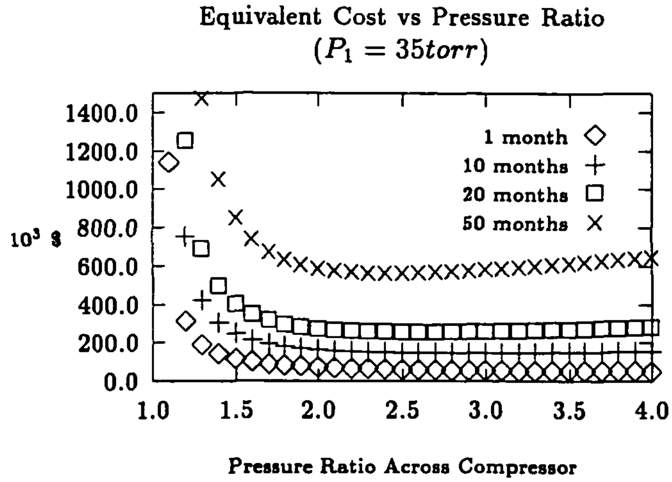

Figure 2: Equivalent cost for $P_1 = 35$ *torr* and various missions.

on the mission specifications. Figure 2 shows the equivalent cost as a function of the pressure ratio for various mission duration. As the length of the mission increases, the minimum of the equivalent cost curve appears at smaller pressure ratio values. Furthermore, the equivalent cost curves that correspond to longer missions possess more pronounced minima. Thus, as the mission duration increases, the range of pressure ratios that can deliver performance close to the optimum becomes narrower. From Figure 2 it can be concluded that a pressure ratio value of approximately 2.5 delivers acceptable system performance for all missions in the range considered.

The above results show that employing an optimization based approach to the design of an independent subsystem, based on mathematical models and an equivalent cost objective function, can yield significant cost reductions and physical insights. In the sequel, the design of an integrated water reclamation system is pursued.

SYSTEM INTEGRATION

Typical systems that recover hygiene water from urine flush involve a separation process (evaporation, pervaporation or air evaporation) followed by a multifiltration step for product purification. Typically the subsystems involved in this process are designed and optimized independently from each other. However, even if the individual subsystems are optimized, there are no guarantees that the resulting overall system will also be optimal. The overall system is first represented in terms of all possible interconnections among the allowable technologies/subsystem, and then it is optimized. In this way, all processing technologies and their interaction are simultaneously considered.

Two avenues for the synthesis of optimal water recovery systems were pursued: heat integration, and multiobjective hybrid system optimization.

HEAT INTEGRATION - Given a set of hot and cold streams of a process, heat integration techniques, in particular pinch analysis, identify the inherent thermodynamic limitations for heat transfer of this process. In addition, the minimum hot and cold utility necessary to achieve the thermodynamic specifications for the process streams is also identified. The resulting process flowsheets feature exchange of heat between the hot and cold streams so that the external energy input to the process is minimized. Applying this approach to water recovery processes will help identify energy efficient processes.

Consider a typical water reclamation system for urine flush employing a two step separation. The first step consists of VCD, or TIMES, or a combination thereof (i.e. hybrid system). In the second step, the distillate from the first step is processed through a multifiltration unit. The operating conditions assumed for this analysis are the following:

Urine Flush: 1 kg/hr
Evaporation Temperature (VCD): 31.5°C
Evaporation Temperature (TIMES): 59°C
Minimum Approach Temperature (ΔT_{min}) : 5°C
Supply & Target Temperature for all streams: 20°C

The inlet stream to the MF unit is first sterilized through heating to 82°C and then cooled to a final temperature of 20°C before passing through the unibed. The target temperature for all streams leaving this process is 20°C, equal to the temperature of the inlet stream. The system configurations that were examined are the following:

S1: VCD unit (no compressor) followed by MF unit (with heat integration).

S2: TIMES unit (no heat pump) followed by MF unit (with heat integration).

S3: 50% of the feed through VCD (as in S1) and 50% of the feed through TIMES (as in S2) followed by MF unit (with heat integration).

S4: VCD unit followed by MF unit (with compressor, latent heat recovery, no heat integration, independent design).

S5: TIMES unit followed by MF unit (with thermoelectric heat pump, latent heat recovery, no heat integration, independent design).

S6: VCD unit followed by MF unit (with heat integration).

S7: TIMES unit followed by MF unit (with heat integration).

S8: 50% of the feed through VCD (as in S6) and 50% of the feed through TIMES (as in S7) followed by a MF unit (with heat integration).

Pinch calculations were involved in the study of systems S1 to S3 and S6 to S8 since these are the only systems that are heat integrated. These calculations were performed by means of an in-house developed software program.

Cases S1, S2, and S3 correspond to various levels of system integration, whereby heat integration and the potential of hybrid systems are explored. In these cases, the vapor compressor system in VCD and the thermoelectric heat pump systems in TIMES have been omitted, thus the required power is zero for all systems in this category. Pinch calculations were employed and the resulting minimum utility requirements are shown in Table 2.

Table 2: Minimum Utility Requirements

Case	Minimum Heating Utility(W)	Minimum Cooling Utility(W)	Power Requirement (W)
S1	645	644	0
S2	830	615	0
S3	438	330	0

Table 3: System Design with no Heat Integration

Case	Heating Requirement (W)	Cooling Requirement (W)	Power Requirement (W)
S4	56	69	16
S5	21	71	195

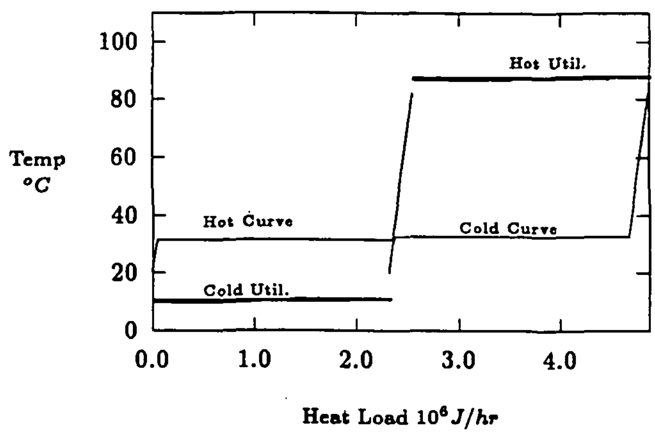

Figure 3: Composite Curve Diagram corresponding to S1

We observe significant minimum heating and cooling utility requirements. Let us consider Figure 3 which depicts the composite curve diagram for system S1. Both the hot and the cold curve, in this diagram, have a plateau that corresponds to the condensation of the distillate and the evaporation of water respectively. The size of these plateaus suggests that phase changes are the dominant processes from an energy consumption point of view. In the absense of equipment that upgrade heat (compressors, heat pumps etc.), recovery of the latent heat content of the condensing vapor stream through heat exchange with the vaporizing stream is thermodynamically infeasible. To ensure thermodynamic feasibility for the overall process and achieve the process targets, the consumption of hot and cold utilities is required. From Table 2 it is established that the hybrid system S3 requires less hot and cold utilities than S1 or S2.

Cases S4 and S5 help quantify the impact that equipment that upgrade heat have on the design of water reclamation systems that involve VCD and TIMES. Simple heat and mass balances lead to Table 4.

Configurations S4 and S5 feature latent heat recovery. The use of the compressor (in VCD) and the thermoelectric heat pump (in TIMES) upgrades the heat contained in the condensing streams thus heat exchange with the vaporizing streams within each process becomes feasible. Although the figures shown in Table 4 do not correspond to minimum utility requirements, a significant reduction in utility consumption, as compared to cases S1 and S2, is observed. The penalty is that electrical power is consumed by the new system. By comparing S4 and S5 based on the information in Table 4, it is seen that TIMES requires less hot utility than VCD. This is mainly attributed to the higher temperature of its product stream compared to the corresponding stream from VCD (59°C vs 31°C). Similarly the cooling requirement is higher for TIMES because the brine is at a higher temperature (60°C vs 31°C for VCD).

To evaluate the potential of the proposed approach for system integration, cases S6, S7 and S8 were developed. Cases S6 and S7 are similar to S4 and S5 with the addition of heat integration. Case S8 corresponds to a 50% TIMES- 50% VCD hybrid system.

Table 4: System Design with Integration

Case	Minimum Heating Utility (W)	Minimum Cooling Utility (W)	Power Requirement (W)
S6	3.3	22	16
S7	3.3	53	195
S8	3.3	37	106

Figures 4, 5, and 6 present the composite curves for the systems S6, S7 and S8 respectively. The different scales in Figures 4, 5, and 6 represent the fact that although the heating and cooling requirements for S6, S7 and S8 are comparable, the total amount of heat transferred from the hot to cold streams varies significantly among the three configurations. Comparing Figures 3 and 4 one can easily visualize the effect of the heat upgrading capability of the compressor in VCD whereby the *Hot Curve* has been sufficiently raised so that latent heat recovery is feasible (increase in the pressure of the vapor leads to increase of the condensation temperature).

The analysis performed in cases S6 and S7 leads to subsystems similar to existing ones. This implies that the existing subsystem designs utilize heat and energy efficiently. The instance of a hybrid system considered in S8 suggests that from an energy efficiency point of view, hybrid systems are not superior. This conclusion is subject to the restrictions imposed in the definition of S8; namely that fixed operating conditions for VCD and TIMES, and given subsystem designs be employed. Different operating conditions (i.e. different evaporation and condensation temperatures etc.) can alter the shape of the composite curves (Figure 5) and lead to flowsheets with different characteristics. A parametric analysis over a large temperature range requires information regarding the quality of the product of either process as a function of its operating temperature. Furthermore the utilization of alternative heat recovery techniques (heat pumping, production of electrical energy) within each subsystem also need to be examined.

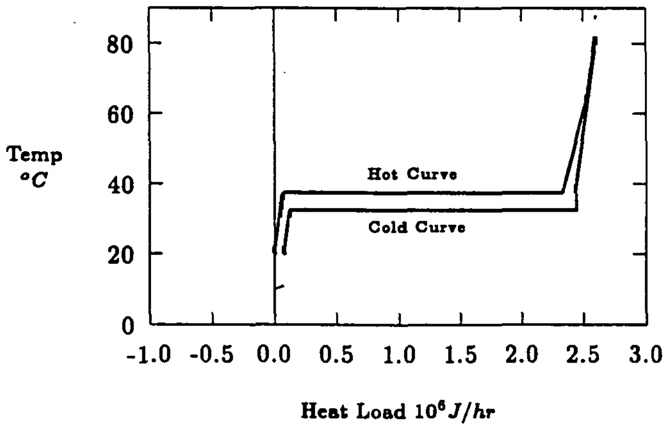

Figure 4: Composite Curve Diagram corresponding to S6

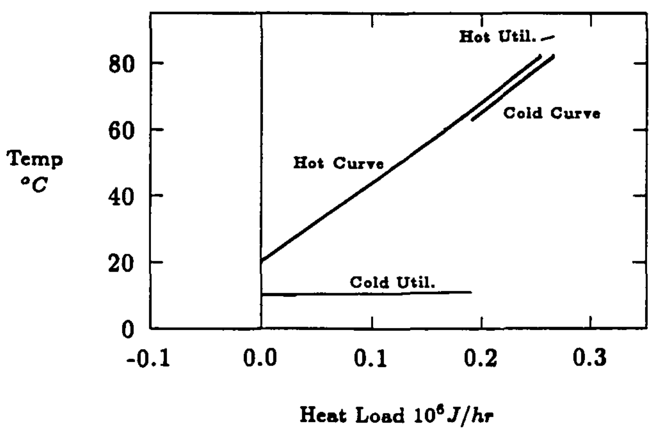

Figure 5: Composite Curve Diagram corresponding to S7

MULTIOBJECTIVE HYBRID SYSTEM OPTIMIZATION - Heat integration aims at minimizing the energy consumption of any given process. Often however, one is interested in a performance measure that can incorporate all contributions to the cost of a water recovery system including weight, power, volume and cost of supply. Thus, the equivalent cost (1) is employed as a multiobjective performance criterion. This performance index allows

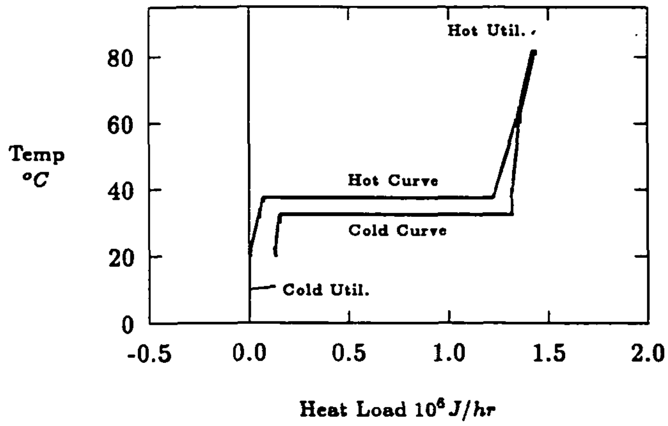

Figure 6: Composite Curve Diagram corresponding to S8

comparison of different flowsheets, including hybrid ones.

The structure under investigation consists of a two step purification procedure. The first step is comprised of VCD and/or TIMES and/or Air Evaporation (AE). The final purification step consists of a Multifiltration Unit (MF). For VCD, TIMES and MF weight, volume and power requirements were calculated based on the information given in [10] and [18]. For AE, power consumption was calculated based on the mathematical model and the subsequent subsystem optimization that was discussed earlier. The weight (W_c) of the wick evaporator and the heat exchangers were calculated by the same optimization procedure. The weight of the remaining equipment (piping, heat pump's compressor, packaging etc.) was considered to depend on the waste stream flowrate. Three such relations were employed:

1. $W_c = 15$ kg

2. $W_c = 35$ kg

3. $W_c = (17x^2 + 3x + 15)$ kg

where x = waste flowrate/(33kg/day). For a nine man crew the value of x does not exceed 1. In this case, the constant weight estimate represents upper and lower values of the weight of the AE unit estimated by the third formula.

The cost of the three competing technologies (VCD, TIMES and AE) is shown as a function of the duration of the mission for a nine man crew in Figure 7. The mission duration affects the total amount of power consumption and the equivalent cost of the volume of the equipment. By observation it can be seen that depending on the length of the mission different technologies may be more attractive. The low specific energy characteristics of VCD make it more attractive for long missions while for shorter missions TIMES and AE demonstrate lower values of the equivalent cost index. In Figure 8, the effect of the weight estimate for the AE unit is quantified. In particular, reducing the weight to 15 kg the corresponding curve drops by a constant amount. This change in the relative position of the TIMES and AE curves (Figure 8) suggests that use of AE is advantageous over use of TIMES over a longer mission duration interval. For the case of a three man crew the same calculations were performed and are summarized in Figure 9. Due to the lower feed flowrate to the corresponding processes, TIMES is superior to VCD over a wider mission duration interval. For the same reason, the weight estimate chosen for AE has a greater effect on the equivalent cost of the unit than it did in the nine man crew case.

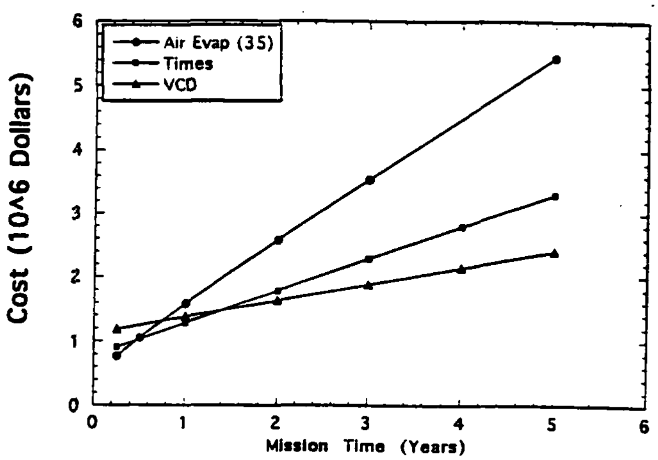

Figure 7: Cost Dependence of Mission Length for 9-Man Crew

The calculations described in the previous paragraph provide significant insight in the process selection procedure when only one technology is employed in the first step of the flowsheet under consideration. However, there is another important alternative that need be explored: do schemes utilizing more than one competing technologies in series or in parallel achieve better performance than single technology schemes? In this direction a hybrid system of TIMES and VCD in parallel followed by an MF unit was considered. The equivalent cost for the overall system as a function of the feed fraction processed through VCD for a nine man crew is shown

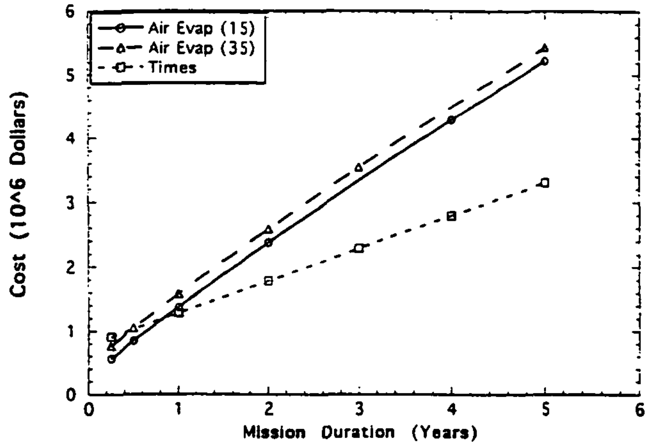

Figure 8: Impact of Fixed Weight on System Cost for AE(9-Man Crew)

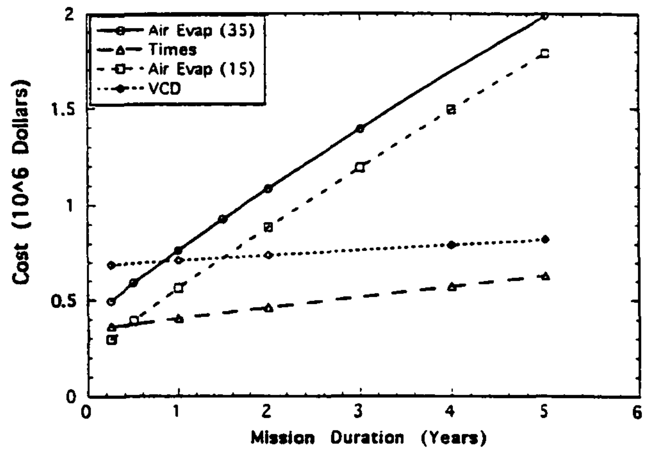

Figure 9: Variation of Cost with Mission Length for a 3-Man Crew

for different missions in Figure 10. One should notice jump discontinuities near feed fraction values equal to 0.0 and 1.0. This occurs since the existence of one unit is associated with a nonzero weight and volume. For small mission durations this fact prohibits the use of any hybrid system. As the duration of the mission increases, the equivalent cost curves show a minimum which for missions longer than 48 months suggests that a hybrid system simultaneously utilizing VCD and TIMES in parallel is advantageous from an equivalent cost point of view over a single technology system.

Hybrid system calculations were also performed in the case of TIMES and AE. Figure 11 depicts the corresponding equivalent cost curves. The sensitivity of the equivalent cost value to the selected weight estimate for the AE unit is also shown in the same Figure. In particular, when one employs the quadratic correlation ($W_c = 17x^2 + 3x + 15$) the cal-

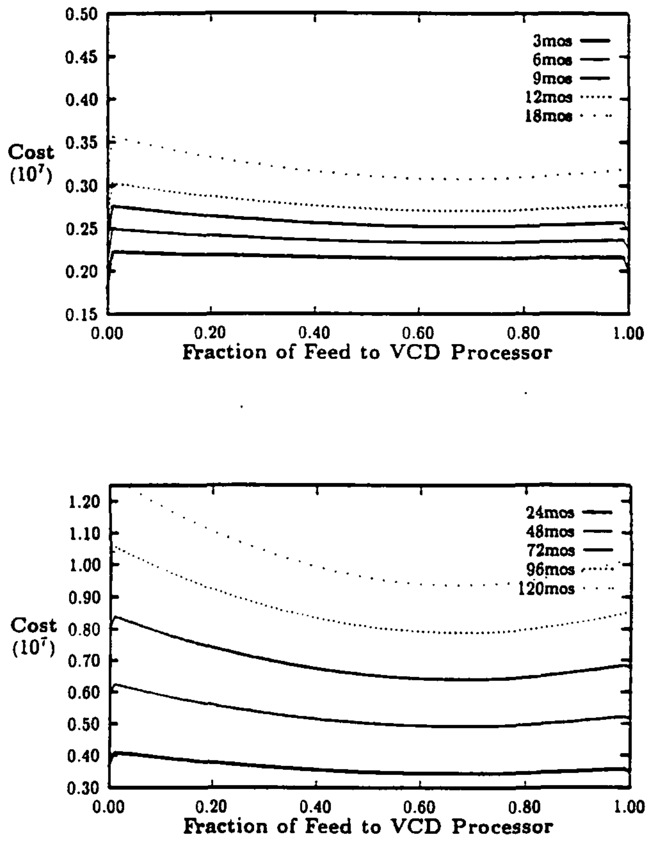

Figure 10: Equivalent Cost for VCD/TIMES Hybrid Systems

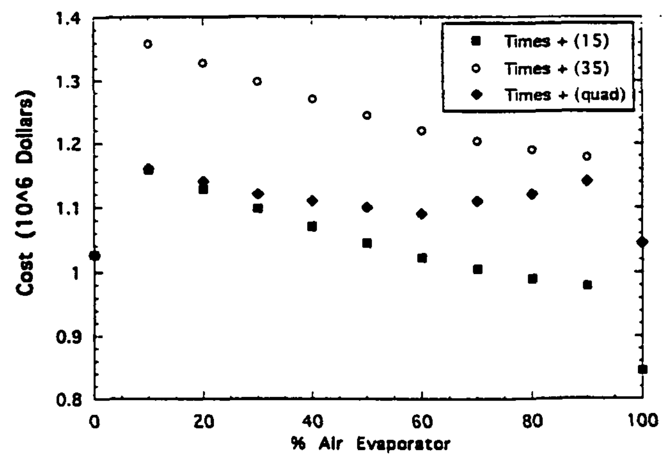

Figure 11: Hybrid TIMES/Air Evaporator Systems: Effect of AE Piping and Compressor Weight Correlations on the Cost (9-man Crew 6 months)

culations predict the existence of a minimum that corresponds to a hybrid configuration.

CONCLUSION

In this paper, we have developed mathematical models for the design of optimal water reclamation systems for long-duration space missions. These models were utilized in evaluating the performance of individual water reclamation technologies. Two subsystems were also simultaneously optimized with regard to the multiple objectives of volume, mass and power consumption. These objectives were quantified through an operational cost which was a linear function of these objectives. The optimization of the VCD and AE subsystems shows that the appropriate choice of operating parameters leads to significant improvements of each technology.

It is then demonstrated that total mission cost reductions can also be achieved by designing a water reclamation system that consists of multiple technologies. An optimization problem is formulated for this purpose based on the mathematical models developed above. Two types of design techniques were employed: heat integration and multiobjective optimization. For heat integration, pinch analysis is used to maximize heat recovery across three subsystems. The results show up to 94% reduction in heating or cooling requirements over a non-integrated design. Multiobjective optimization shows that considering a combination of technologies in the ECLSS can lead to cost reductions for long-range missions.

This work suggests that many options, beyond series and parallel configurations exist, for an overall optimal water reclamation system. Hence, a systematic methodology, capable of searching for the optimal flowsheet over all possible hybrid configurations of such systems, needs to be developed. Research efforts in that direction are currently underway.

Acknowledgment

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Nomenclature

W_T = weight of system (g)
P_T = power need for system (W)

V_T = volume of system (m^3)
T_m = duration of Use
C_w = cost per unit mass (\$/g) = \$10/g
C_p = cost of power (\$/KW-hr)
= \$210/KW-hr
C_v = cost per unit volume per time (\$/m^3-t) = 31,800/m^3-month
F = molar flow rate of air
X_{wo} = mole fraction of water in air phase at wick outlet
X_{wi} = mole fraction of water in air phase at wick inet
X_{wos} = mole fraction of saturated water in air phase at wick inet
T_{wi} = temperature of water in air phase at wick inlet
T_{wis} = saturation temperature of water in air phase at wick inlet
T_{wo} = temperature of water in air phase at wick outlet
T_{wos} = saturation temperature of water in air phase at wick outlet
T_{ci} = temperature of water in air phase at condensor inlet
L = length of wick evaporator
T_{fi} = temperature of stream entering fan
X_{ho} = mole fraction of water in air phase at heater outlet
Q_C = heat removal in condensor
Q_H = heat removal in heater
f_{obj} = objective function

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