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DEVELOPMENT ASSESSMENT OF
WASH WATER RECLAMATION

BY

DAVID F. PUTNAM

AUGUST 1976

PREPARED UNDER CONTRACT NO. NAS2-8239

BY

UMPQUA RESEARCH COMPANY
MYRTLE CREEK, OREGON

FOR

AMES RESEARCH CENTER

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

UMPQUA
RESEARCH

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FINAL REPORT

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FOREWORD

An analytical study and assessment of state-of-the-art wash water reclamation technology for advanced manned spacecraft is presented. All non-phase-change unit operations, unit processes and subsystems currently under development by NASA are considered. Included among these are: Filtration, Ultrafiltration, Carbon Adsorption, Ion Exchange, Chemical Pretreatment, Reverse Osmosis, Hyperfiltration and certain Urea Removal techniques. Performance data are given together with the projected weights and sizes of key components and subsystems. In the final assessment, a simple multifiltration approach consisting of surface-type cartridge filters, carbon adsorption and ion exchange resins receives the highest rating for 6-man earth orbital missions of up to 10 years in duration.

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1.0 INTRODUCTION AND SUMMARY

This is an analytical study and assessment of state-of-the-art wash water reclamation technology. It covers all non-phase-change unit operations, unit processes and subsystems currently under development by NASA. Each approach to wash water reclamation is described in detail. Performance data are given together with the projected weights and sizes of key components and subsystems.

This study concludes that a simple multifiltration subsystem composed of surface-type cartridge filters, carbon adsorption and ion exchange resins is the most attractive approach for spacecraft wash water reclamation in earth orbital missions of up to 10 years in duration. The high rating for this approach derives mainly from its basic simplicity, its ability to operate at low pressure, its lack of interfaces with other subsystems and its high safety and adaptability to flight conditions.

The final comparison in the tradeoff assessment was between multifiltration and reverse osmosis. Although previous studies (see Ref 1) have shown reverse osmosis subsystems to have a lower total equivalent weight for long duration missions than multifiltration subsystems, several recent developments have occurred to lessen that advantage. These are:

1. There are fewer waste contaminants in wash water than previously projected (total solids = 5.6 vs. 11.9 g/man-day).
2. Higher carbon loadings have been achieved than previously (0.167 vs. 0.047 g TOC/g carbon).
3. Higher-capacity ion exchange resins have recently been identified (1.5 vs. 1.0 meq/g).

The final assessment (see Section 8) shows that multifiltration is considerably lighter than reverse osmosis but uses somewhat more expendable material, so that after a period of six or seven years the total equivalent weight of multifiltration becomes a bit greater than for reverse osmosis. However, this disadvantage is overcome by other assessment factors. The overall score, on the basis of 100 points maximum, is 89.0 for multifiltration compared to 67.7 for reverse osmosis.

It is concluded that multifiltration will be a lighter, simpler, more reliable flight system than reverse osmosis, at least for missions up to 10 years in duration, and in addition, if NASA develops multifiltration rather than reverse osmosis to flight status, considerable cost savings will accrue by not having to address the following problems, which are exclusively associated with reverse osmosis.

- Development of a high pressure (400 to 1050 psi) feed pump.
- Development of reverse osmosis modules.
- The need for development of a pretreatment technique for RO brine that will control foaming and volatile component carry-over in the VCD unit.
- The need for development of a pretreatment teachnique to adjust and control the pH of waste wash water to the range preferred by the reverse osmosis membrane of choice.
- The sensitivity to the choice of cleansing agents.
- The need for development of a pressure damping device.
- The need for development of a back pressure regulator.

There are no equivalent development problems associated with multifiltration.

2.0 GROUNDRULES AND BASIC ASSUMPTIONS

2.1 Crew Size

Six.

2.2 Wash Water and Soap Usage Model

This model was defined in the contract statement of work and is presented in Table 2-1. It was originally developed in Reference 1, which discusses the rationale for selecting the values shown.

Table 2-1. WASH WATER AND SOAP USAGE MODEL

Item	Water Usage lb/man-day	Water Usage kg/man-day	Soap Usage[1] (active ingredients) g/man-day
Clothes Washer (wash and rinse)	24	10.89	0.6
Shower	8	3.63	1.2
Personal Hygiene & House Keeping	4	1.81	0.2
Dishwasher	0	0	0
Experiment	1	0.45	0
TOTAL:	37	16.78	2.0

[1] Sodium Dodecylbenzene Sulfonate ($C_{12}H_{25}-C_6H_4-SO_3Na$), molecular weight=348

2.3 Wash Water Solids Input Model

This model is shown in Table 2-2. It was developed during the first phase of the contract (see Reference 2) and is based on experimental data obtained under rigorously controlled conditions. The values are approximately one fourth as much as previously used values based on theoretical projections.

2.3.1 Ion Balance

In order to obtain an ion balance on the wash water solids input model shown in Table 2-2, it is necessary to know the amount of alkalinity present. Unfortunately, alkalinity was not one of the parameters measured during the

Table 2-2. WASH WATER SOLIDS INPUT MODEL
(mg/man-day except as noted)

	LAUNDRY WATER Clothes & Towel Mat'l	LAUNDRY WATER Crew	SHOWER WATER crew	SOAP[1]	TOTAL	TOTAL ppm
SUSPENDED SOLIDS Particle Size:						(water = 16.78 l/man-day)
>30μm	135.	22.3	470.	0	627.	37.4
8 to 30μm	224.	165.	168.	0	557.	33.2
3 to 8μm	4.7	0	4.4	0	9.1	0.5
1.2 to 3μm	0	2.4	0.3	0	2.7	0.2
0.45 to 1.2μm	4.7	12.9	5.9	0	23.5	1.4
TOTAL SUSPENDED SOLIDS	368.	203.	649.	0	1219.	72.7
DISSOLVED SOLIDS:						
Chloride	23.5	98.9	96.6	0	219.	13.1
Lactic Acid	6.9	152.0	61.9	3.6	224.	13.3
Sodium	96.8	96.4	109.	151.	453.	27.0
Urea	90.2	253.	257.	0.3	600.	35.8
Potassium	13.8	63.5	70.4	0.1	148.	8.8
Calcium	12.5	4.9	3.4	0.7	21.5	1.3
Ammonia	3.1	6.7	1.8	0	11.6	0.70
Magnesium	13.9	5.5	1.0	0.2	20.6	1.2
Iron	1.9	0.13	0.14	0	2.2	0.13
Copper	0.30	0.20	0.22	0	0.72	0.043
Soap[1]	0	0	0	1844	1844	110.
Other[2]	68.8	560.	473.	0	1102	65.7
TOTAL DISSOLVED SOLIDS	332.	1241.	1074.	2000.	4647.	277.
TOTAL SOLIDS	700.	1444.	1723.	2000.	5866.	350.
PHYSICAL AND CHEMICAL PROPERTIES:						
Turbidity (FTU- l/man-day)	432.	631.	893.	0	1956.	116. FTU
Color (after filtration to 0.45μm) (CU -l/man-day)	177.	94.	161.	0	432.	25. CU
Specific Cond. (μmho-l/cm-man-day)	221.	880.	484.	406.	1991.	118. μmho/cm
TOC (after filtration to 0.45μm)	39.	214.	246.	1109.	1608.	96.

---

[1] Sodium Dodecylbenzene Sulfonate ($C_{12}H_{25}-C_6H_4-SO_3Na$), molecular weight = 348.

[2] Probably includes: free fatty acids, cholesterol, triglycerides, glucose, amino acids, waxes, creatinine, squalene, paraffins, uric acid and other organic materials.

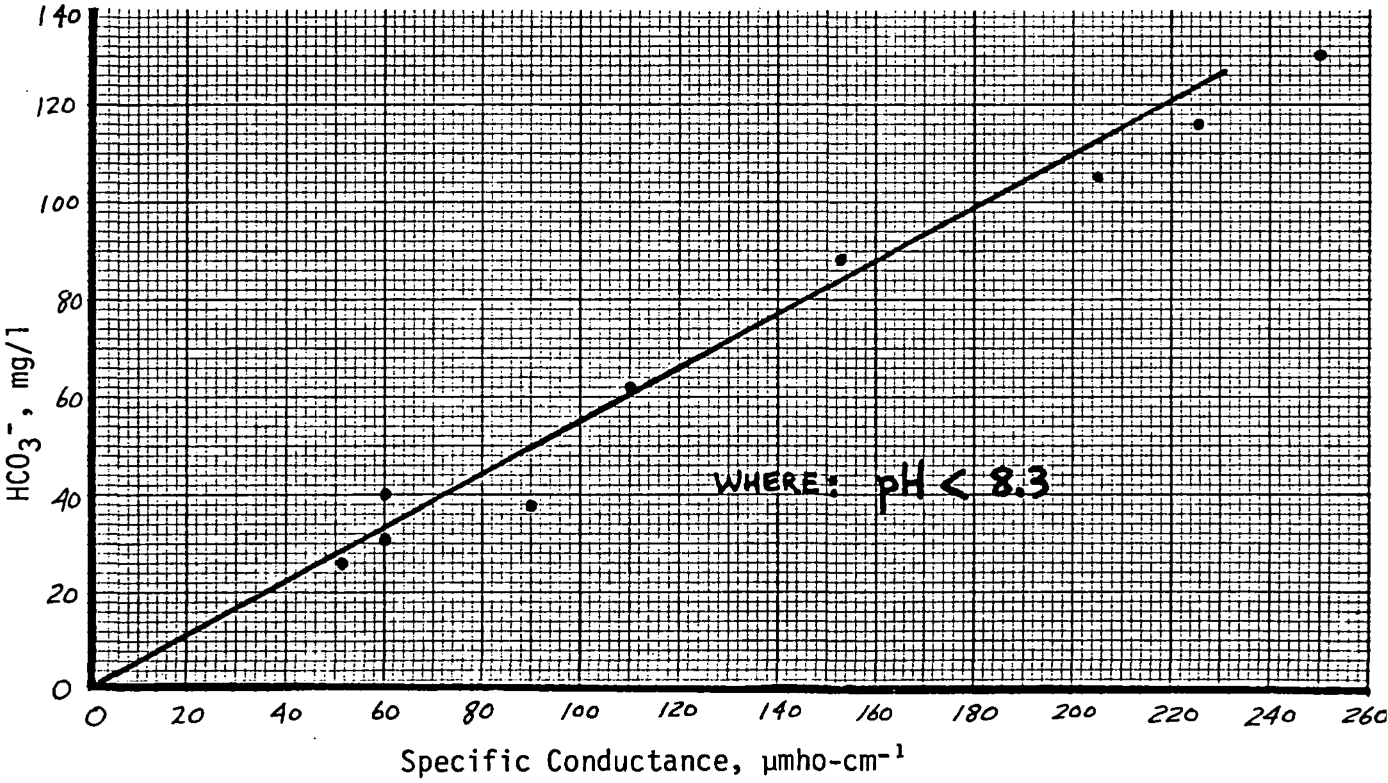
experimental study of wash water constituents. A guess at the amount of alkalinity present can be made by assuming the relationship between specific conductance and alkalinity shown in Figure 2-1. This relationship has been observed by URC in natural water sources. When the pH is less than 8.3, then all of the alkalinity appears as HCO_3^- and none as $CO_3^=$. This would be the case for wash water.

The specific conductance of the ionic species in wash water can be calculated by subtracting out the soap contribution as follows:

$$118\ \mu\text{mho-cm}^{-1} - \frac{406\ \mu\text{mho-l-cm}^{-1}\text{-man}^{-1}\text{-day}^{-1}}{16.78\ \text{l-man}^{-1}\text{-day}^{-1}} = 93.8\ \mu\text{mho-cm}^{-1}$$

Then, from Figure 2-1 the alkalinity corresponding to this value of specific conductance is : $HCO_3^- = 52$ mg/l.

Figure 2-1. OBSERVED ALKALINITY vs. SPECIFIC CONDUCTANCE FOR NATURAL WATER. (Results of URC Tests)



An ion balance was calculated using this figure for alkalinity and is presented in Table 2-3. The balance is remarkably close. In fact, it is a good deal closer than is usually obtained in the best laboratories. The criterion in Standard Methods (Reference 4) for an acceptable ion balance requires the absolute value of the difference between the sum of the cations and the sum of the anions to be less than or equal to the following formula:

$$|\Delta \text{ ions}| \leq 0.1065 + 0.0155\ \Sigma \text{ anions}$$

In this case:

$$|\Delta \text{ ions}| \leq 0.1065 + 0.0155(1.2189)$$

$$0.0001 \leq 0.1254$$

It is felt that the closeness of this ion balance should not be interpreted as validating the assumed value of alkalinity.

Table 2-3. ION BALANCE ON WASH WATER SOLIDS INPUT MODEL

CATIONS	mg/l		eq wt	meq/l
Ca^{++}	1.3	÷	20.04	0.0649
Mg^{++}	1.2	÷	12.16	0.0987
K^+	8.8	÷	39.10	0.2251
Na^+	18.0	÷	22.99	0.7829
NH_4^+	0.7	÷	18.04	0.0388
Fe^{+++}	0.13	÷	18.62	0.0070
Cu^{++}	0.043	÷	31.77	0.0014
				1.2188
ANIONS				
HCO_3^-	52	÷	61.02	0.8522
Cl^-	13.0	÷	35.45	0.3667
				1.2189

2.4 Duty Cycle.

See Reference 3. 8 hr/day, sunlit side, low earth orbit.

2.5 Electric Power Penalties.

See Reference 3.

	lb/watt	kg/watt
a) Continuous Power		
Regulated 115 VAC, 60 hz	0.725	0.329
Regulated 115 VAC, 400 hz, 3 phase	0.710	0.322
Regulated 28 VDC	0.591	0.268
b) Sunlit Side Power (low earth orbit)		
Regulated 115 VAC	0.351	0.159
Regulated 28 VDC	0.270	0.122
Unregulated 28 VDC	0.154	0.070

2.6 Thermal Rejection Penalties.

See Reference 3.

a) Thermal Rejection to Air	0.25	0.113
b) Thermal Rejection to Coolant	0.18	0.082

2.7 Component Weights.

Component weights are for projected flight qualified units. Contractor projections are used where available. Elsewhere, the values are URC best estimates.

2.8 Spares.

A 30 per cent allowance for spares is added to the base weight.

2.9 Expendables.

Expendables are computed from the performance data summarized in Section 3.

2.10 Wash Water Quality Standards.

Tentative standards for wash water were established in December 1971, by the National Academy of Sciences, National Research Council at the request of NASA Headquarters. A copy of the report is reproduced in Appendix

B of Reference 1. The standards are summarized in Table 2-4.

Table 2-4. TENTATIVE STANDARDS FOR WASH WATER

PHYSICAL PARAMETERS	
Color, cobalt units	≤ 15
Conductance, specific, μmho-cm^{-1} at 25°C	≤ 2000
Foaming	Nonpersistent more than 15 sec.
Odor	Nonobjectionable
CHEMICAL CONSTITUENTS	
Carbon, total organic, mg/l	≤ 200
Detergents	Not specified
Lactic acid, mg/l	≤ 50
Nitrogen, ammonia, mg/l	≤ 5.0
Oxygen demand, chemical, mg/l	Not specified
pH	5.0 to 7.5
Sodium chloride, mg/l	≤ 1000
Solids, dissolved, at 180°C, mg/l	≤ 1500
Urea, mg/l	≤ 50
MICROBIOLOGICAL	
Micro-organisms, number per ml, standard 48 hr plate count	≤ 10

3.0 UNIT OPERATIONS AND PROCESSES

This section describes the unit operations and processes currently under development by NASA for use in non-phase change wash water reclamation subsystems. In general, the subsystems are designed to accomplish three major functions:

a) removal of suspended materials,
b) removal of dissolved materials,
c) control of microbiological growth.

3.1 Removal of Suspended Materials.

Suspended materials include all those materials that are not in true solution. Turbidity, which is a measure of the amount of light scattered by a suspension, is an indication of the presence of suspended materials. Suspended materials may be removed by various types of filters. A number of filter types have been studied in connection with space wash water and various amounts of performance data are available. In general, both ultrafiltration and reverse osmosis remove essentially 100% of the suspended materials from a solution. All other filters remove less than 100%. Reverse osmosis, in addition to removing suspended material, also removes many soluble materials. Ultrafiltration and common filters do not remove soluble material. Ultrafiltration can be designed to operate with very little fouling and performance degradation. Common filters usually plug up in time and must be replaced. However, some designs may be cleaned by backflushing. The water required for backflushing represents a loss in processing efficiency, a characteristic that filter backflushing has with ultrafiltration and reverse osmosis. Reverse osmosis, unlike ultrafiltration, is sensitive to suspended materials in respect to fouling and performance degradation. Some form of pre-filtration is usually recommended for reverse osmosis when applied to space wash water. Chemical pretreatment has been used to coagulate colloidal material to enhance its filterability.

3.2 Removal of Dissolved Materials.

Dissolved materials are commonly divided into two major categories: organic and inorganic. NASA has investigated activated carbon for the removal of organics, ion exchange resins for the removal of inorganics, reverse osmosis for the removal of both organics and inorganics, electrolytic pretreatment for the removal of organics and chemical pretreatment for the precipitation, flocculation and coagulation of both organic and inorganic materials.

3.3 Control of Microbiological Growth.

In NASA sponsored programs the following techniques have been used with varying degrees of success to control microbiological growth:

a) microbiological filters
b) ultraviolet irradiation
c) addition of biocides
d) operation at pasteurization temperature, 74° C (165° F)

Microbiological filters and ultraviolet irradiation were used in the McDonnell Douglas 60-day manned chamber test (see Reference 8) and failed to satisfactorily control microbiological growth. Biocides must be used in relatively large doses (see Reference 16) to assure adequate microbiological control and thus they impose a large penalty on adsorption and other types of reclamation processes. The current NASA method of choice is operation at pasteurization temperature. This has been tried by a number of different investigators and found to work satisfactorily when system temperatures are maintained near 74°C (165°F).

3.4 Filtration.

Some of the types of filters that have been evaluated with space wash water and their ability to remove suspended materials (as judged by turbidity removal) are listed in Table 3-1.

Table 3-1. TURBIDITY REMOVAL FROM SPACE WASH WATER BY VARIOUS FILTERS

Type of Filter	Turbidity Removal, %	Source of Information
Sand	70	Abcor, Reference 5
Glass Fiber	75	Abcor, Reference 5
0.9 µm absolute	82	McDonnell Douglas, Reference 6
0.45 µm absolute	89	Umpqua Research, Reference 2
Ultrafiltration	98.8	Abcor, References 5,7

Surface type cartridge filters were the first type used for removal of suspended materials from space wash water. This type has been used in several manned chamber tests with acceptable performance. Very little R&D work has been done, however, toward achieving the higher filter loadings that are potentially possible with an optimum choice of the size, type and number of graded filters used in series.

In the McDonnell Douglas 60-day manned chamber test (see Reference 8) a series of 30, 10, 3, 0.25, 0.15, 0.15 and 0.12 μm surface-type cartridge filters were used. No loading data were reported. In the McDonnell Douglas 90-day manned chamber test (see Reference 9) 30, 3 and 1 μm surface-type cartridge filters were used in series. The loading data for these filters is presented in Table 3-2.

Table 3-2. FILTER LOADING DATA FROM McDONNELL DOUGLAS 90-DAY TEST (SURFACE TYPE FILTERS)

Filter Size, μm	Total Solids Filtered, g	No of Filters Used, #	Wt of Each Filter, g	Filter Loading, g solids/g filter
30	190.7	4	100	0.477
3	41.7	2	100	0.209
1	0*	2	100	-----

*Below detectable limit.

At NASA Langley Research Center experiments were conducted on a filtration-reverse osmosis technique for purification of domestic wash water (see Reference 10). The experimental system contained a series of 50, 25, 10, 5 and 1 μm depth-type cartridge filters followed by a hollow-fiber reverse osmosis module. This series of filters did not prevent fouling of the hollow-fiber reverse osmosis module during the test program. The complete set of filters was changed when the process flow dropped to a predetermined value. The average loading for two filter sets is shown in Table 3-3.

Table 3-3. FILTER LOADING DATA FROM NASA LaRC DOMESTIC WASH WATER TESTS (DEPTH TYPE FILTERS)

Filter Size, μm	Total Solids Filtered, g	No of Filters Used, #	Wt of Each Filter, g	Filter Loading, g solids/g filter
50	32	2	454	0.0352
25	47	2	454	0.0518
10	46	2	454	0.0507
5	109	2	454	0.1200
1	64	2	454	0.0705

It is impossible to determine from these data how many of the filters were really loaded to their limits. Individual pressure drop data would be most useful in this respect. Also, the particle size distribution implied in Table 3-3 cannot be compared to values in Table 3-2 or Table 2-2 because the filter ratings are nominal versus absolute and the wash water is domestic versus spacecraft type.

The particle size distribution of the wash water model (see Table 2-2) indicates that a better series of filters than that shown in Table 3-2. (30, 8 and 1 μm) would be 30, 8 and 0.45 μm, which will be used for the present study. The 30 μm is assumed to have the same loading factor as the 30 μm filter in the 90-day test. The 8 μm filter is assumed to have the same loading factor as the 3 μm filter in the 90-day test. The 0.45 μm filter is assumed to have the same life as the 8 μm filter (in the 90-day test the 1 μm filter had the same life as the 3 μm filter). With these assumptions, the expected usages and loadings were calculated and are shown in Table 3-4.

The physical size and weight information for these surface-type cartridge filters is summarized in Table 3-5.

Table 3-4. EXPECTED USAGES AND LOADINGS OF SURFACE-TYPE CARTRIDGE FILTERS

Filter Size, µm	Solids Filtered,[4] g solids/man-day	Filter Loading, g solids/g filter	Filter Usage g filter/man-day
30	0.627	0.477[1]	1.31
8	0.557	0.209[2]	2.67
0.45	0.0353	0.0128	2.67[3]
TOTAL	1.2193	0.6988	6.65

[1] assumed loading (see 30 µm filter, Table 3-2)
[2] assumed loading (see 3 µm filter, Table 3-2)
[3] assumed life (same as 8 µm filter)
[4] see Table 2-2 for total particle size distribution of suspended solids

Table 3-5. PHYSICAL SIZE AND WEIGHTS OF SURFACE-TYPE CARTRIDGE FILTERS

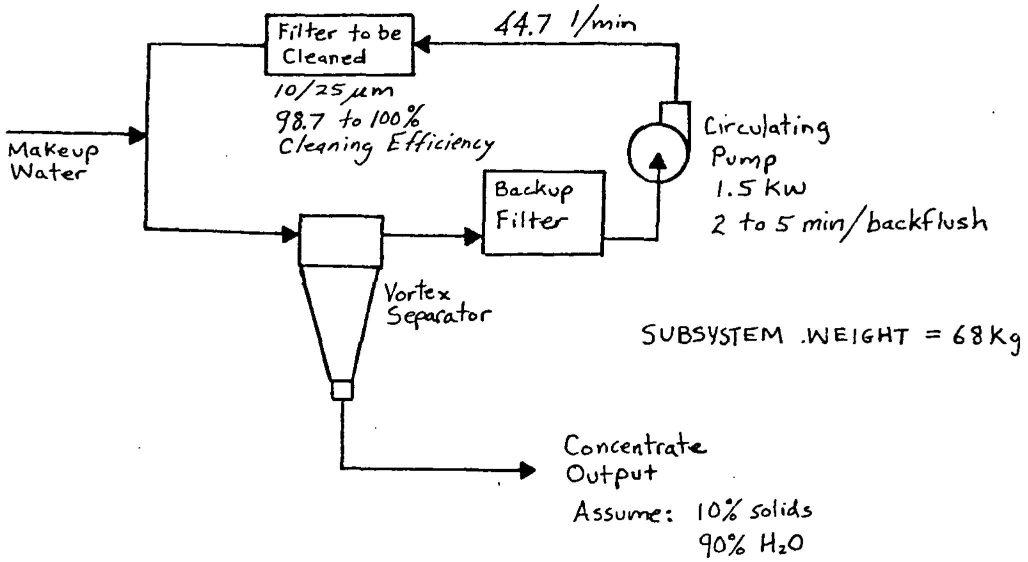
Item	Installed Weight, Kg	Dimensions	Installed Volume, cm^3
Housing	0.5[1]	10 cm diam x 36 cm	383
Filter element	0.1[2]	6.6 cm diam x 25 cm	130

[1] projected Flight Weight
[2] actual weight of a commercially available off-the-shelf element

3.4.1 Filtration with Backflush Cleaning.

Martin Marietta Corporation (see Reference 11) has investigated a concept for cleaning surface filters by backflushing. A schematic of Martin's subsystem is shown in Figure 3-1.

Figure 3-1. FILTER BACKFLUSHING DEVICE (Ref 11)



The filter to be cleaned is placed in the position indicated and backflushed with impingement jets for 2 to 5 minutes. The filter has to be specially designed for backflushing and to fit the backflush unit. The solids that are dislodged by backflushing are concentrated by centrifugal force in the vortex separator and discharged from the unit. The small amount (10 to 15%) of solids that are not removed by the vortex separator are removed by the system backup filter. When the backup filter becomes loaded, it is inserted in the cleaning position and backflushed in the same manner as any other filter.

The Martin subsystem has been successfully tested in zero-gravity flights using graded road dust and distilled water. It has not been evaluated with real wash water. For the purpose of this study it is assumed that the output solids are contained in a slurry composed of 90% water and 10% solids.

3.5 Ultrafiltration.

Abcor, Inc., describes ultrafiltration in Reference 12 as follows:

"Ultrafiltration (UF) is a pressure driven membrane separation process which utilizes a semi-permeable membrane to remove suspended and colloidal solids from water. In contrast to reverse osmosis membranes which exhibit high rejection efficiencies for dissolved salts and organics, ultrafiltration membranes readily pass inorganic salts and most low molecular weight organic molecules but reject suspended solids, microorganisms and viruses, colloids, and dissolved macromolecules.

"In the operation of ultrafiltration systems, a feed solution is introduced into and pumped through a membrane unit. Suspended and colloidal solids, which are retained by the membrane, are removed as a fluid concentrate. Water and some dissolved materials pass through the membrane under the applied hydrostatic pressure, and are removed as permeate.

"Ultrafiltration systems are characterized by high water recoveries, high fluxes and low operating pressures. High water recoveries (sometimes greater than 99%) can be achieved since osmotic pressure limitations are absent. Fluxes in the range of 20-200 gal/ft^2-day (gfd) can be achieved, consequently membrane surface area requirements are small. Operation is generally at 10-50 psig, and low pressure pumps and piping can be utilized.

"The operation of ultrafiltration can be severely limited by factors other than the intrinsic characteristics of the membrane employed. The more critical factors include feed type, operating temperature and the hydrodynamic flow conditions along the membrane surface. The latter is directly related to concentration build-up at the membrane surface called 'concentration polarization.' Under certain conditions increased concentration polarization may lead to membrane fouling by the precipitation of sparingly soluble colloids or gels. In systems operating on a mixed feed of colloidal matter and dissolved solids, such as would be the case with washwater, membrane fouling can be severe, even when relatively high feed flow rates are employed. In such cases operation at elevated temperatures can retard membrane fouling. Operation at temperatures in the order of 60°C has been shown to significantly change the fouling characteristics of shower waste."

Compared to a 0.45 μm cartridge filter (see Table 3-1) ultrafiltration removes approximately 99 versus 89% of the turbidity from space wash water.

The design parameters presented in Table 3-6 were obtained from Abcor, Inc. (see References 5 and 12), and can be used to determine the number of UF modules required in the design of a wash water subsystem.

Table 3-6 DESIGN DATA FOR ABCOR, INC., ULTRAFILTRATION MODULES.

Driving Pressure = 3.4 atmg (50 psig)
Membrane Flux = 127.3 l/hr-m^2 (75 gal/day-ft^2)
Water Recovery = 99.5%
Recirculation Rate = 11.4 l/min-module (3gpm/module)
Pressure Drop = 0.68 atm (10 lb/in^2)
Module Size = 1.27 cm diam x 45.7 cm long (½" diam x 18")
Mass Transfer Area = 0.01858 m^2/module (0.2 ft^2/module)
Module Housing Weight = 2.268 kg/module (5lb module)
Module Weight = 0.1134 kg/module (¼ lb/module)
Design Life = 1 year

3.6 Chemical Pretreatment.

DeBell & Richardson, Inc. (see Reference 13), experimented with the addition of coagulating and flocculating chemicals to remove soap from space wash water. The highest removal rate occurred for Olive Leaf soap in ersatz wash water. It was found that adding 170 ppm of $FeCl_3$ (from a 40% $FeCl_3$ solution) to an ersatz wash water solution containing 1800 ppm Olive Leaf soap caused 95% of the Olive Leaf to coagulate. Adding an additional 0.25 ppm of Retan 425 (an anionic polyacrylamide) caused flocculation. Mixing was required at both rapid (100 rpm) and slow (30 rpm) rates with a paddle-type stirrer. The treated water equilibrated at a pH of between 3 and 4 as a result of the $FeCl_3$, which would necessitate a pH adjustment before reuse. Little or no work was done with real wash water. It was concluded that $FeCl_3$ pretreatment of wash water appeared feasible for Olive Leaf soap. In experiments with Neutrogena the removal was in the range of 60 to 70 per cent. With Miranal JEM it was in the range of 8 to 13 per cent. The authors felt that any cleansing agent ultimately selected by NASA, if other than Olive Leaf and/or Neutrogena, would have to be experimentally studied to determine how and to what degree it could be removed from waste wash water by chemical pretreatment.

3.7 Carbon Adsorption.

Activated carbon is used to remove dissolved organic materials. There are numerous types of carbon made from various base materials including pecan shells, coconut shells, wood, coal and petroleum coke. The base materials are converted to char particles which are then activated by exposure to an oxidizing gas or steam at high temperature. This process produces a porous structure in the char with a large internal surface area. Many variations in the dimensions of the cavities and internal surfaces are possible. Such variations can produce carbons with high affinities for specific molecules.

Activated carbon has been used in experimental multifiltration systems to treat wash water since the earliest days of the space program (see Reference 14). It was used in the McDonnell-Douglas 60-Day Manned Chamber Test (see Reference 8) but no loading data are available from this test. Carbon beds were also used in the McDonnell Douglas 90-Day Manned Chamber Test (see Reference 9). Bed loading data are shown in Table 3-7. Recent work by Abcor, Inc. (see Reference 12) has resulted in identifying a carbon with higher adsorption capacity than that used in the 90-Day Test. A summary of these carbon capacity data also is presented in Table 3-7.

Table 3-7. CAPACITY DATA FOR ACTIVATED CARBON USED FOR WASH WATER RECLAMATION

Type of Carbon	Loading, g TOC/g Carbon	Source of Data
Barnebey-Cheney PC	0.047	McDonnell Douglas, Reference 9
Calgon Filtrasorb 400[2]	0.15	Abcor, Inc., Reference 12
Nuchar WV-H	0.10[1]	"
Witco 718	0.073[1]	"
Pittsburg BPL	0.067[1]	"
Barnebey-Cheney PC	0.062[1]	"
Barnebey-Cheney PA	0.058[1]	"

[1] Calculated from reported "apparent adsorptive capacity."

[2] Bulk density = 0.40 g/ml (25 lb/cu ft)

3.7.1 Regeneration of Carbon

Regeneration experiments on both impregnated and nonimpregnated carbons have been performed by Abcor, Inc., and are reported in Reference 12. Significant capacity losses were reported on each successive regeneration as follows:

Number of Regenerations	Carbon Capacity (see Reference 12) (non-impregnated Filbrasorb 400)
0	0.15 g TOC/g carbon
1	0.14 "
2	0.05 "

The report concluded that although carbon regeneration is feasible, the capacity losses noted in the regeneration mode used in the study were too great to justify the incorporation of the additional equipment required to accomplish the regeneration.

3.8 Ion Exchange.

Ion exchange resins are used to remove dissolved ionic species from solution. Most of the ionic species found in wash water are inorganic salts. There are basically four types of resins: 1) strongly acid cation; 2) weakly acidic cation; 3) strongly basic anion; and 4) weakly basic anion. Abcor, Inc. (see Reference 12), found that the weak resins did not remove ionic species from wash water whereas good removal efficiencies were reported for strong resins and measured capacities were found to be in agreement with manufacturer specifications.

Strongly acidic cation exchange resins remove cations from solution. The removed cation is replaced with a hydrogen ion from the resin. In the case of sodium chloride this reaction is represented as follows:

$$R_RSO_3H + NaCl \longrightarrow R_RSO_3Na + HCl$$

It should be pointed out that for sodium bicarbonate the reaction tends to liberate CO_2 and water as follows:

$$R_RSO_3H + NaHCO_3 \longrightarrow 2RSO_3Na + H_2O + CO_2$$

Thus, if cation resins are used first, then anion resins should not be required for the removal of HCO_3^- ions. Strong base anion resins are required, however, for the removal of other anions in wash water, mainly Cl^-(see Table 2-3). This reaction is represented as follows:

$$R_RNR_3OH + HCl \longrightarrow R_RNR_3Cl + H_2O$$

The ion exchange resins under discussion have a preferred order in which ions are exchanged. The hierarchy is shown in Table 3-8 with the ions listed in descending order of preference. That is, the resins prefer ions that are higher on the list where equal concentrations are concerned. This means that any ion that happens to be absorbed on the resin will be exchanged for one that is higher up the list, but will not be exchanged for one that is lower on the list. For instance, in the case of Na^+ and

Mg^{++}, the following reaction would occur:

$$2R_RSO_3Na + MgCl_2 \longrightarrow 2R_RSO_3Mg + 2NaCl$$

Obtaining resins that would not decompose at pasteurization temperatures (74°C, 165°F) has been a problem in the past. However, Abcor, Inc., has experimented with two resins (see Reference 12) that performed up to the manufacturer's ratings. These two resins and their capacities are listed in Table 3-9.

Some natural resins (zeolites) are reported (see Reference 15) to favor the removal of NH_4^+, whereas most synthetic resins, such as those in Table 3-9, prefer divalent ions and therefore have limited use for removal of NH_4^+ from waste waters. The natural zeolite mentioned in Reference 15 as being most effective for ammonia removal is Hector Clinoptilolite. No reference could be found to this material having been tried on space wash water; whereas Rohm and Haas Amberlite IR-120+(Abcor, Ref 5), Dowex 50W-X8 (Rutgers, Ref 24) and Baker ANGC-101 (Martin Ref 23) were all tried.

Table 3-8. DISPLACEMENT SERIES FOR ION EXCHANGE RESINS (from Reference 12)

CATION	ANION
Th^{++++}	$SO_4^{=}$
La^{+++}	$CrO_4^{=}$
Ba^{++}	I^-
Sr^{++}	NO_3^-
Ca^{++}	Br^-
Mg^{++}	Cl^-
Cs^+	OH^-
Rb^+	F^-
K^+	
Na^+	
Li^+	
H^+	

Table 3-9. CAPACITY OF ION EXCHANGE RESINS (Ref 12)

RESIN TYPE	IDENTIFICATION	CAPACITY meq/g
Strong acid cation	Amberlite IR-120+	1.53
Strong base anion	Amberlite IRA-400	1.36

3.8.1 Regeneration of Ion Exchange Resins

Experiments and calculations by Abcor, Inc., presented in Reference 12 indicate that regeneration of the ion exchange materials listed in Table 3-9 may be desirable. Sulfuric acid is recommended for regenerating the cation resins and sodium hydroxide is recommended for regenerating the anion resins. The basic information required for calculating the amounts of regenerant materials needed is given in Table 3-10.

Table 3-10. RELATIONSHIP BETWEEN AMOUNT OF REGENERANT AND ION EXCHANGE CAPACITY (Ref 12)

REGENERANT USAGE meq/ml	CATION RESIN (Amberlite IR-120+) CAPACITY, meq/ml	ANION RESIN (Amberlite IRA-400) CAPACITY, meq/ml
0.75	0.53	0.48
2.3	1.05	0.75
4.6	1.24	0.94
7.6 (maximum)	1.35	1.20

NOTES:

1. Resin specific weight = 0.88 g/ml (cation), 0.87 g/ml (anion).
2. Regenerant solution concentrations are 1 normal.
3. 4 bed volumes of rinse water are required per regeneration.

3.9 Reverse Osmosis.

Reverse Osmosis is a pressure driven membrane process that removes most suspended and dissolved materials. Early NASA sponsored work on applying reverse osmosis to spacecraft wash water reclamation was done by Chemtric, Inc. (Reference 16). This work involved experiments with a duPont hollow-fiber permeator and a Westinghouse tubular RO module, and was carried out at ambient temperature. Relatively large doses of biocide (up to 1%) were used unsuccessfully to control microbial activity. This experience, together with other unsuccessful attempts to control microbiological growth for reasonably long periods (see Reference 8) led NASA to investigate a number of promising membranes and sponsor a series of efforts (see References 1, 17, 18, 19, 20, 21) to develop an RO membrane that would work on spacecraft wash water at pasteurization temperature, 74°C (165°F). The basic problems and the design goals of this effort are summarized in Reference 1.

The most promising high temperature RO membranes that have been evaluated by NASA to date are summarized in Table 3-11. Of the nine membrane materials listed, only one (Envirogenics Systems) has been developed to the full size module stage, and these RO modules had relatively good performance in a 1000 hour test conducted by McDonnell Douglas (see Reference 6). Of the five coupons also tested by McDonnell Douglas only two were recommended for further development. These two materials both showed excellent rejection factors for the parameters of interest and exhibited little or no performance degradation over the test period of approximately 200 hours.

The dynamic membrane (Zr(IV) Oxide Polyacrylic Acid) listed in Table 3-11 was tested at Clemson University and has been subjected to only 19 hours of continuous operation. The reported rejection factors were somewhat erratic (see Table 3-12) and appeared to decline with increasing concentration. Urea exhibited a peculiar trend in that its rejection was almost nil at first, but later increased to around 70%. Because of the small amount of test time on the dynamic membrane and the equivocal nature of some of the data, it is felt that long-term performance projections cannot be made for this concept until considerably more testing has been accomplished.

An example of the kind of performance degradation that can and usually does occur with time is illustrated in Table 3-13, which summarizes the 1000 hour test data on the Envirogenics 6-man unit. Note that rejection factors for every one of the nine parameters shown were significantly lower

Table 3-11 REVERSE OSMOSIS MEMBRANE PERFORMANCE DATA AT 74°C (165°F)

Manufacaturer	Membrane	Usage Restrictions	Recommended pH Range	Test Element	Test Time hrs	Test Press. psig	Flux Range gfd	PERCENT REJECTION Total Residue	Chloride	Urea	Lactic Acid	Ref.	Recommended for further Development (see Reference 6)
Envirogenics Systems	Sulfonated Polysulfone	Membrane should be kept wet	0-14	2" diameter Coupon	227 159	800 500	16-19 16-19	78 91	79 86	30 31	72 97	6,18	no
North Star R&D Institute	Composite Coated Polysulfone film	None-Dry Membrane	1-13	2" diameter Coupon	207 92 73	800 650 500	4-5 3-6 nil	95 94	96 97	84 86	93 98	6,21	yes
Gulf Environmental Systems	Cellulose Acetate Composite	Dry Membrane	5.5-6.0	2" diameter Coupon	247 146	800 500	5-8 3-6	98 97	98 97	57 91	88 93	6	yes
Research Triangle Institute	Plasma Polymerized Polysulfone	None-Dry Membrane	unknown	2" diameter Coupon	212 100	800 500	2-10 2-10	79 92	72 93	61 9	87 64	6	no
Gulf South Research Institute	Ethyl Cellulose	Membrane should be kept wet	3.5-10	2" diameter Coupon	96 100	800 500	2-30 15-21	15 24	14 32	50 63	52 46	6	no
Clemson University	Zr (IV) Oxide-Polyacrylic Acid	Membrane should be kept wet	>8	7-channel ceramic tube ½" diam x 14"	19	1000	28-50	-	-	60	-	17	*not rated by Ref. 6*
Envirogenics Systems	Di and Tri-Acetate Blend	Membrane should be kept wet	unknown	6-man unit	1000	300	3-8	98	97	61	95	6,18,22	yes
General Electric	Sulfonated Polyphenylene Oxide (PPO)	Membrane should be kept wet	7	Cylindrical plate & frame 1 channel/2 membrane unit	300	600	3-7	87	85	48	80	19,22	not rated by Ref. 6
Celanese Research	Polybenzimidazole (PBI)	none - Dry Membrane	>7	Hollow Fiber Module 1" diam x 30" w/40 fibers	300	600	0.3-1.2	98	98	85	96	20,22	not rated by Ref.6

Table 3-12. PERFORMANCE OF Zr(IV) OXIDE-POLYACRYLIC ACID DUAL-LAYER MEMBRANE. (Based on a 19-hr test, See Ref. 16, pp. 41 & 48)

Parameter	Raw Wash Water	Concentrated Wash Water	Electrolytically Pretreated Urine
Total Organic Carbon			
Amount, m/l	183	4421	-
Rejection Factor	.96	.96	-
Ammonia			
Amount, mg/l	31	82	800
Rejection Factor	.78	.88	.53
Urea			
Amount, mg/l	44	255	2250
Rejection Factor	.06	.70	.68
Specific Conductance			
Amount, μmho-cm^{-1}	640	4421	18500
Rejection Factor	.91	-	.62

Table 3-13. PERFORMANCE DEGRADATION FOR ENVIROGENIC SYSTEMS' 80 GPD (6-man) RO UNIT. (calculated from data presented in Ref. 6 for a 1000-hour test)

Parameter	0-6 Weeks	6-12 Weeks
Total Organic Carbon	87.8	82.1
Specific Conductance	96.8	85.0
Ammonia	65.8	53.3
Turbidity	97.8	85.7
Total Residue	97.8	88.6
Urea	61.1	5.4
Lactic Acid	94.7	88.7
Chloride	97.4	85.5
MBS	98.4	92.5

during the second six-week period than the first. In the case of urea, the rejection factor declined to almost zero. Typical performance declines are also shown in Reference 22 for 300 hour periods and as a function of brine concentration.

3.9.1 RO Module Design.

Currently, there are four types of physical constructions used to package an RO membrane into a module of useful size. The advantages and disadvantages of each approach are discussed below.

Spiral Wound. The spiral-wound configuration consists of two sheets of membrane material separated by a porous support material. The membrane sheets are joined along three sides and the fourth edge is attached to a tube that has perforations inside the seal area. The membranes and support material along with a mesh spacer are rolled around the central tube to form a spiral or "jelly roll". This configuration has a high packing density (surface area/volume), short feed flow path, and low pressure losses as the mesh spacer acts as a turbulence promoter to produce good mixing and minimization of concentration polarization and fouling effects at lower velocities than in other systems. The design has moderate to serious problems in handling large-size particulate matter.

Tubular. Tubular modules commonly contain membranes which are assembled in the shape of cylinders and placed either on the outside or inside of porous tubes (the membranes are commonly inserted into ½ inch diameter porous fiber-glass-reinforced epoxy tubes). Tubular modules can also contain porous ceramic tubes with either cellulosic or dynamic-type membranes cast in-situ. Tubular systems will handle larger particulate matter without plugging than other module types. The tubular design usually requires fluid velocities of at least 1 m/sec to maintain turbulent flow, and hence has high energy requirements. Packing densities are low, with relatively large volumes required for each unit of membrane area.

Plate and Frame. Plate and frame modules use a multiple plate design consisting of flat membrane sheets placed in metal frames which are held in racks similar to those used in plate and frame filter presses. Plate and frame units have low packing densities and require heavy support structures. Pumping energy requirements are high and uniform velocity distributions are difficult to achieve. Modules of this type have the advantage of accommodating easily fabricated membrane shapes and are widely used in evaluation of candidate membrane materials.

Hollow Fiber. Hollow fiber modules contain large quantities of hollow fiber membranes with dimensions of approximately 50 μm OD and 25 μm ID packed into a cylindrical shell in a configuration much like a shell and tube heat exchanger. These assemblies have very large total surface areas. The feed is pumped into the shell side of the module and the product permeates the fibers and is drawn off at the module end. Hollow fiber systems are characterized by low permeation rates and high sensitivity to fouling by particulate matter. They also have high losses in the product water flow path, which reduces the available driving pressure.

There are two basic modes of operation that are used in RO systems:

1. Brine - recycle
2. Once-through

The advantages and disadvantages of each of these approaches are discussed below.

Brine-Recycle. The brine-recycle approach has the advantage that a relatively small percentage of product water is produced on each cycle, so the mass flows entering and exiting the module are not significantly different. Thus the velocities necessary to effect a reduction in concentration polarization and fouling can be easily maintained throughout the module. A disadvantage is that more pumping power is required than in a once-through system. A recycle mode is usually operated batch-wise in order to expose the module to a lower average brine concentration than it would be subjected to if the process were continuous. In the continuous case the concentration in the recycle loop is allowed to build up until the desired recovery fraction is achieved, and from that point on brine is continuously bled from the recycle loop at the desired concentration. Thus the RO mdoule is continually exposed to the maximum brine concentration. In a batch process, when the recycle loop reaches the maximum concentration level, essentially all of the brine is expelled and the recycle loop is filled with a new batch of raw waste water. Thus the RO module in this case sees an average concentration which is considerably lower than in the continuous flow case.

Once-Through. In the once-through mode of operation it is very difficult to maintain the minimum internal velocities that are required by RO modules to reduce fouling and concentration polarization. For a 93% recovery, once-through system, there is approximately 1/14 as much exit flow as entrance flow. Therefore either the exit and entrance areas must also reflect this ratio, or the entering velocity will be 14 times as great as the exit velocity. Two approaches to solving this problem are (1) utilization of a number of uniformly sized modules in a parallel/series arrangement as shown in Figure 3-2 and (2) utilization of several modules of different size in a series arrangement as shown in Figure 3-3.

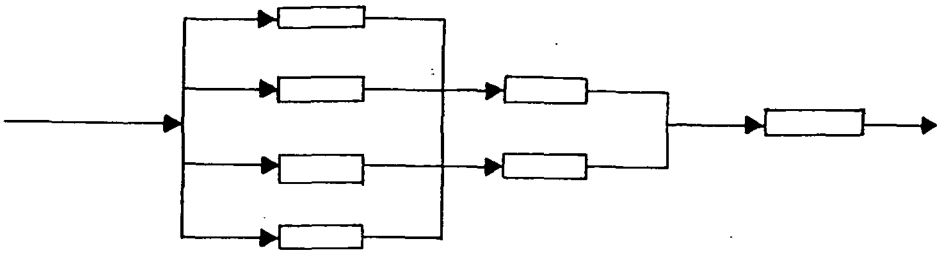


Figure 3-2. PARALLEL/SERIES ARRANGEMENT OF UNIFORMLY SIZED REVERSE OSMOSIS MODULES.

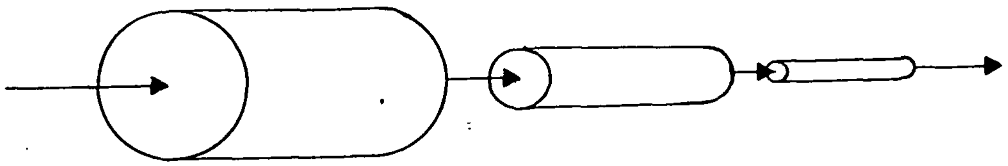


Figure 3-3. SERIES ARRANGEMENT OF VARIOUS SIZED REVERSE OSMOSIS MODULES.

A basic approach to sizing RO modules is presented in Reference 1. This approach considers such module sizing factors as:

- pressure
- intrinsic permeability
- solute diffusivity
- concentration polarization
- flow rate
- recovery fraction
- Chilton-Colburn J factor

Of all the candidate membranes (see Table 3-11) the only one for which there is sufficient data to confidently size a module is the 6-man unit built by Envirogenics Systems. This brine-recycle unit used eight identical spiral wound modules in series, each approximately 2.5 cm in diameter and 56 cm long with 0.31 m^2 of active mass transfer area. The 1000 hour performance test conducted by McDonnell Douglas demonstrated that these units performed satisfactorily during the first 8 weeks of the 12 week test. In the last four weeks of the test, rejection factors rapidly deteriorated, especially for urea and lactic acid.

The test set-up is shown schematically in Figure 3-4. Note that during the test the brine and product streams were continually recycled and fresh waste wash water was added at one week intervals. It is felt that this method of testing yields fairly realistic performance data for the RO modules and product water polishing beds; however, loading data for the particulate filters would bear little resemblance to an actual once-through situation. This is because these filters remove suspended solids contained in the recirculated brine stream. These solids are formed by coagulation and precipitation during the concentration step in the RO loop and do not return to their preconcentration state upon return to the feed storage tank where dilutuion occurs.

The basic design data for Envirogenic Systems' modules as developed in the MDAC 1000 hour test are summarized in Table 3-14.

3.10 Urea Removal.

In early investigations of wash water recovery methods it was found that cellulose acetate RO membranes (the only type available at the time) had a poor urea rejection factor and that activated carbon generally had a low adsorption capacity for urea. This prompted investigation into other ways of removing urea. The general approach persued was to first decompose urea to ammonia and carbon dioxide, and then remove the ammonia with an ion exchange resin (see References 5, 23 and 24).

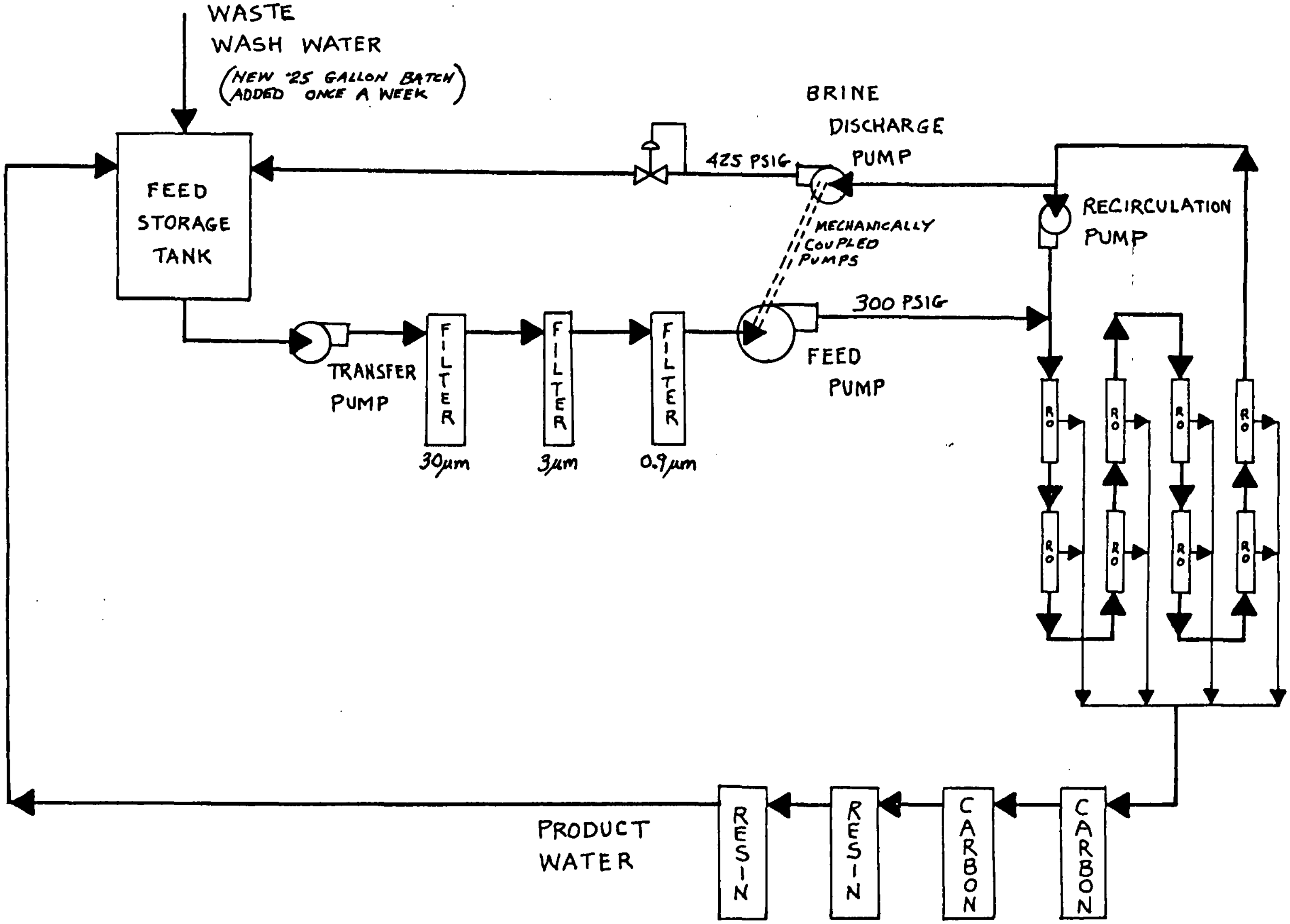


Figure 3-4. TEST SET-UP SCHEMATIC FOR ENVIROGENICS SYSTEMS 6-MAN RO UNIT (Ref 6)

Table 3-14. DESIGN DATA FOR ENVIROGENICS SYSTEMS SPIRAL WOUND, DI- AND TRI- ACETATE BLEND REVERSE OSMOSIS UNIT

Nominal size = 6 man (37 lb H_2O/man-day)
Design duty cycle = 8 hr/day
Driving pressure = 300 psig
Recirculation flow = 0.8 gpm
Water recovery = up to 98%
Module size = 1" diam x 22" long
Mass transfer area = 3.3 ft^2/module
Membrane flux (average) = 3.9 gal/day-ft^2
Module weight = 2 lb/module
# of modules = 8 in series
Module usefull life = 8 weeks at 64 lb H_2O/module-day
= 3583 lb H_2O/module
Carbon useage (Calgon Filtrasorb 400) = 0.62 lb for 43000 lb H_2O
14.4 x 10^{-6} lb carbon/lb H_2O
Resin useage (Rohm & Hass Amberlite IR 120 Na form) = 1.37 lb for 43000 lb H_2O
31.9 x 10^{-6} lb resin/lb H_2O
Rejection factors = see Table 3-12
Power for pumps and controls = 786 w
Power for heating = 600 w for 8 modules
39 w for waste line

Abcor, Inc. (see Reference 5) investigated five methods of urea decomposition, the results of which are shown in Table 3-15.

Table 3-15. ABCOR RESULTS OF UREA DECOMPOSITION EXPERIMENTS (Ref 5)

Method	Amount Used g/l	Amount Used g/g of Urea	Urea Removed from 50 mg/l Solution at 45°C After 2 Hours of Treatment, %
NaOCl (pH = 5.0)	0.2	4	88
Ozone + U.V.	1.	20	80
Urease	0.1	2	69
Ozone	1.	20	55
NaOCl (pH = 7.0)	0.2	4	45

Martin Marietta Corporation (see Reference 23) and Rutgers University (see Reference 24) both investigated the Urease method, including an immobilized variation, with about the same results as Abcor.

Martin recommended Baker ANGC-101 resin for NH_4^+ removal. Rutgers used Dowex 50W-X8 resin and reported a capacity for NH_4^+ of 4.08 meq/g.

Westgate Research Corporation (see Reference 25) is developing an Ozone + U.V. reactor under a contract with the U.S. Army which is jointly sponsored by NASA (Contract DAMD-17-75-C-5013). The device is described in Reference 25 as follows:

> "The UV-ozone reactor fabricated from stainless steel is 7 inches in diameter and 8 inches long. The reactor holds about 2.5 liters of water which is held by centrifugal action against the outer wall by the rotating, flow-directing fins. The fins are rotated by means of the electric motor at the base of the reacor at a speed sufficient to maintain positive separation of the gas and water phases.
>
> "Ozone from the ozone generator is diffused uniformly into the water by means of porous diffuser tubes mounted along the reactor wall. The UV radiation is directed into water from the two, 4-watt UV lamps which are housed within the quartz sheath in the center of the reactor.
>
> "The water flow in and out of the reactor is continuous at 1.25 liters/hour. Metering pumps are used to introduce and remove the water from the reactor.

"Oxygen from the ECS supply is metered into the ozone generator at a flow rate of 0.5 standard liters/min to generate 15 mg O_3 per minute. The oxygen with traces of unreacted ozone are removed from the reactor to the ECS catalytic oxidizer where the residual ozone is decomposed to oxygen.

"The estimated weight, size and power of a prototype-system version of the components are:

Quantity	Component	Size	Weight	Maximum Power
1	UV-Ozone Reactor	7 in dia x 8 inches	5 lbs	33 watts
2	Water Pumps	8 3/4 x 3½ x 2 5/8"	2 lbs	42 watts
1	Ozone Generator	12 x 8 x 8 inches	5 lbs	25 watts

Electrical Energy/lb of Water Purified = 36.3 watt-hrs/pound"

The data given above are summarized in Table 3-16. The weight and power values have been increased somewhat to reflect a packaged unit with controls, displays and alarms.

Table 3-16. DESIGN DATA FOR WESTGATE RESEARCH UV-OZONE REACTOR.

water flow = 1.25 l/hr

O_2 flow = 584 mg O_2/min (0.5 std l/min)

O_3 flow = 15 mg O_3/min

Overall dimensions (est) = 10 cm x 3.5 cm x 3.5 cm

Total weight = 7.3 kg

Total power = 120 watts

Electrolysis is another method of urea decomposition. It has been extensively investigated for pretreatment of raw urine (see References 26 and 27) but not for wash water. The electrolysis process decomposes urea to nitrogen, carbon dioxide and water, and ammonia to nitrogen and hydrogen. Chloride is a necessary component of the solution to be electrolized.

4.0 SUBSYSTEM CONFIGURATION.

The purpose of this section is to describe the wash water reclamation systems that have already been tested or are under present or future consideration by NASA. A system description and schematic diagram is provided for each approach. The pertinent performance data for these approaches are summarized in Section 3 under the appropriate unit operation and/or processes.

4.1 Tested Subsystems.

The only subsystems included in this category are those that have been put together and tested as complete man-in-the-loop units, and these are multifiltration subsystems. A multifiltration subsystem utilizes the unit operations and processes of: particulate filtration, carbon adsorption, ion exchange and some form of microbial control.

4.1.1. Multifiltration, McDonnell Douglas 60-Day Test.

A schematic is shown in Figure 4-1 and overall performance data are reported in Reference 8. Microbial control was not adequately maintained in this ambient system that relied on U-V irradiation and microbial filters. No filter or bed loading data are available.

4.1.2. Multifiltration, McDonnell Douglas 90-Day Test.

A schematic of this subsystem is shown in Figure 4-2. The subsystem operated satisfactorily except when temperatures in the beds dropped below their design values. Bed loading and other performance data are presented in Reference 9. The information pertinent to this study is summarized in Section 3.

4.2 Developmental Subsystems.

Subsystems were considered to be in this category when a full-scale unit had been subjected to at least 500 hours of simulated man-in-the-loop bench testing.

4.2.1. Reverse Osmosis, Envirogenic Systems Unit.

A schematic of this unit is presented in Figure 3-4. It was subjected to 1000 hours of testing by McDonnell Douglas using recirculated real wash water that was renewed on a weekly basis during the 12 week test period. Pertinent data are reported in Reference 6 and Section 3.

4.3. Proposed Subsystems.

These are subsystems that have been recently proposed and are under serious consideration for development to preprototype status.

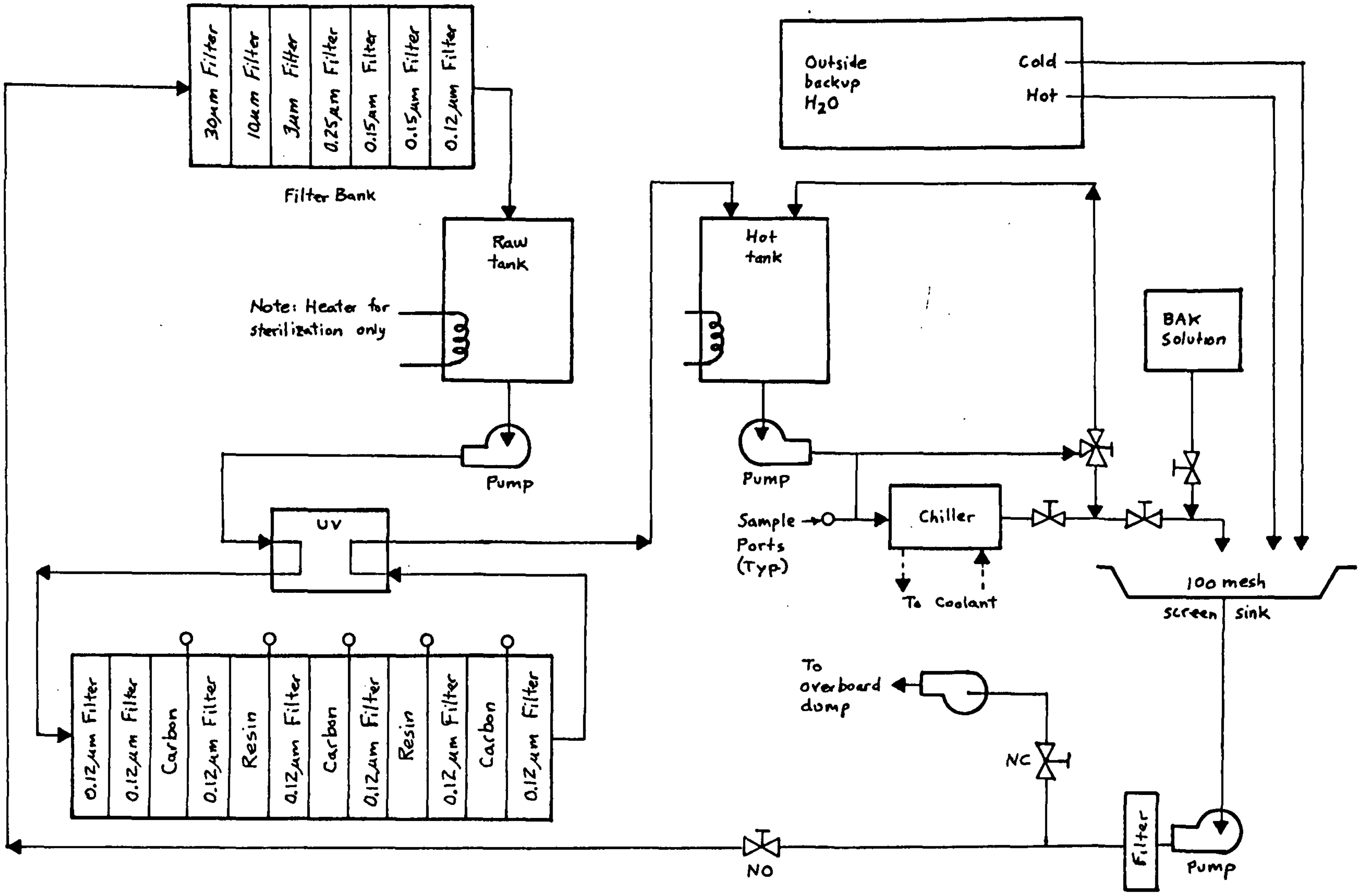


Figure 4-1. MULTIFILTRATION SUBSYSTEM, McDONNELL DOUGLAS 60-DAY TEST (Ref 8)

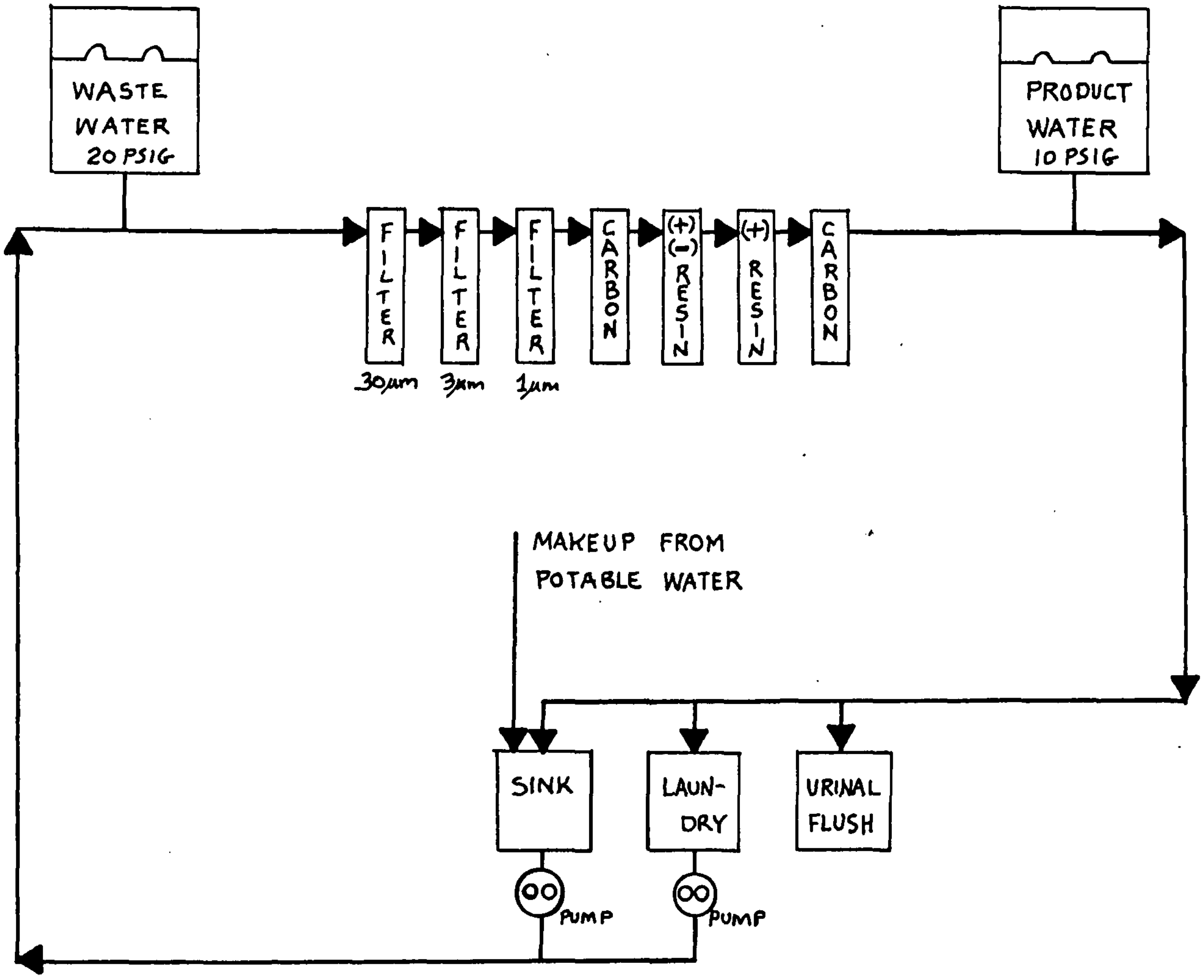


Figure 4-2. MULTIFILTRATION SUBSYSTEM, McDONNELL DOUGLAS 90-DAY TEST (Ref 9)

4.3.1 Reverse Osmosis

A schematic of an integrated wash water subsystem utilizing a reverse osmosis unit is presented in Figure 4-3. A schematic of a reverse osmosis unit for this system is shown in Figure 4-4. The design requirements and specifications are given in Reference 1. The RO unit in Figure 4-4 is depicted as a once-through type. However, the subsystem (Figure 4-3) could also accommodate a recirculation type RO unit. The type of RO membranes, the operating pressure and the number and configuration of membrane modules was left open.

4.3.2 Hyperfiltration.

"Hyperfiltration" is the term that has been applied to the dynamic reverse osmosis membranes (Zr(IV) Oxide Polyacrylic Acid) being developed at Clemson University. In a recent Request for Proposal (see Reference 28) NASA requested proposals for the development of this membrane into a 3-man pre-prototype unit complete with a low-power feed-pressurization pump, a replaceable membrane module, a urea-ammonia removal unit, a back-pressure control unit, a heated waste-storage tank, a replaceable filter, hydraulic damping components, a brine storage tank, and associated ancillary controls and instrumentation. Umpqua Research Company's schematic interpretation of this once-through subsystem is shown in Figure 4-5. The concentrated wash water discharged from the RO unit is processed by a vapor compression distillation unit. The required controls would be similar to those shown in Figures 4-3 and 4-4. Performance data may be found in Section 3 (Table 3-12).

4.3.3 Ultrafiltration.

Abcor has recommended (see References 7 and 12) a basically multifiltration subsystem that incorporates ultrafiltration, non-regenerable carbon adsorption, ozonation and regenerable ion exchange. The basic approach is shown in Figure 4-6. A schematic of the subsystem is shown in Figure 4-7.

4.3.4 Multifiltration.

The basic form of the multifiltration approach is always a prime candidate for wash water recovery because of its inherent simplicity, low initial weight and relative insensitivity to gravity effects. A subsystem schematic is shown in Figure 4-8. The required controls would be similar to those shown in Figure 4-3. Performance data are summarized in Tables 3-4, 3-5, 3-7, 3-9, and 3-10.

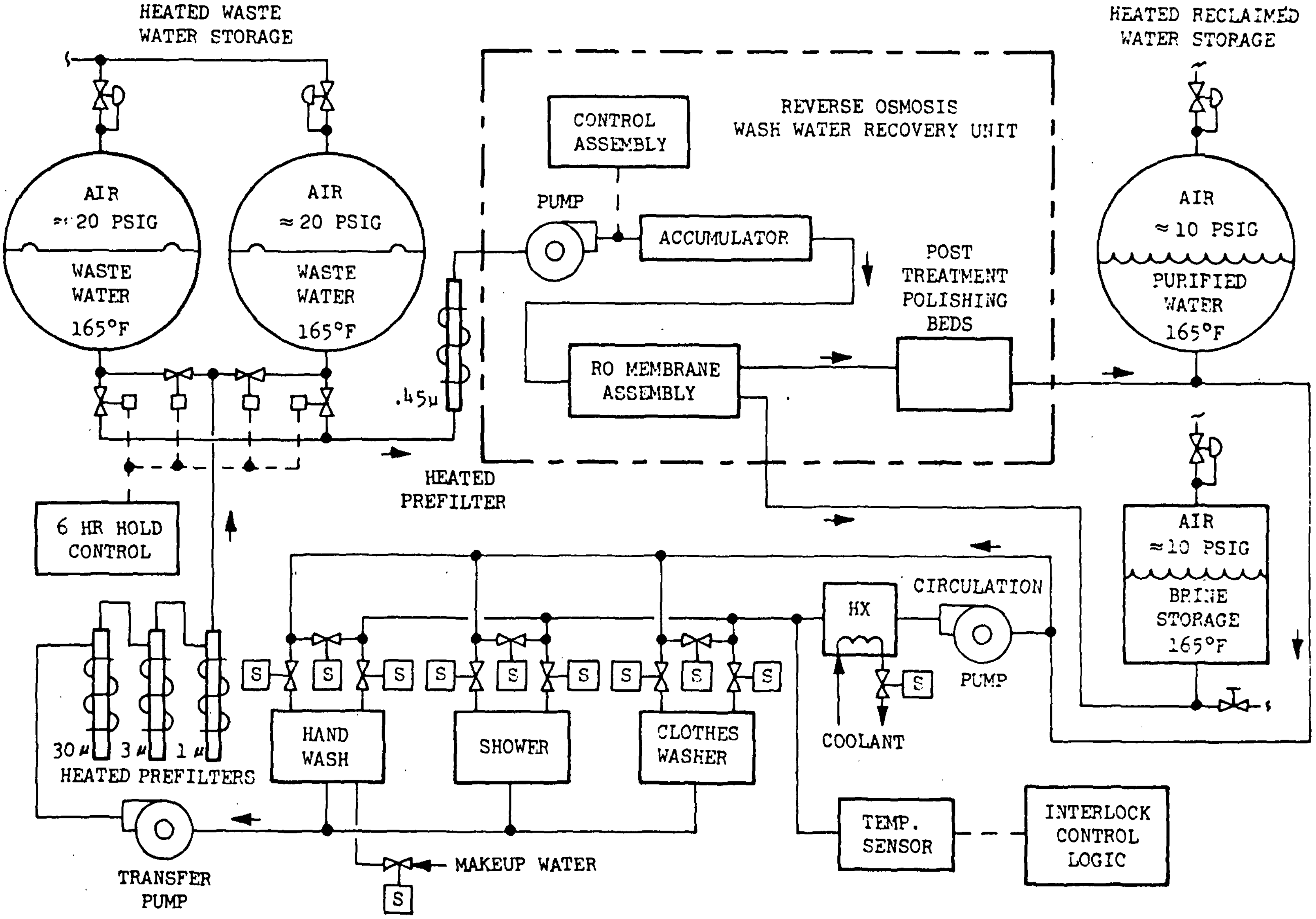
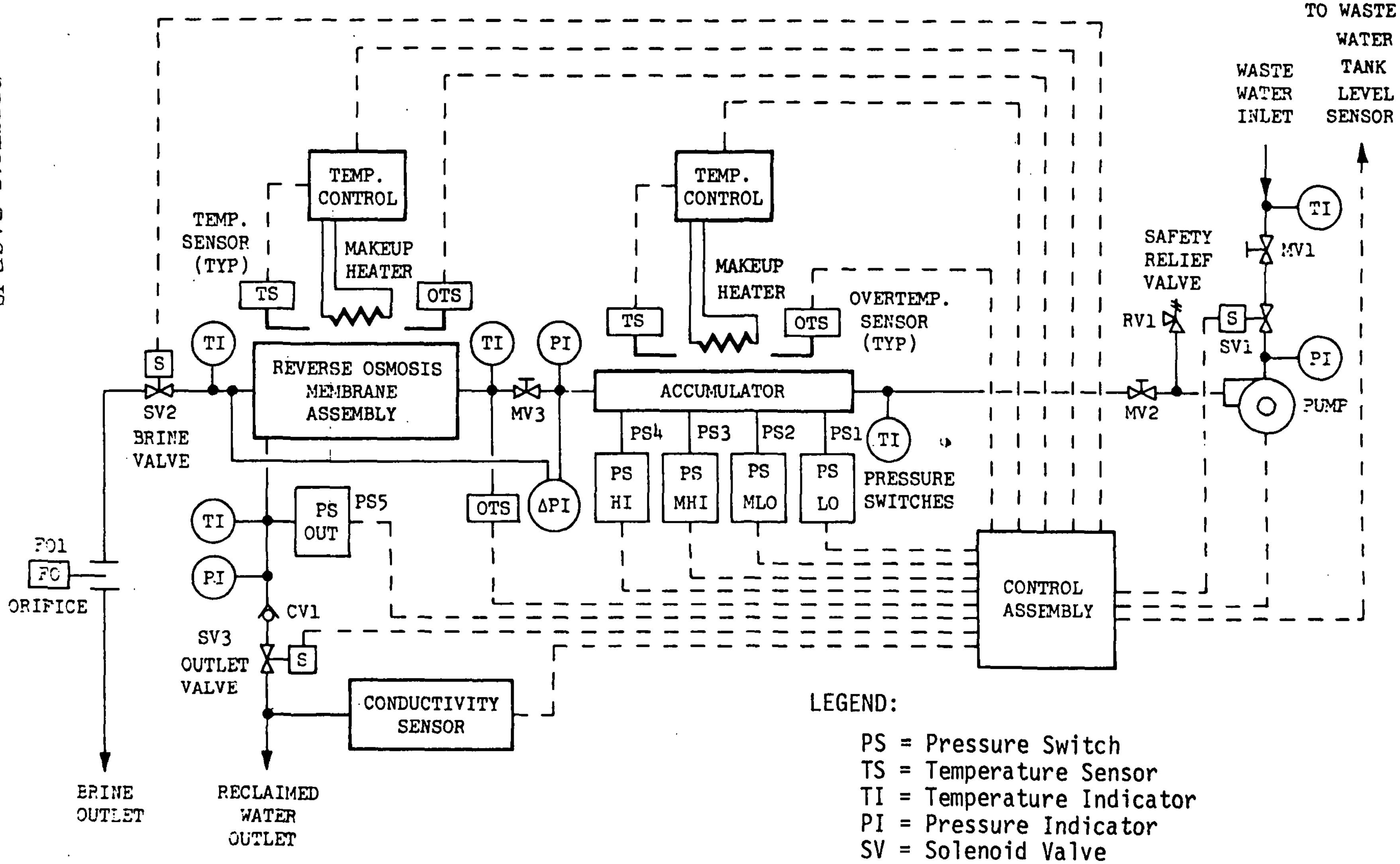


Figure 4-3. INTEGRATED WASH WATER RECOVERY SUBSYSTEM (Ref 1)



LEGEND:

PS = Pressure Switch
TS = Temperature Sensor
TI = Temperature Indicator
PI = Pressure Indicator
SV = Solenoid Valve
S = Solenoid
OTS = Overtemperature sensor
FO = Flow orifice

Figure 4-4. REVERSE OSMOSIS WASH WATER RECOVERY UNIT (Ref 6)

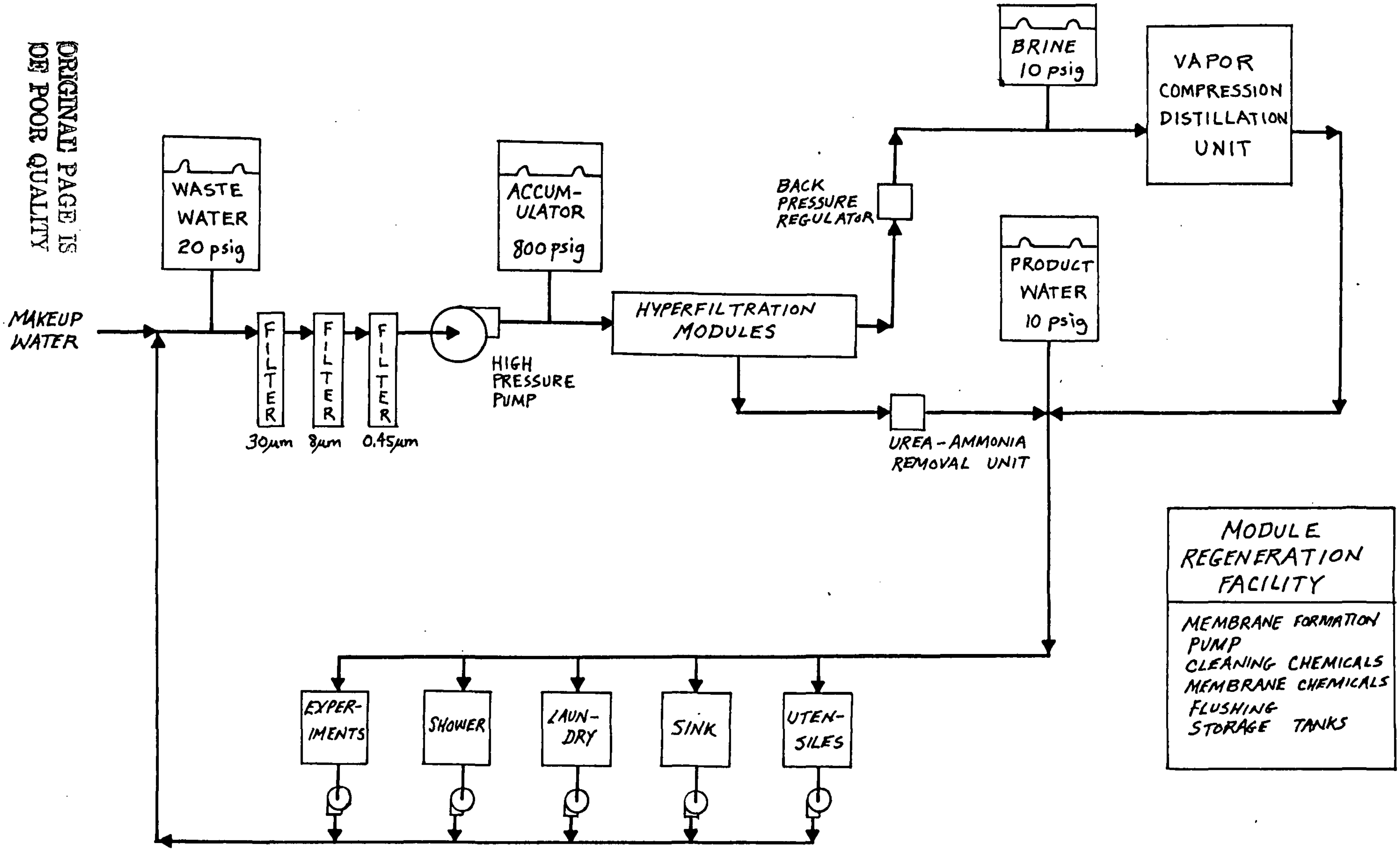


Figure 4-5. HYPERFILTRATION WASH WATER RECOVERY SUBSYSTEM SCHEMATIC (URC)

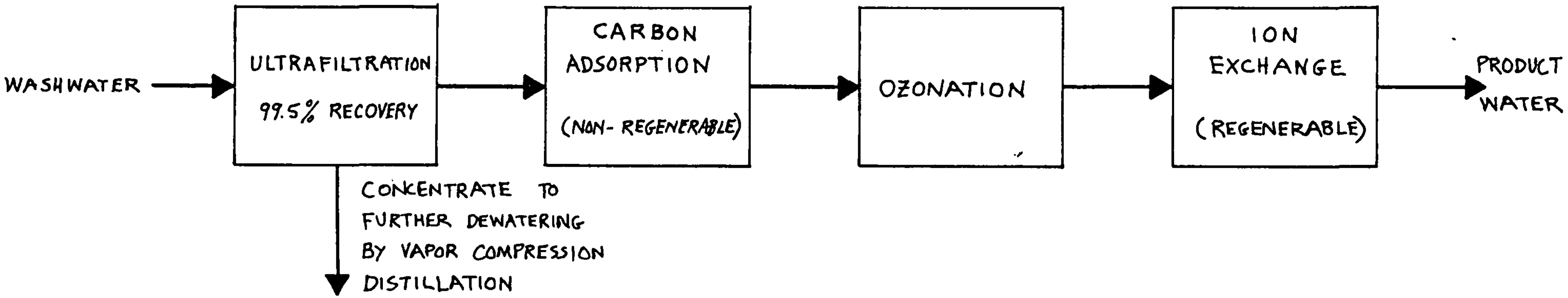


Figure 4-6. ULTRAFILTRATION - ABCOR, BASIC APPROACH (Ref 5)

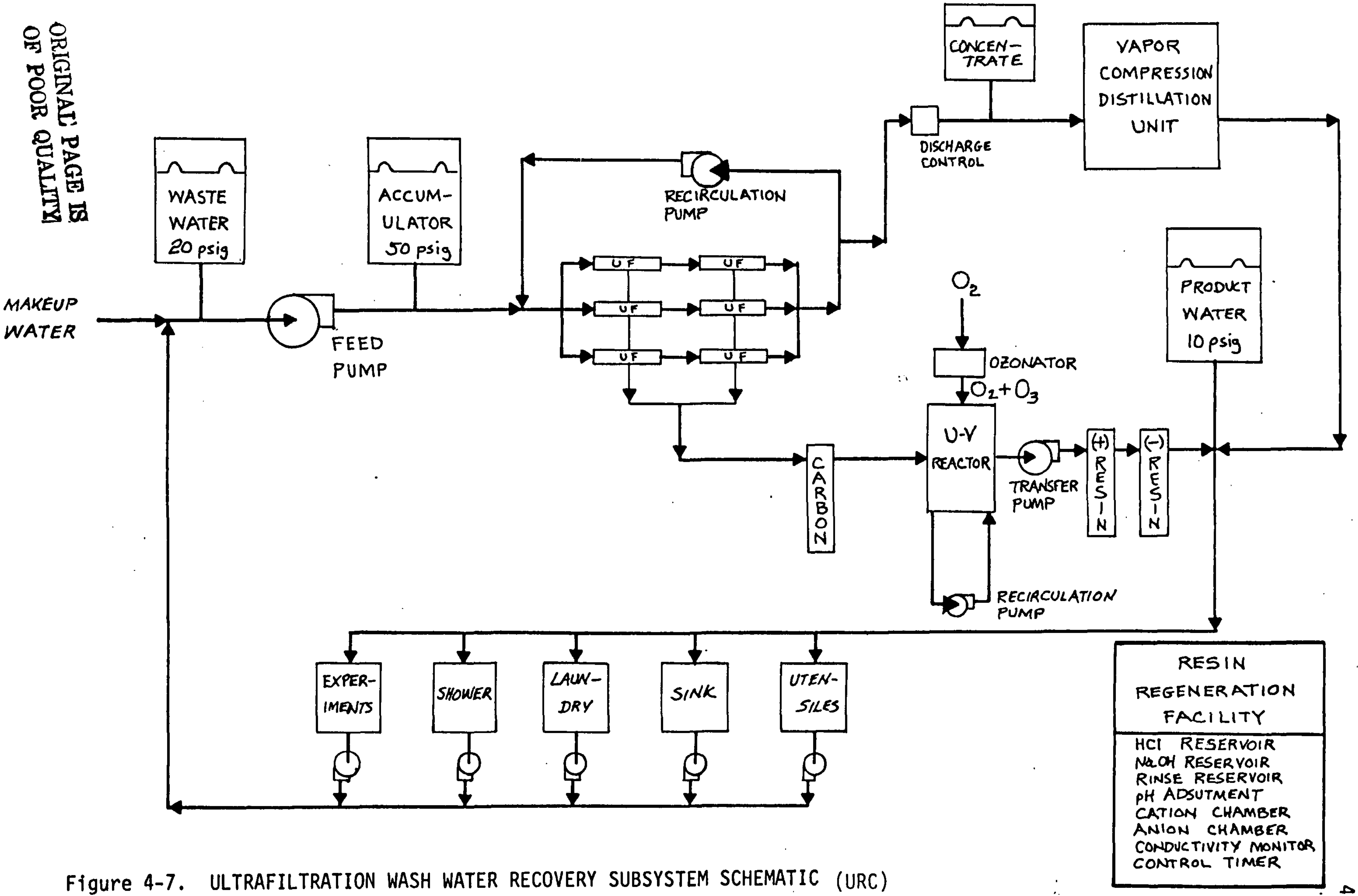


Figure 4-7. ULTRAFILTRATION WASH WATER RECOVERY SUBSYSTEM SCHEMATIC (URC)

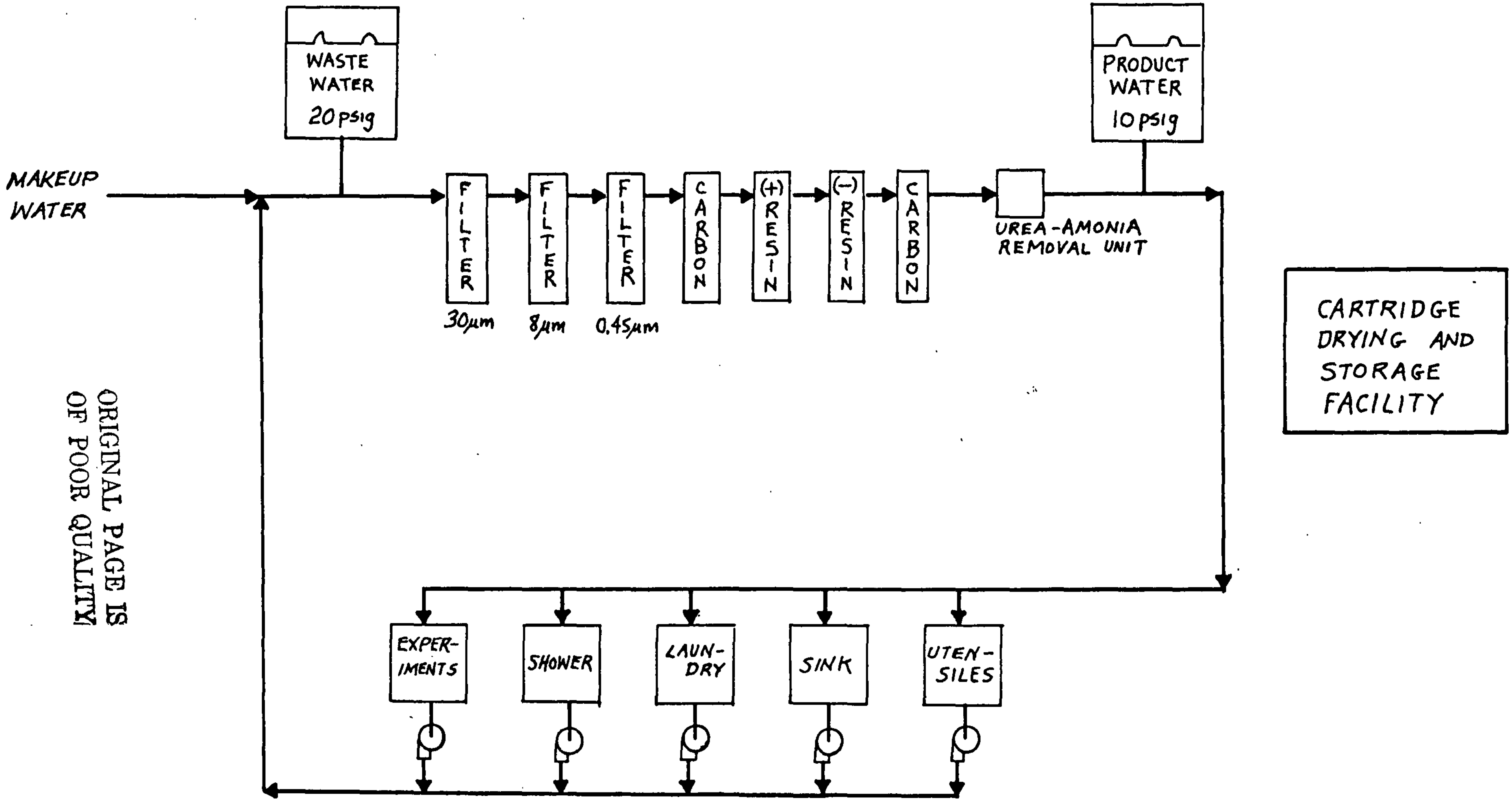


Figure 4-8. MULTIFILTRATION WASH WATER RECOVERY SUBSYSTEM SCHEMATIC (URC)

4.4 Other Possible Subsystems.

Other possible subsystems can be otained by various substitutions and/or alternative combinations of the unit processes discussed in Section 3. Such variations are considered and evaluated in Section 8.

5.0 PRELIMINARY TRADEOFF ANALYSIS

In order to obtain tradeoff results that are truly comparable it is usually necessary to analyze complete subsystems. However, in this study, the various filtration methods under consideration for the particulate removal step can be compared to each other on a direct basis. This is because each filtration approach is assumed to have the same impact on whatever unit operations and/or processes are subsequently used for the removal of dissolved materials.

Data show (see Reference 6) that filtration of space wash water with a 0.9 μm filter provides sufficient removal of suspended material to insure little or no fouling of a reverse osmosis membrane module[1] over a 77-day period. Longer term effects are not known. Other data show (see Reference 9) that a 1 μm filter is sufficient to protect carbon adsorption and ion exchange beds from fouling over 20-day and 45-day periods respectively. These periods were the useful lifetimes of the beds. It is not known if finer pre-filtration would have produced higher material loading factors and extended the life of these beds.

Until such time as there is definite information that shows if, and the extent to which, filtration to levels below 0.45 μm benefits reverse osmosis modules, carbon beds, and ion exchange resins, trade-off comparisons giving an advantage to ultrafiltration for its ability to filter submicron particles cannot be made. At this time, any low-end filtration benefits that ultrafiltration may offer must be ignored. It will be assumed that ultrafiltration provides the same benefits as any filter in which suspended material is removed down to the 0.45 μm level. With this groundrule it is possible to compare some of the various methods of removing suspended material alone without having to look at downstream processes as well.

The three methods of particulate filtration to be analyzed are:

1. Surface type cartridge filter (Section 3.4)
2. Filtration with backflush cleaning (Section 3.4.1)
3. Ultrafiltration (Section 3.5)

A schematic representation of each filtration approach is depicted in Figure 5-1. It is assumed that waste water is available at 1.4 atmg and 74°C from a waste water holding tank and that after filtration the water leaves at 1.0 atmg and 74°C. The other groundrules and basic assumptions for this analysis are summarized in Section 2.

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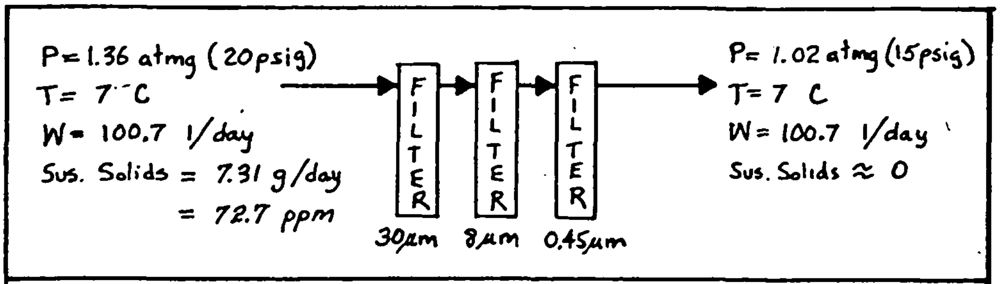
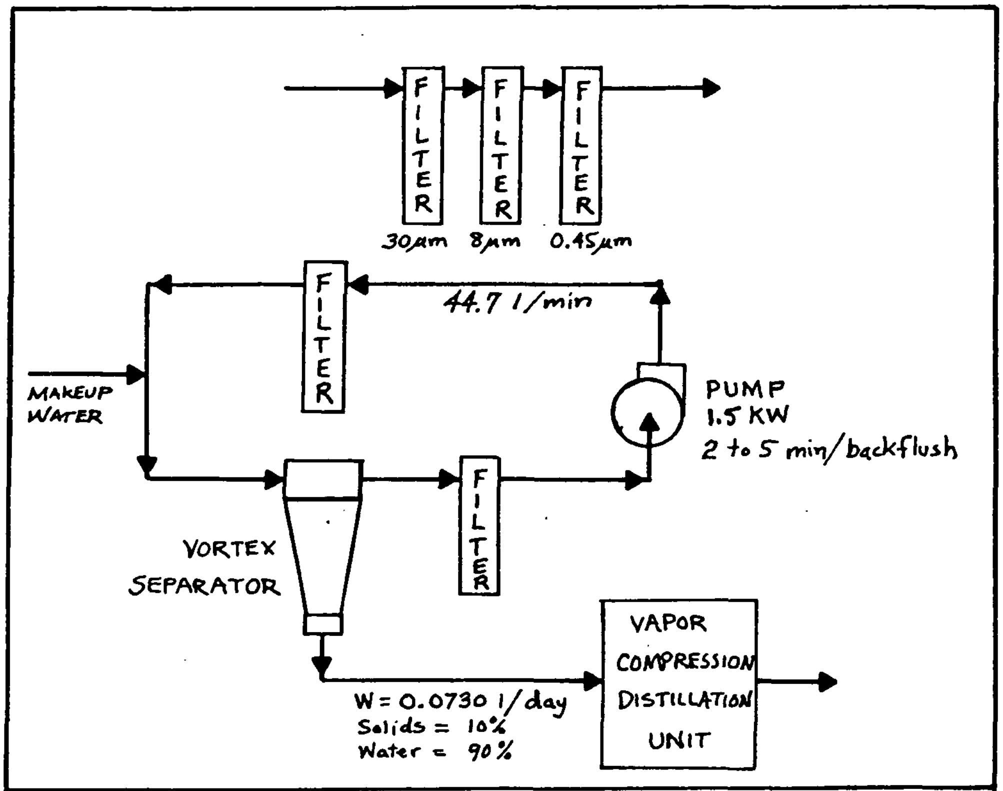
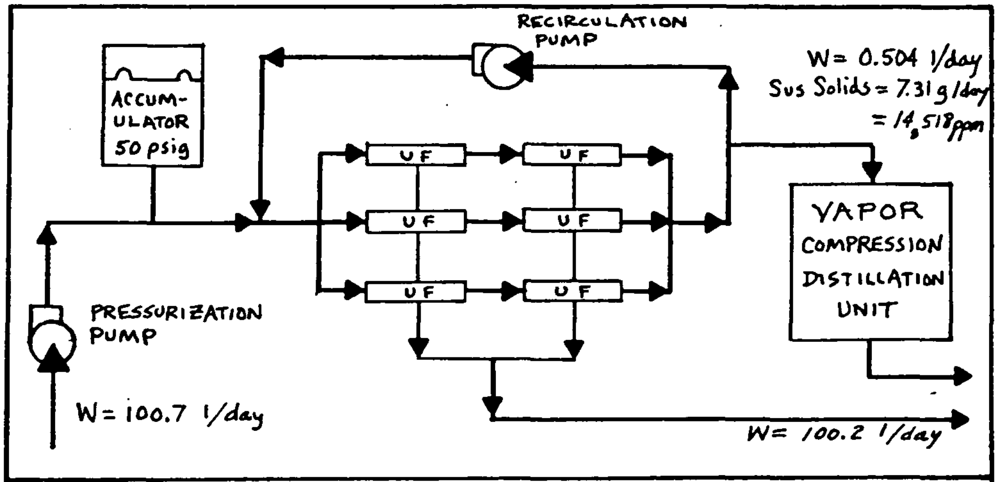
[1] Envirogenics spiral wound, cellulose di- and tri-acetate blend.



A. FILTRATION BY SURFACE-TYPE CARTRIDGE FILTERS



B. FILTRATION WITH BACKFLUSH CLEANING



C. ULTRAFILTRATION

Figure 5-1. PARTICULATE FILTRATION METHODS CONSIDERED IN TRADEOFF ANALYSES

5.1 Surface-type Cartridge Filters.

The total equivalent weight and expendable rate for surface-type cartridge filters are summarized in Table 5-1.

Table 5-1. SURFACE-TYPE CARTRIDGE FILTERS: WEIGHT, POWER AND EXPENDABLES

(see Figure 5-1A)

Item	Source	Installed Weight kg	Power Equiv. Weight kg	Thermal Rej. Equiv. Weight kg	Total Equiv. Weight kg	Expendable Rate kg/year
A. Filter Housings(3)	(Table 3-5)	1.5			1.5	
B. Filter Cartridges	(footnote 1)					14.6
C. Plumbing, Fittings, etc.	(estimate)	0.5			0.5	
D. Spares	(30% of A + C)	0.6			0.6	
E. Heating	(footnote 2)	0.7	11.1	7.9	19.7	
	TOTAL:	3.3	11.1	7.9	22.3	14.6

1. Expendable rate(Table 3-4) = 6.65 g/man-day x 6 men = 39.9 g/day = 0.0399 kg/day = 14.6 kg/yr
2. Heat for maintaining 74°C:

3 components @ 20 w each (estimate) = 60 w
heating tapes: 3 1/3 m @ 3 w/m (estimate) = 10 w
TOTAL = 70 w

Installed wt (estimate) = 70 w x 10 g/w (est) = 0.7 kg
Power equiv wt (¶2.5) = 70 w x 0.159 kg/w (Sec 2.5) ≐ 11.1 kg
Thermal rej equiv wt (¶2.6) ≐ 70 w x 0.113 kg/w (Sec 2.6) = 7.9 kg

5.2 Filtration with Backflush Cleaning.

The total equivalent weight and expendables rate for filtration with backflush cleaning are summarized in Table 5-2.

Table 5-2. FILTRATION WITH BACKFLUSH CLEANING:
WEIGHT, POWER AND EXPENDABLES

Item	Information Source	Installed Weight kg	Power Equiv. Weight kg	Thermal Rej. Equiv. Weight kg	Total Equiv. Weight kg	Expendable Rate kg/yr
A. Filters	(Table 5-1)	2.6			2.6	
B. Cleaning Unit	(Figures 3-1 and 5-1B)	68.0	239[1]	170[2]	477.0	
C. Spares	(30% of B)	20.4			20.4	
D. VCD Penalty	(Footnote 3)	1.2	0.2	0.1	1.5	
E. Heating	(Footnote 4)	2.0	31.8	22.6	56.4	
	TOTAL:	94.2	271.0	192.7	557.9	0

1. Power equiv. wt. = 1.5 kw x 0.159 kg/watt = 239 kg
2. Thermal rej. Equiv. wt. = 1.5 kw x 0.113 kg/watt = 170 kg
3. The VCD penalty is for processing 0.0730 l/day of concentrate in a vapor compression distillation (VCD) unit. The penalties were computed by proportioning the VCD weights and powers (see Reference 3) according to the ratio (0.0730/32.5).

	VCD 6-Man Design (Ref 3)	Backflush Unit Proportion	Penalty kg/w	Backflush Unit VCD Penalty
Feed rate, l/day	32.5	0.0730		
Duty Cycle, hr	8	8		
Electric Power, w	480	1.1	0.159	0.2 kg
Thermal Rej.	480	1.1	0.113	0.1 kg
Installed wt, kg	404	.9		1.2 kg
Spares wt, kg	118	.3		

4. Heat for maintaing 74°C: 7 components @ 20 w each (estimate) = 140 w
20 m of line @ 3 w/m (estimate) = 60 w
TOTAL = 200 w

Installed weight = 200 w x 10 g/w (estimate) = 2.0 kg
Power equiv wt = 200 w x 0.159 kg/w (Section 2.5) = 31.8 kg
Thermal rej equiv wt = 200 w x 0.113 kg/w (Section 2.6) = 22.6 kg

5.3 Ultrafiltration.

The total equivalent weight and expendables rate for ultrafiltration are summarized in Table 5-3.

Table 5-3. ULTRAFILTRATION:
WEIGHT, POWER AND EXPENDABLES
(see Figure 5-16)

Item	Information Source	Installed Weight kg	Power Equiv Weight kg	Thermal Rej Equiv Weight kg	Total Equiv Weight kg	Expendable Rate kg/yr
A. UF Modules (6)	(Footnote 1)	13.6			13.6	0.68
B. Pressurization Tank	(Ref. 3)	20.6			20.6	
C. Pressurization Pump	(Footnote 2)	4.7	3.1	2.2	10.0	
D. Circulation Pump	(Footnote 3)	5.9	35.5	25.2	66.6	
E. Plumbing,Fittings,etc.	(estimate)	4.5			4.5	
F. Spares	(30% of A+B+C+D+E)	14.8			14.8	
G. VCD Penalty	(Footnote 4)	8.1	1.2	0.8	10.1	
H. Heating	(Footnote 5)	2.4	38.2	27.1	67.7	
	TOTAL:	74.6	78.0	55.3	207.9	0.68

1. UF Modules (See design data in Table 3-6)

No. of Modules = (100.7 l/day ÷ 8 hr/day) ÷ (127.3 l/hr-m^2 x 0.01858 m^2/module)
= 5.32 modules call: 6 modules

Wt. of Module housings = 6 module x 2.268 kg/module = 13.6 kg

Expendable wt. of UF modules = 6 module/yr x 0.1134 kg/module ÷ 365 days/yr
= 0.00186 kg/day = 0.679 kg/yr

2. Pressurization Pump

duty cycle = 2 hr/day
efficiency = 25%
flow = 16.78 kg/man-day x 6 men ÷ 2 hr/day = 50.34 kg/hr
power = 50.34 kg/hr x 2.205 lb/kg x 50 lb/in^2 x 144 in^2/ft^2
x 1.355 w-sec/ft-lb ÷ {(η = 0.25) x 62.4 lb/ft^3 x 3600 sec/hr}
= 19.3 w

Power equiv wt (¶2.5) = 19.3 w x 0.159 kg/w = 3.1 kg

Thermal rej equiv wt (¶2.6) = 19.3 w x 0.113 kg/w = 2.2 kg

Table 5-3 Continued

3. Circulation Pump

Module configuration = assume 3 parallel banks of 2 modules each

flow = 3 gpm/module bank x 3 module banks = 9 gpm

ΔP = 10 psig/module in series x 2 = 20 psig

efficiency = 35%

power = 9 gal/min x 8.33 lb/gal x 20 lb/in^2 x 144in^2/ft^2
x 1.355 w-sec/ft-lb ÷ {(η = 0.35) x 62.4 lb/ft^3
x 60 min/hr}
= 223 w

Power equiv wt (¶2.5) = 223 w x 0.159 kg/w = 35.5 kg

Thermal rej equiv wt (¶2.6) = 223 w x 0.113 kg/w = 25.2 kg

4. VCD Penalty

The VCD penalty is for processing 0.504 l/day of concentrate in a vapor compression distillation (VCD) unit. The penalties were computed by proportioning the weights and powers of a 6-man VCD unit (see Reference 3) accoridng to the flow ratio (0.504/32.5).

	VCD 6-Man Design (Ref 3)	Ultrafiltration Unit Proportion	Penalty kg/w	Ultrafiltration Unit VCD Penalty
Feed Rate, l/day	32.5	0.504		
Duty Cycle, hr/day	8	8		
Electric power,w	480	7.4	0.159	1.2 kg
Thermal rej, w	480	7.4	0.113	.8 kg
Installed wt, kg	404	6.3		8.1 kg
Spares wt, kg	118	1.8		

5. Heat for maintaining $74^{o}C$

9 components @ 20 w each (estimate) = 180 w

20 m of line @ 3 w/m (estimate) = 60 w

240 w

Installed wt (estimate) = 240 w x 10 g/w = 2.4 kg

Power equiv wt (¶ 2.5) = 240 w x 0.159 kg/w = 38.2 kg

Thermal Rej equiv wt (¶ 2.6) = 240 w x 0.113 kg/w = 27.1 kg

5.4 Summary of Particulate Filtration Methods.

Weight and power penalties for the three particulate filtration methods depicted in Figure 5-1 are summarized in Table 5-4. Tradeoff curves are presented in Figure 5-2. These show that particulate filtration with surface type cartridge filters results in the lowest total equivalent weight for missions up to 12 years duration.

Table 5-4. SUMMARY OF PARTICULATE FILTRATION METHODS: WEIGHT, POWER AND EXPENDABLES

Item	Information Source	Installed Weight kg	Equiv Weight kg	Thermal Rej Equiv Weight kg	Total Equiv Weight kg	Expendable Rate kg/yr
Surface Type Cartridge Filters	(Table 5-1)	3.3	11.1	7.9	22.3	14.6
Filtration with Backflush Cleaning	(Table 5-2)	94.2	271.0	192.7	557.9	0
Ultra-filtration	(Table 5-3)	74.6	78.0	55.3	207.9	0.68

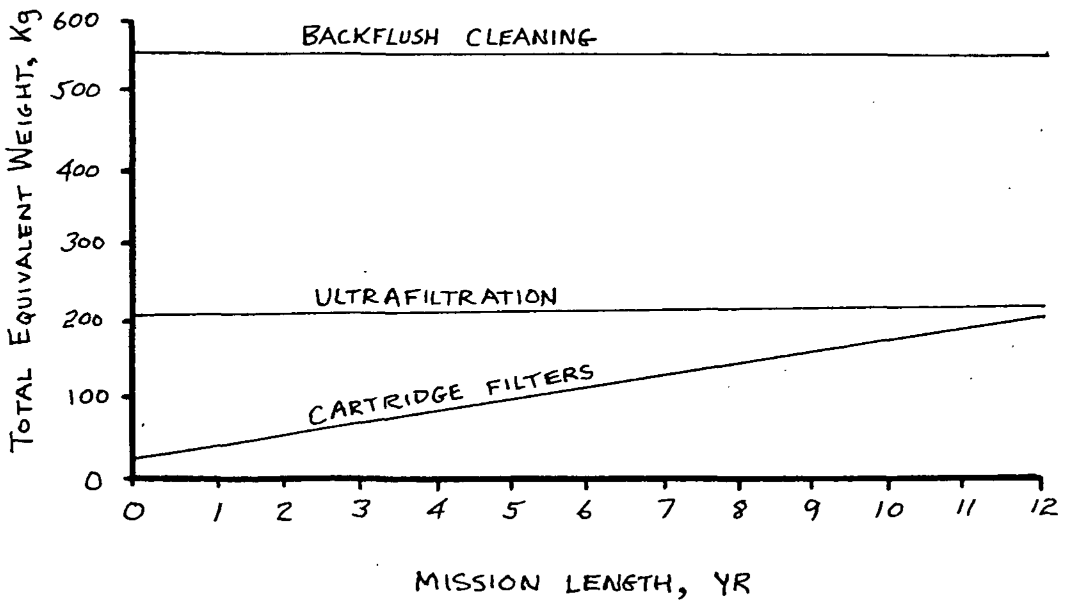


Figure 5-2. PARTICULATE FILTRATION METHODS, TRADEOFF CURVES

6.0 COMPARABLE BASELINE SUBSYSTEMS.

The preliminary tradeoff analysis (Section 5) shows that surface-type cartridge filters have a decided equivalent weight advantage over other methods of removing suspended materials from space wash water. In addition, the method is considerably less complex than the other approaches. It is, therefore, the method of choice for removal of suspended materials. Thus, the basic approaches to non-phase change wash water recovery are reduced to: 1) multifiltration and
2) reverse osmosis.

In this section, these two subsystems are defined on a comparable basis and weight, power and expendable figures are calculated. In addition, several variations of each approach are considered and a number of different assumptions are made in respect to various performance factors. This is done in order to realistically bracket the possible range of operation and determine the sensitivity of the analysis to variations in performance assumptions.

6.1 Multifiltration Baseline Subsystem.

The baseline multifiltration subsystem is shown in Figure 6-1. Only the wash water recovery equipment is included in the tradeoff analysis because the other components are common to all wash water recovery methods under consideration. The total equivalent weight and expendables for the baseline subsystem are summarized in Table 6-1.

There are several variations of the baseline subsystem, and these are treated in the following paragraphs.

6.1.1 MF Performance Based on 90-Day Test Data.

The bed loading data used for the baseline system was reported by Abcor, Inc. (see Tables 3-7 and 3-9), and are the highest loadings reported to date. In the McDonnell Douglas 90-Day Manned Chamber Test (see Reference 9) a carbon loading of 0.047 g TOC/g carbon was reported for Barnebey-Cheney PC carbon and the total resin usage was reported as 20.2 g/man-day. There were two resin beds, Dow ARM-381 mixed resin followed by ARC-351 cation resin.

The expendable rates for these materials are calculated below and the results are summarized in Table 6-2.

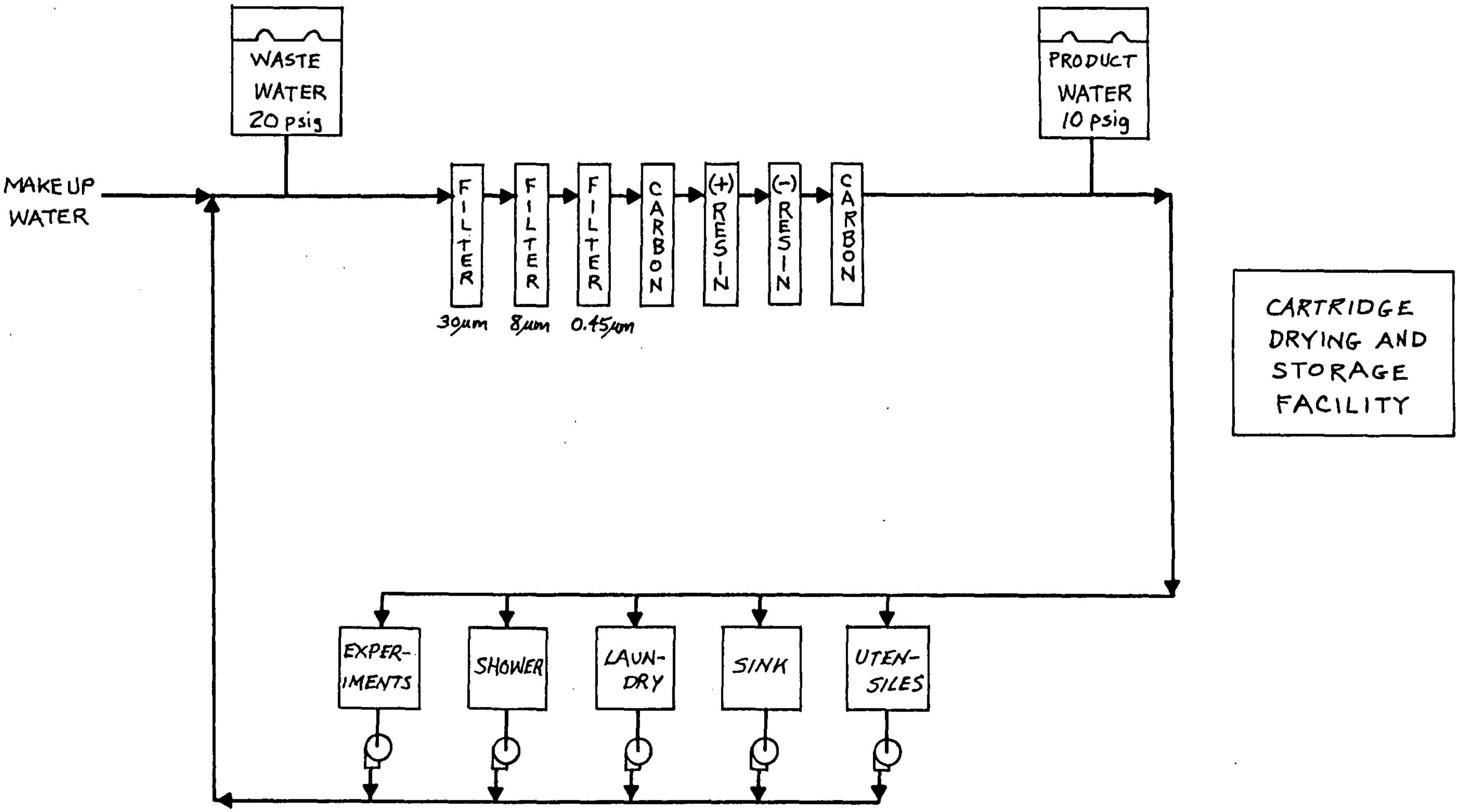


Figure 6-1. MULTIFILTRATION BASELINE WASH WATER RECOVERY SUBSYSTEM

Table 6-1 MULTIFILTRATION BASELINE SUBSYSTEM: WEIGHT, POWER AND EXPENDABLES (see Figure 6-1)

Item	Information Source	Installed Weight kg	Power Equiv Weight kg	Thermal Rej Equiv Weight kg	Total Equiv Weight kg	Expendable Rate kg/year
Surface-Type Cartridge Filters	(Table 5-1)	3.3	11.1	7.9	22.3	14.6
Carbon Beds	(Footnote 1)	1.0			1.0	23.5
Cation Resin	(Footnote 2)	0.5			0.5	29.3
Anion Resin	(Footnote 3)	0.5			0.5	9.9
Waste Water Tank	(Ref 3)	15.0			15.0	
Product Water Tank	(Ref 3)	15.0			15.0	
Plumbing, Fittings, etc.	(estimate)	1.5			1.5	
Cartridge Drying	(estimate)	12.0			12.0	
Controller	(estimate)	5.0	8.0	5.7	18.7	
Spares	(30%)	15.1			15.1	
Heating	(Footnote 4)	3.5	55.7	39.6	98.8	
	TOTAL:	72.4	74.8	53.2	200.4	77.3

1. Carbon Beds.

amount of soluble TOC (Table 2-2) = 1608 mg TOC/man-day x 6 men =
9.648 g TOC/day

loading for Filtrasorb 400 (Table 3-7) = 0.15 g TOC/g Carbon

amount of carbon = 9.648 g TOC/day ÷ 0.15 g TOC/g Carbon = 0.0643 kg/day =
23.5 kg/yr

weight of carbon canisters = 0.5 kg/canister x 2 canisters = 1.0 kg

2. Cation Resin.

amount of cations (Table 2-3) = 1.2188 meq/l x 16.78 l/man-day x
6 men = 122.7 meq/day

loading for Amberlite IR-120^+ (Table 3-10) = 1.35 meq/ml ÷ 0.88 g/ml =
1.53 meq/g

Table 6-1. Continued

amount of resin = 122.7 meq/day ÷ 1.53 meq/g resin = 0.0802 kg/day =
29.3 kg/yr
weight of resin canister = 0.5 kg/canister x 1 canister = 0.5 kg

3. Anion Resin.

amount of anions (Cl^-, Table 2-3) = 0.3667 meq/l x 16.78 l/man-day x
6 men = 36.92 meq/day
loading for Amerlite IRA-400 (Table 3-9) = 1.36 meq/g
amount of resin = 36.92 meq/day ÷ 1.36 meq/g resin = 0.0271 kg/day =
9.9 kg/yr
weight of resin canister = 0.5 kg/canister x 1 canister = 0.5 kg

4. Heat for Maintaining 74°C.

4 canisters @ 20 w each (estimate) = 80 w
2 tanks @ 120 w each (Ref 9) = 240 w
10 m of line @ 3 w/m (estimate) = 30 w
350 w

installed weight (estimate) = 350 w x 10 g/w = 3.5 kg
Power equiv wt (¶2.5) = 350 w x 0.159 kg/w = 55.7 kg
Thermal rej equiv wt (¶2.6) = 350 w x 0.113 kg/w = 39.6 kg

Table 6-2. VARIATIONS OF THE MULTIFILTRATION BASELINE SUBSYSTEM - WEIGHT, POWER AND EXPENDABLES

Item	Information Source	Installed Weight kg	Power Equiv Weight kg	Thermal Rej Equiv Weight kg	Total Equiv Weight kg	Expendable Rate kg/yr
Baseline MF Subsystem	Table 6-1	72.4	74.8	53.2	200.4	77.3
With 90-Day Test Data	¶6.1.1	72.4	74.8	53.2	200.4	133.7
With Urea Removal by UV-O_3	Table 6-3	135.7	202.0	143.6	481.3	77.3
With Regenerable Resins	Table 6-4	142.8	155.6	110.6	409.0	42.0
With Chemical Pretreatment	Table 6-5	109.9	99.8	71.0	280.7	70.3

Table 6-3. UREA REMOVAL BY UV-O_3 FOR MF-WEIGHT, POWER AND EXPENDABLES

Item	Installed Weight kg	Power Equiv Weight kg	Thermal Rej Equiv Weight kg	Total Equiv Weight kg	Expendable Rate kg/yr
Installed wt	48.7	127.2	90.4	266.3	0
Spares (30%)	14.6			14.6	
	63.3	127.2	90.4	280.9	0

Carbon Beds.

Amount of soluble TOC (Table 6-1, footnote 1) = 9.648 g TOC/day

Loading of carbon used in 90-Day Test (Ref 9) = 0.047 g TOC/g carbon

Amount of carbon (90-Day Test) = 9.648 g TOC/day ÷ 0.047 g TOC/g carbon =
= 0.205 kg/day

Amount of carbon (Baseline) (Table 6-1) = 0.0643 kg/day

Additional carbon expendables over baseline = 0.205 - 0.0643 = 0.1407 kg/day
= 51.4 kg/yr

Resins.

Amount of resin (90-Day Test) = 20.2 g/man-day x 6 men = 0.121 kg/day

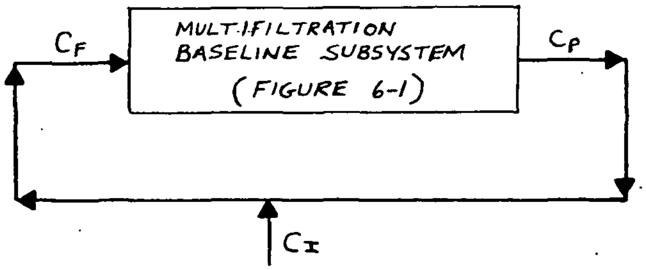
Amount of resin (Baseline) (Table 6-1) = 0.0802 + 0.0271 = 0.1073 kg/day

Additional resin expendables over baseline = 0.121 - 0.1073 = 0.0137 kg/day
= 5.0 kg/yr

6.1.2 Urea Removal by UV-O_3 for MF.

Abcor, Inc. (Reference 12) reports that the urea removal efficiency for a multifiltration subsystem similar to the multifiltration baseline subsystem (Figure 6-1) was 60%. Abcor is concerned that this is too low a percentage removal for a recycle system in which the product water must not exceed 50 mg/l of urea (see Table 2-4). The pertinent analysis is as follows:

a) The basic flow loop and nomenclautre are given in Figure 6-2.



Nomenclature:
C_I = concentration of input material, mg/l
C_F = concentration of feed material, mg/l
C_P = concentration of product material, mg/l
R_J = removal or rejection factor $\equiv (C_F - C_P)/C_F$

Figure 6-2. FLOW LOOP FOR ANALYSIS OF THE MULTIFILTRATION BASELINE SUBSYSTEM

b) The applicable equations are:

$$C_F = C_P + C_I \qquad 6\text{-}1$$

$$C_P = (1 - R_J)\, C_F \qquad 6\text{-}2$$

Combining equations 6-1 and 6-2:

$$C_I = R_J\, C_F \qquad 6\text{-}3$$

$$C_I = C_P/(\,1/R_J - 1) \qquad 6\text{-}4$$

c) The maximum allowable urea input for C_P = 50 mg/l and R_J = 0.6 C_I is calculated by equation 6-4.

$$C_I = 50\ (\,1/.6\ - 1) = 75 \text{ mg/l}$$

Abcor's input water contained 72 mg/l, thus their concern. However, this water had urea added to it according to the old McDonnell Douglas formula (see Reference 1). The Umpqua Research Study (see Reference 2) determined that considerably less urea will be present in wash water and that the model presented in Table 2-2 is the one that should be applied. In this model the input concentration for urea is 35.8 mg/l. The lowest urea removal factor that can be accommodated with a urea input of 35.8 mg/l is calculated by eq. 6-4:

$$35.8 = 50/\ (\,1/R_J - 1)$$

$$1/R_J = 50/35.8\ + 1\ = 2.397$$

$$R_J\ =\ 0.42$$

It is felt that the multifiltration baseline system will be capable of obtaining closer to 60% urea removal and that a special additional urea removal step will not be required. However, the weight, power and expendables for an additional urea removal step, based on the Westgate Research (WR) UV-O_3 concept, are estimated as follows:

efficiency of urea removal by UV-O_3 (Table 3-15) = 80%
amount of O_3 required (Table 3-16) = 20 g/g urea
amount of O_3 available (Table 3-16) = 15 mg O_3/min
duty cycle = 8 hr
O_3 generated by WR unit = 15 mg O_3/min x 60 min/hr x 8 hr = 7.2 g/day
amount of urea input (Table 2-2) = 600 mg/man-day x 6 men = 3.6 g/day
amount of O_3 required = 20 g O_3/g urea x 3.6 g urea/day = 72 g/day
# of WR units required based on O_3 demand = 72 g/day ÷ 7.2 g/day = 10

amount of water processed by WR unit (Table 3-16) = 1.25 l/hr x 8 hr/day = 10 l/day
amount of water requiring processing (Table 2-1) = 100.7 l/day
# of WR units required based on water demand: 100.7 l/day ÷ 10 l/day = 10

This analysis shows that the Westgate Research UV-O_3 unit described in Table 3-16 must be scaled up by a factor of 10 to accommodate the 6 man baseline case of this study. A direct scale up of weight and power results in a 73 kg unit requiring 1.2 kg of electric power. However, it will be assumed that these weight and power figures would be reduced by 1/3 in a flight development program. The calculated values are:

Installed wt = 73 kg - (1/3)(73 kg)= = 48.7 kg
Spares (30%) = = 14.6 kg
Power equiv wt = 1.2 kw - (1/3)(1.2 kw) = 0.8 kw x 0.159 kg/w = 127.2 kg
Thermal reg equiv wt = = 0.8 kw x 0.113 kg/w = 90.4 kg
TOTAL = 280.9 kg

These values are summarized in Table 6-3. The total weight, power and expendables for multifiltration with Urea removal by UV-O_3 are summarized in Table 6-2.

6.1.3 Regenerable Resins for MF.

Abcor, Inc. (see Reference 12) proposes using regenerable ion exchange resins in connection with multifiltration. In this scheme sulfuric acid would be stored on board to regenerate cation resins and sodium hydroxide would be stored to regenerate anion resins. The lowest level of regenerant usage shown in Table 3-10 (0.75 meq regenerant/ml resin) was recommended. The amounts of H_2SO_4 and NaOH required are calculated as follows:

H_2SO_4 Requirement

H_2SO_4 (Table 3-10) = 0.75 meq H_2SO_4/ml resin ÷ 0.53 meq cations/ml resin
= 1.42 meq H_2SO_4/ meq cations
cations (table 2-3)= 1.2188 meq/l x 100.7 l/day x 365 day/yr
= 44,798 meq cations/yr
H_2SO_4 = 44,798 x 1.42 = 63,613 meq H_2SO_4/yr
= 63,613 meq H_2SO_4/yr x 49 mg H_2SO_4/meq H_2SO_4
= 3.1 kg/yr

NaOH Requirement

NaOH (Table 3-10) = 0.75 meq NaOH/ml resin ÷ 0.48 meq anions/ml resin
= 1.56 meq NaOH/meq anions
Anions (Table 2-3)= 0.3667 meq/l x 100.7 l/day x 365 day/yr
= 13,478 meq anions/yr
NaOH = 13,478 x 1.56 = 21,026 meq NaOH/yr
= 21,026 meq NaOH/yr x 40 mg NaOH/meq NaOH
= 0.84 kg/yr

Total Regenerants

H_2SO_4 + NaOH = 3.1 + 0.84 = 3.94 kg/yr

Amount of Resin Saved

cation resin + anion resin (Table 6-1) = 29.3 + 9.9 = 39.2 kg/yr

Net Expendable Savings from Baseline

Savings = 39.2 - 3.94 = 35.3 kg/yr

The installed weight and power figures for a resin regenerating subsystem are taken from Abcor (see Reference 12).

Installed weight (see Ref. 12) = 51 lb ÷ 2.205 lb/kg = 23.1 kg
Spares (30%) = 6.9 kg
Installed wt incl spares = 30.0 kg

Electrical power (see Ref. 12) = 196 kw-hr/yr
assume duty cycle = 8 hr/wk (1 regeneration/wk)
power = 196 kw-hr/yr ÷ (8 hr/wk x 52 wk/yr
= 471 w
Power equiv wt (¶2.5) = 471 w x 0.159 kg/w = 74.9 kg
Thermal rej equiv wt (¶2.6) = 471 w x 0.113 kg/w = 53.2 kg

VCD Penalty

First calculate the flow of regenerants to the VCD
H_2SO_4 + NaOH = 63.6 + 21.0 = 84.6 eq/yr
Since regenerants are used in a 1 normal solution:
Regenerant Flow = 84.6 eq/yr x 1 l/eq = 84.6 l/yr

Regeneration will occur once a week and 4 bed volumes of rinse water are required for each of the two beds. Since each bed is about 2 liters in size, approximately 16 l/wk of rinse water is required.

The total flow that must be processed in a VCD is then:

$$\text{Total flow} = (84.6\ \text{l/yr} \div 365\ \text{day/yr}) + (16\ \text{l/wk} \div 7\ \text{day/wk})$$

$$= 0.23 + 2.29 = 2.52\ \text{l/day}$$

The VCD penalty is obtained by proportioning weights and powers of a 6-man VCD Unit (see Ref 3) according to the ratio of flows (2.52/32.5).

	VCD 6-man Design(Ref 3)	Resin Regen Unit Proportion	Penalty	Resin Regen Unit VCD Penalty
Feed rate, l/day	32.5	2.52		
Duty cycle, hr	8			
Electric Power, w	480	37.2	0.159 kg/w	5.9 kg
Thermal Rej, w	480	37.2	0.113 kg/w	4.2 kg
Installed Wt, kg	404	31.3		40.4
Spares Wt, kg	118	9.1		
			TOTAL:	50.5 kg

These equivalent weights are summarized in Table 6-4 and the totals are added to the baseline MF figures and entered in Table 6-2.

Table 6-4. REGENERABLE RESINS FOR MF-
WEIGHT, POWER AND EXPENDABLES

Item	Installed Weight kg	Power Equiv Weight kg	Thermal Rej Equiv Weight kg	Total Equiv Weight kg	Expendable Rate kg/yr	Expendable Resin rate without Regen kg/yr
Installed Weight	23.1	74.9	53.2	151.2	3.94	39.2
Spares (30%)	6.9			6.9		
VCD Penalty	40.4	5.9	4.2	50.5		
	70.4	80.8	57.4	208.6	3.94	39.2

Net savings on baseline MF expendable rate = 39.2 - 3.94 = 35.3 kg/yr

6.1.4 Chemical Pretreatment for MF.

In order to determine to what extent chemical pretreatment could benefit multifiltration, it will be assumed that a coagulant and flocculant are available that would precipitate 100% of the cleansing agent from solution and allow its subsequent removal by filtration on a 30 µm filter. Such a pretreatment in effect shifts the load from the activated carbon to the particulate filters, which have a considerably greater loading factor than carbon. The weight, power and expendable figures are presented in Table 6-5, and the totals are added to the baseline MF figures and entered in Table 6-2.

6.1.5 Comparison of Multifiltration Options.

The multifiltration options discussed above are summarized in Table 6-2 and plotted in Figure 6-3 for mission lengths up to 10 years.

6.2 Reverse Osmosis Baseline Subsystem.

The baseline reverse osmosis subsystem is shown in Figure 6-4. Only the reclamation equipment in Figure 6-4 is included in the tradeoff analysis because the other equipment is common to all wash water recovery systems under consideration. The baseline RO subsystem is shown in the brine-recycle mode rather than in the once-through mode because that is the only full-scale version tested to date. Also, the small weight savings that would accrue by elimination of the recirculation pump would probably be more than offset by the ramifications of having to design modules for lower flows and face velocities.

The baseline RO subsystem assumes the best performing RO membranes (North Star and Gulf Environmental Systems, Table 3-11). It is also assumed that these membranes can be packaged into a spiral wound module. Urea-removal and/or other polishing operations are not needed in the baseline RO subsystem because of the high rejection factors of the selected membranes.

The weight, power and expendable rate for the baseline RO subsystem are summarized in Table 6-6. Variations of the baseline system are treated in the following paragraphs.

Table 6-5. CHEMICAL PRETREATMENT FOR MF
WEIGHT, POWER AND EXPENDABLES

Item	Information Source	Installed Weight kg	Power Equiv Weight kg	Thermal Rej Equiv Weight kg	Total Equiv Weight kg	Expendable Rate kg/yr	Expendable Carbon Rate Without Chemical Pretreatment kg/yr
Contact Tank	(estimate)	20.6			20.6		
Stirrer	(estimate)	4.7	3.1	2.2	10.0		
Plumbing, Fittings, etc.	(estimate)	2.5			2.5		
Spares	(30%)	8.3			8.3		
Heating	(footnote 1)	1.4	21.9	15.6	37.5		
Surface-type Cartridge Filters	(footnote 2)					9.3	
Carbon	(footnote 3)					6.8	23.5
Chemicals	(footnote 2)					0.4	
	TOTAL:	37.5	25.0	17.8	78.9	16.5	23.5

Net savings on baseline MF expendable rate = 23.5 - 16.5 = 7.0 kg/yr

1. Heat for maintaining 74°C

1 Tank @ 120 w (Reference 9) = 120 w
6 m of line @ 3 w/m (estimate) = 18 w
138 w

installed wt (estimate) = 138 w x 10 g/w = 1.4 kg
Power equiv wt (¶2.5) = 138 w x 0.159 kg/w = 21.9 kg
Thermal rej equivwt (¶2.6) = 138 w x 0.113 kg/w = 15.6 kg

2. Filters

amount of cleansing agent (Table 2-2) = 110 mg/l x 100.7 l/day x 365 day/yr = 4.04 kg/yr

amount of cleansing agent TOC = 4.04 kg/yr x 216 gC/348 g soap = 2.51 kg/yr

amount of chemical (¶3.6) = 4.04 kg/yr x 0.1 g chemical/g soap = 0.404 kg/yr

amount of 30 μm filters (Table 3-4) = (4.04 + 0.404) kg solids/yr ÷ 0.477 g solids/ g filter = 9.32 kg/yr

Table 6-5. CHEMICAL PRETREATMENT FOR MF WEIGHT, POWER AND EXPENDABLES

(Continued)

3. Carbon Beds

amount of carbon saved (Table 3-7) = 2.52 kg TOC/yr ÷ 0.15 g TOC/g carbon = 16.7 kg/yr

amount of carbon used (Table 6-1)= 23.5 kg/yr - 16.7 kg/yr = 6.8 kg/yr

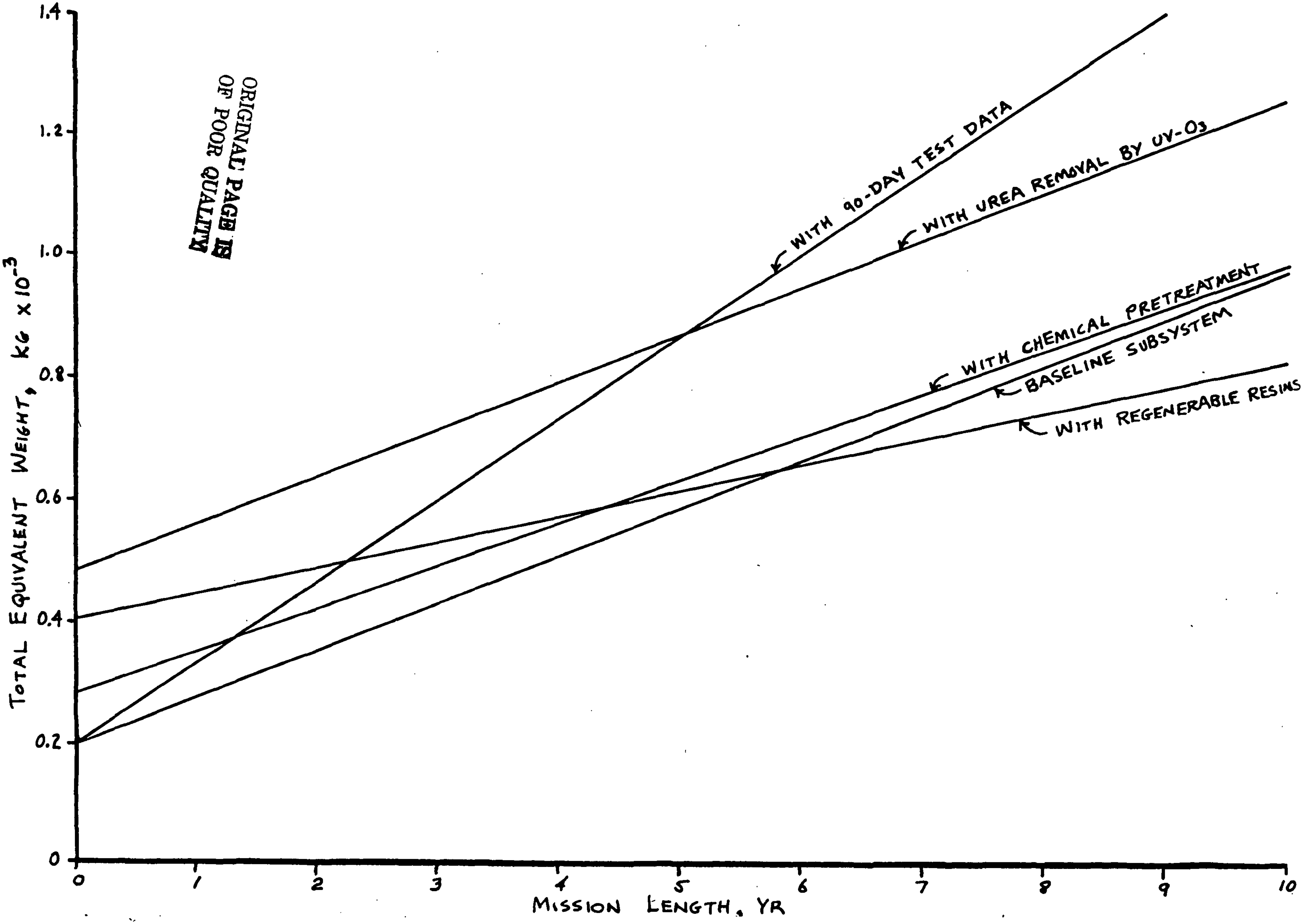


Figure 6-3. COMPARISON OF MULTIFILTRATION OPTIONS

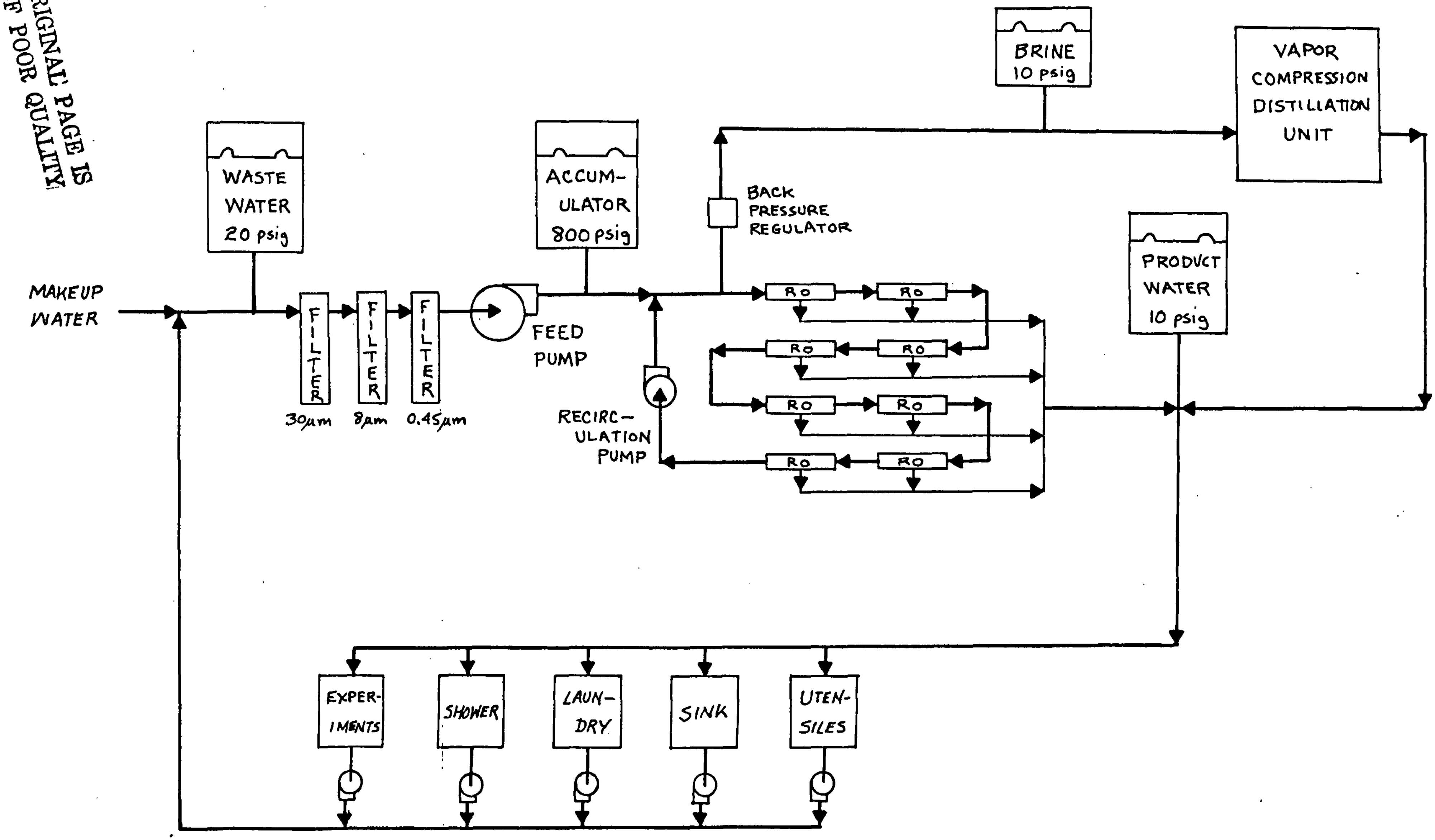


Figure 6-4. REVERSE OSMOSIS BASELINE SUBSYSTEM

Table 6-6. REVERSE OSMOSIS BASELINE SUBSYSTEM WEIGHT, POWER AND EXPENDABLES

(see Figure 6-4)

Item	Information Source	Installed Weight kg	Power Equiv Weight kg	Thermal Rej Equiv Weight kg	Total Equiv Weight kg	Expendable Rate kg/yr
Surface-Type Cartridge Filters	(Table 5-1)	3.3	11.1	7.9	22.3	14.6
RO Module Housings	(footnote 1)	24.0			24.0	
RO Modules	(footnote 2)					7.3 {life = 1 yr
Accumulator	(assumed)	4.0			4.0	
HP Feed Pump (250 w)	(footnote 3)	10.0	39.8	28.3	78.1	
Recirc Pump (39.7 w)	(footnote 4)	5.9	6.3	4.5	16.7	
Back Press Reg	(estimate)	2.0			2.0	
Brine Storage Tank	(estimate)	10.0			10.0	
Waste Water Tank	(Ref 3)	15.0			15.0	
Product Water Tank	(Ref 3)	15.0			15.0	
Controller (100 w)	(footnote 5)	9.0	15.9	11.3	36.2	
Plumbing, Fittings, etc.	(estimate)	9.5			9.5	
Spares	(30%)	31.3			31.3	
VCD Penalty	(footnote 6)	97.0	14.2	10.1	121.3	2.2
Heating	(footnote 7)	5.8	92.2	65.5	163.5	
	TOTAL:	241.8	179.5	127.6	548.9	24.1

Power Summary

Power for pumps & controls = 389.7 w

Power for heating = 580 w

1. RO Module Housings

Installed weight = 6 kg/housing x 4 housings = 24.0 kg

(note: there are 2 modules per housing)

Table 6-6. REVERSE OSMOSIS BASELINE SUBSYSTEM WEIGHT, POWER AND EXPENDABLES

(continued)

2. RO modules

Assume a high rejection membrane such as North Star or Gulf Environmental Systems (Table 3-11). Flux for these membranes is in the 3 to 6 gallon/ft^2-day range. Assume membranes are packaged in spiral wound modules. With these assumptions, the size, weight, configuration and number of modules is the same as shown in Table 3-14 for Envirogenics Systems 6-man unit.

Module weight = 0.907 kg
# of modules = 8
total weight of 8 modules = 0.907 kg/module x 8 modules = 7.3 kg

expendable rate of modules:

Life	Expendable Rate kg/yr
2 mo	43.8
6 mo	14.6
1 yr	7.3
2 yr	3.7
5 yr	1.5

3. HP Feed Pump

Duty Cycle = 8 hr/day
Power (Ref 29, Tables 3-2 and 4-4) = 250 w
Installed wt (estimated) = 10 kg
Power equiv wt (¶2.5) = 250 w x 0.159 kg/w = 39.8 kg
Thermal rej. equiv wt (¶2.6) = 250 w x 0.113 kg/w = 28.3 kg

4. Recirculation Pump

module configuration = 8 modules in series
flow = 0.8 gpm
ΔP = 5 psi/module x 8 modules = 40 psi
efficiency = 35%
power = 0.8 gal/min x 8.33 lb/gal x 40 lb/in^2 x 144 in^2/ft^2 x 1.355 w-sec/ft-lb ÷ (35% x 62.4 lb/ft^3 x 60 min/hr)
= 39.7 w

Table 6-6 REVERSE OSMOSIS BASELINE SUBSYSTEM WEIGHT, POWER AND EXPENDABLES

(Continued)

Power equiv wt (¶2.5) = 39.7 w x 0.159 kg/w = 6.3 kg

Thermal rej equiv wt (¶2.6) = 39.7 w x 0.113 kg/w = 4.5 kg

5. Controller

installed weight (estimate) = 9.0 kg
Power (estimate) = 100 w
Power equiv wt (¶2.5) = 100 w x 0.159 kg/w = 15.9 kg
Thermal rej equiv wt (¶2.6) = 100 w x 0.113 kg/w = 11.3 kg

6. VCD Penalty

assume water recovery = 94%

	VCD 6-man Design(Ref 3)	RO Unit Proportion	Penalty	RO Unit VCD Penalty
Feed rate, l/day	32.5	6.04		2.20 kg/yr*
Duty cycle, hr/day	8	8		
Electric power, w	480	89.2	0.159 kg/w	14.2 kg
Thermal rej, w	480	89.2	0.113 kg/w	10.1 kg
Installed wt, kg	404	75.1		}97.0 kg
Spares wt, kg	118	21.9		

*Assumes chemical pretreatment at the rate of 1 g/l:
expendable rate = 6.04 l/day x 365 day/yr x 1 g/l = 2.20 kg/yr

7. Heat for maintaining 74°C

11 components @ 20 w each (estimate) = 220 w
2 Tanks @ 120 w each (Ref 9) = 240 w
40 m of line @ 3 w/m (estimate) = 120 w
580 w

installed wt (estimate) = 580 w x 10 g/w = 5.8 kg
Power equiv wt (¶2.5) = 580 w x 0.159 kg/w = 92.2 kg
Thermal rej equiv wt(¶2.6)= 580 w x 0.113 kg/ w = 65.5 kg

6.2.1 Envirogenics Systems 6-Man RO Unit.

It is assumed that a flight version of the Envirogenics 6-man unit (see Figure 3-4) would weigh the same as the baseline RO unit. However, module life would be shorter, carbon and resin beds would be required for post treatment polishing, and power would be greater.

Module life

module life (Table 3-14) = 3583 lb H_2O/module
amount of water to be processed = 100.7 l/day x 2.205 lb/l ÷ 8 modules
= 27.76 lb/day-module
module life = 3583 ÷ 27.76 = 129 day = 0.354 yr
expendable rate of modules = 0.907 kg/module x 8 module ÷ 0.354 yr
= 20.5 kg/yr

Carbon beds

carbon usage (Table 3-14) = 14.4×10^{-6} kg carbon/kg H_2O
expendable rate of carbon = $14.4 \times 10^{-6} \times 100.7$ kg H_2O /day x 365 day/yr
= 0.53 kg/yr

Resin Beds

resin usage (Tabe 3-14) = 31.9×10^{-6} kg resin/kg H_2O
expendable rate of resin = $31.9 \times 10^{-6} \times 100.7$ kg H_2O/day x 365 day/yr
= 1.17 kg/yr

Power

pumps and controls = 786 w
heating = 639 w
TOTAL = 1425 w

power equiv wt = 1425 w x 0.159 kg/w = 226.6 kg
thermal rej equiv wt = 1425 w x 0.113 kg/w = 161.0 kg

Calculation of weight, power and expendables

installed weight = 241.8 kg (same as baseline)
expendable rate = filters + modules + carbon + resin + VCD Penalty
= 14.6 + 20.5 + 0.53 + 1.17 + 2.2 = 39.0 kg/yr

power equiv wt = filters + pumps, controls & heating
= 11.1 + 226.6 = 237.7 kg/yr

thermal rej equiv wt = filters + pumps, controls & heating
= 7.9 + 161.0 = 168.9 kg/yr

6.2.2 Hyperfiltration.

It is assumed that a flight version of this concept (see ¶4.3.2) would operate in a recirculation mode and would have the same weight and power as the baseline RO subsystem. Although membrane flux is higher than for the baseline unit, packing density would most likely be enough lower to offset this advantage. Other assumptions are that module regeneration will be possible and that a special urea removal step will not be required because the hyperfiltration rejection factor for urea would be 60% (see ¶6.1.2).

Module life

expendable rate of modules = 0

Module regeneration

installed wt (assumed) = 35 kg
expendable rate (assumed) = 3.3 kg/yr {assumes module regeneration each 100 days}

Recirculation power

Recirculation power will probably be greater for hyperfiltration than for the baseline unit because a considerably higher surface velocity is required for hyperfiltration. However, because there is insufficient data available to allow computation of a recirculation power requirement, hyperfiltration will be assumed to use the same power as the baseline subsystem.

Calculation of weight, power and expendables

installed weight = baseline + module regeneration =
241.8 + 35 = 276.8 kg

expendable rate = filters + VCD Penalty + module regeneration
= 14.6 + 2.2 + 3.3 = 20.1 kg/yr

These values are summarized in Table 6-7.

6.2.3 UV-O_3 Urea Removal for RO.

The weight, power and expendable values for urea removal by UV-O_3 are given in Table 6-3. These values are added to the baseline RO values and entered in Table 6-7.

6.2.4 Chemical Pretreatment for RO

Coagulation, flocculation and filtration of the cleansing agent would benefit reverse osmosis by reducing the dissolved solids load and thus allowing a greater water recovery fraction for a given brine concentration. If all of the cleansing agent were removed in this fashion from the baseline RO subsystem, the water recovery fraction would increase from 94% to 96% at a brine concentration of approximately 500 ppm (see Reference 1, Figure 8-2). The weight, power and expendables for chemical pretreatment are summarized in Table 6-5. These figures would apply to the RO subsystem except that the expendable rate of 6.8 kg/yr for carbon would not be included. The new VCD penalty for a water recovery of 96% is:

VCD Penalty

water recovery = 96%

	VCD 6-man Design (Ref 3)	RO unit Proportion	Penalty	RO unit VCD Penalty
Feed rate, l/day	32.5	4.03		1.47 kg/yr*
Duty cycle, hr/day	8	8		
Electric power, w	480	59.5	0.159 kg/w	9.5 kg
Thermal rej, w	480	59.5	0.113 kg/w	6.7 kg
Installed wt, kg	404	50.1		64.7 kg
Spares wt, kg	118	14.6		

*assumes chemical pretreatment at the rate of 1 g/l:
expendable rate = 4.03 l/day x 365 day/yr x 1 g/l = 1.47 kg/yr

The saving in VCD penalty over the baseline case is:

	VCD penalty RO baseline H_2O Recovery = 94%	VCD penalty H_2O recovery = 96%	Savings in VCD penalty
installed wt and spares, kg	97.0	64.7	32.3
power equiv wt, kg	14.2	9.5	4.7
thermal rej equiv wt, kg	10.1	6.7	3.4
expendable rate, kg/yr	2.20	1.47	0.73

The weight, power and expendable figures for reverse osmosis with chemical pretreatment are calculated as shown in Table 6-8 and are summarized in Table 6-7 with the other RO subsystem variations.

6.2.5 Comparison of Reverse Osmosis Options.

The reverse osmosis options discussed above are summarized in Table 6-7 and plotted in Figure 6-5 for mission lengths up to 10 years.

Table 6-7 VARIATIONS OF THE REVERSE OSMOSIS BASELINE SUBSYSTEM - WEIGHT, POWER AND EXPENDABLES

Item	Information Source	Installed Weight kg	Power Equiv Weight kg	Thermal Rej Equiv Weight kg	Total Equiv Weight kg	Expendable Rate kg/yr
Baseline RO Subsystem	Table 6-6	241.8	179.5	127.6	548.9	24.1
Envirogenics 6-Man Unit	¶6.2.1	241.8	237.7	168.9	648.4	39.0
Hyperfiltration	¶6.2.2	276.8	179.5	127.6	583.9	20.1
With UV-O_3 Urea Removal	¶6.2.3	305.1	306.7	218.0	829.8	24.1
With Chemical Pretreatment	Table 6-8	247.0	199.8	142.0	587.4	33.1

Table 6-8 CHEMICAL PRETREATMENT FOR RO WEIGHT, POWER AND EXPENDABLES

Item	Information Source	Installed Weight kg	Power Equiv Weight kg	Thermal Rej Equiv Weight kg	Total Equiv Weight kg	Expendable Rate kg/yr
Baseline RO Subsystem	Table 6-6	241.8	179.5	127.6	548.9	24.1
Chemical Pretreatment	Table 6-5	37.5	25.0	17.8	78.9	9.7
VCD Penalty	¶6.2.4	-32.3	-4.7	-3.4	-40.4	-0.73
		247.0		142.0	587.4	33.1

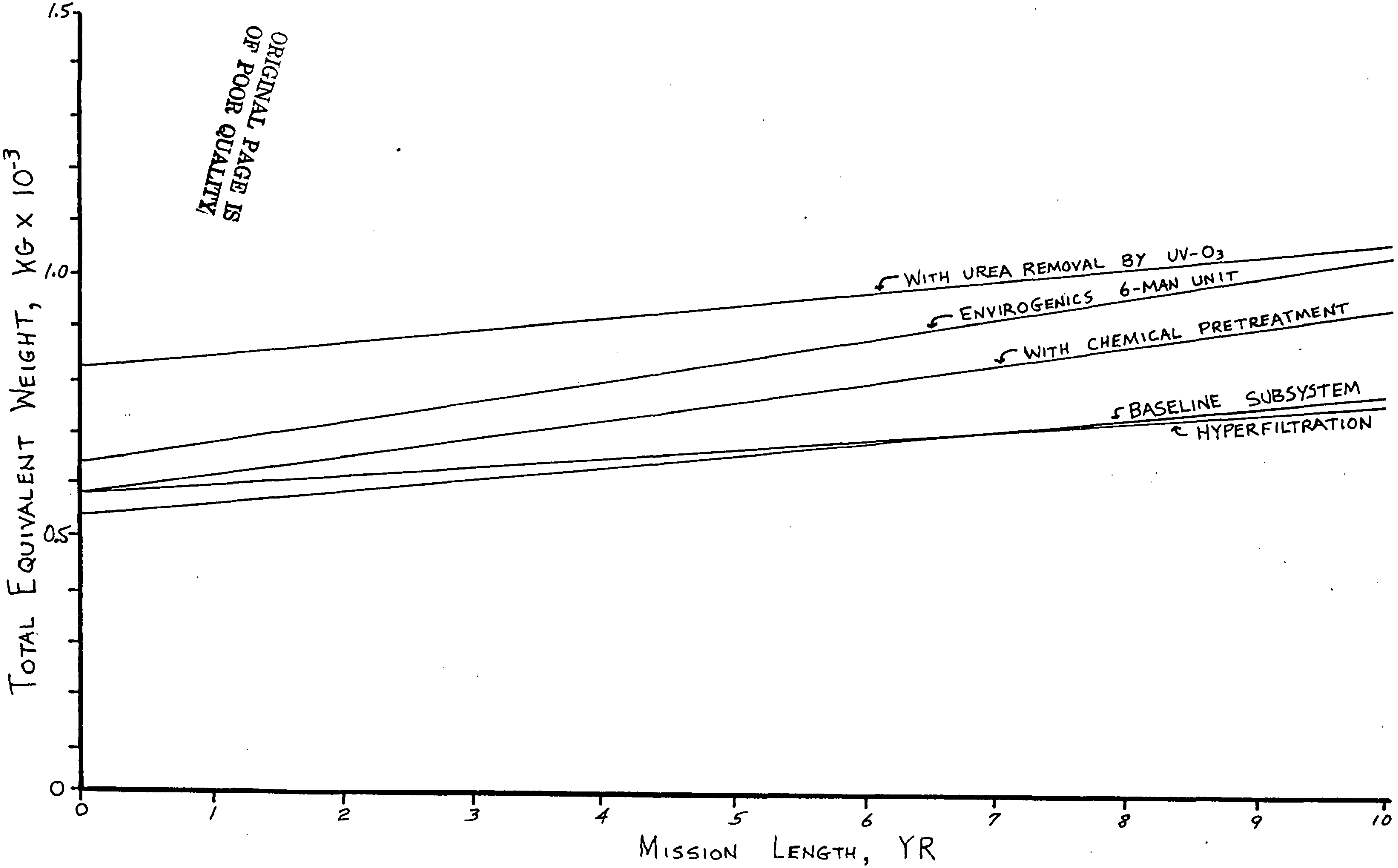


Figure 6-5. COMPARISON OF REVERSE OSMOSIS OPTIONS

7.0 ASSESSMENT MODEL

The assessment model is based on the one used in Reference 3 for evaluating spacecraft waste management subsystems. In mathematical terms the model is:

$$S_{TOTAL} = (M_{CS})\ (M_{CP}) \sum_{i=1}^{6} s_i \qquad 7\text{-}1$$

Where: S_{TOTAL} = the total rating score for a given candidate process;
M_{CS} = Critical Safety Coefficient for the candidate process;
M_{cp} = Critical Performance Coefficient for the candidate process;
s_i = comparison-category terms, scored separately for the candidate process and then summed.

Reference 3 describes the model as follows:

> "This model form, which consists of a combination of weighted summation (additive) terms and coefficient (multiplicative) terms, is very similar not only to those typically used by systems analysts in the aerospace industry, but also to several popular models used in the chemical process industries for comparative evaluation of new commercial-venture alternatives. The successful application of these trade-off models as management descision-structuring tools, for purposes similar to those of interest in this study, has been well documented."

In Reference 3, six categories were selected for the term s_i in equation 7-1. Since the wash water recovery subsystems under consideration in this study are, like those in Reference 3, intended for use in the area of spacecraft waste management life support, it is appropriate to use the same six evaluation categories as were used in Reference 3 and the same rating factors.

The six evaluation categories are the following:

- General safety characteristics
- Operating complexity of the system
- Simplicity of interfacing
- Adaptability to flight conditions
- Versatility
- Penalties (weight, volume, power, thermal)

These six categories together with their weighting factors and the criteria for assigning points in each category are described in Table 7-1.

Table 7-1 WEIGHTING FACTORS AND POINT ASSIGNMENT CRITERIA FOR COMPARISON CATEGORIES, S_i, IN ASSESSMENT MODEL.

Evaluation Category	Weighting Factor Maximum Point Value	Point-assignment Criteria
1. General Safety Characteristics (S_1)	20	Points are assigned for freedom, generally, from potential safety hazards such as fire, atmosphere contamination, explosion, bacteriological problems, crew injury, and equipment damage to other sub-systems. High-risk range (0-5 pts.); moderate risk range (6-15 pts.); low to insignificant risk range (16-20 pts.).
2. Operating Complexity of the Subsystems (S_2)	18	Highest points are assigned for greatest simplicity of operating procedures and least technical complexity in hardware functions. Favorable consideration is also given to higher potential for effective, reliable automation of operations; reduced crew time and stress during maintenance; and ease of modularizing equipment. Excessive complexity range (0-4 pts.); moderate complexity range (5-14 pts.); low to insignificant complexity (15-18 pts.)
3. Simplicity of Interfacing (S_3)	12	Highest points are assigned for least requirement for interfaces with other spacecraft subsystems and services for operaion of the candidate-process sub-system. Typical interfaces include vacuum source, oxygen or nitrogen supplies, water supply, biocide source, power connections, plumbing, etc. Excessive interfacing complexity range (0-3 pts.); moderate interfacing complexity range (4-8 pts.); low to insignificant interfacing complexity range (9-12 pts.).

Table 7-1 WEIGHTING FACTORS AND POINT ASSIGNMENT CRITERIA FOR COMPARISON CATEGORIES, S_i, IN ASSESSMENT MODEL.

(Continued)

4. Adaptability to Flight Conditions (S_4)	16	Points are assigned proportional to an estimated probability that the candidate-process sub-system will be operational for an assumed application (in the 1980-1990 time period) based on confidence in information and approaches to problem solutions (i.e., fail-operational/fail-safe; failure-mode effect analysis). Includes consideration of potential sensitivity to flight conditions (zero-g, vibration and shock, etc.).
5. Versatility (S_5)	7	Points are assigned according to the potential adaptability of the candidate process sub-system to various mission applications. Involve variable such as crew size, power and heat sources availability (i.e., solar cells, radioisotope sources, etc.), spacecraft configurations (e.g., vehicle free volume, equipment load capacity, etc.), and mission duration. Low versatility range (0-1); moderate versatility range (2-5); high to ideal versatility range (6-7).
6. Penalties (S_6)	27	Points assigned proportional to actual estimated values for installed weight, spares weight, volume, power and thermal rejection requirements for each candidate process sub-system, all converted to equivalent-weight values for simplicity in points assignment.
TOTAL:	100	

The range of scoring values for the critical, potentially abortive or catastrophic factors (system go/no-go importance) M_{CS} and M_{CP} in the model was selected to be zero (preemptive rejection of the candidate) to one (no likelihood of problems, and therefore no impact on the selection of this candidate). Criteria for the assignment of scoring values for these two coefficients involved estimates of probabilities that no critical safety or performance problems will be likely to occur in operational design version of the candidate process sub-system, based upon currently available information.

8.0 ASSESSMENT

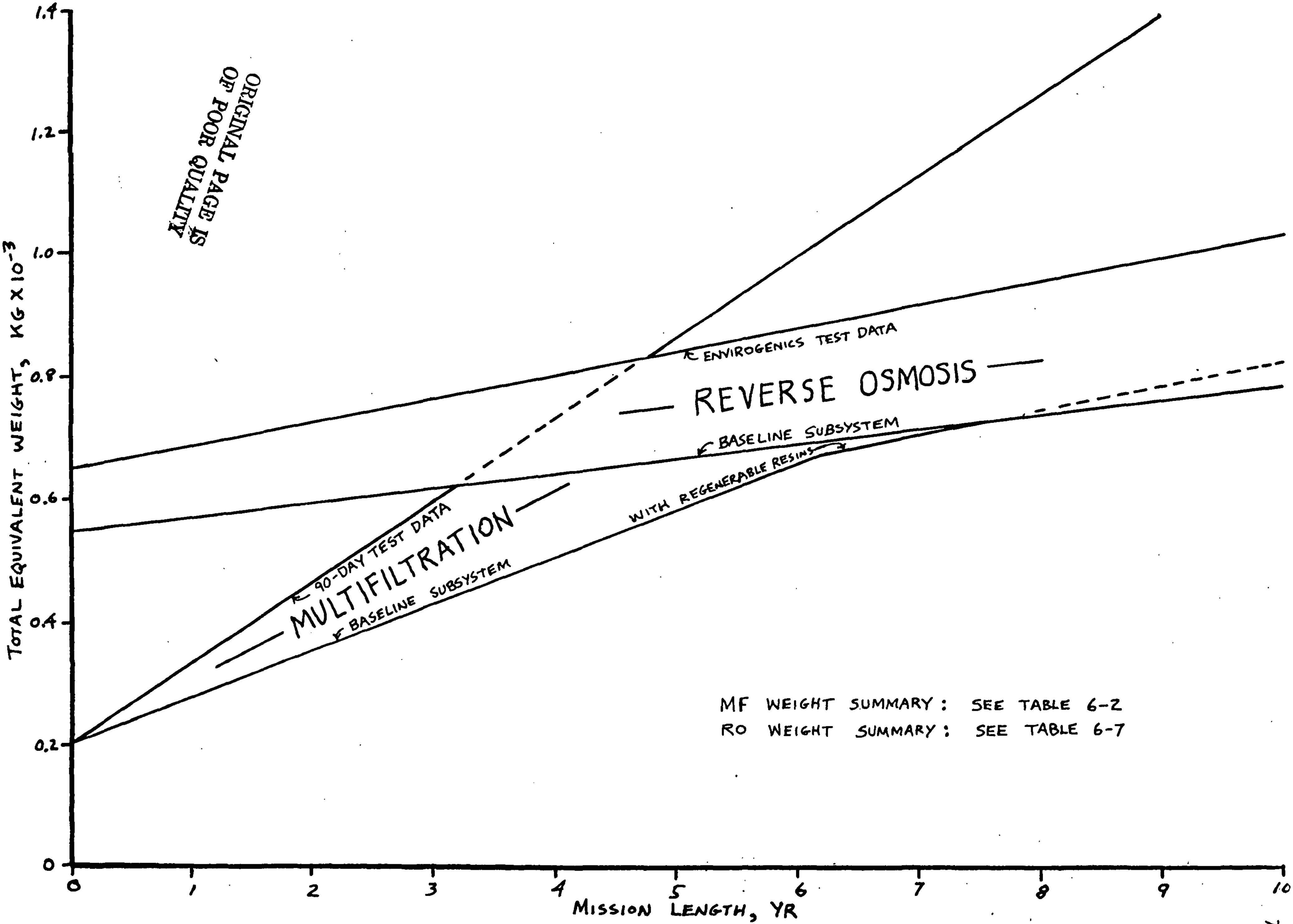
First, a weight comparison of multifiltration and reverse osmosis subsystems is presented. This is followed by a qualitative assessment of the two approaches using the assessment model defined in Section 7.

8.1 Weight Comparison of MF and RO Subsystems.

Weight comparisons are presented in Figure 8-6. In all cases multifiltration is initially lighter but has a higher expendable rate than reverse osmosis so that after 5 years the total weights are about the same for both approaches (within 10 per cent).

8.2 Overall Assessment of MF and RO Subsystems.

The overall assessment of multifiltration and reverse osmosis subsystems, using the assessment model defined in Section 7, is presented in Table 8-1. This assessment shows a clear advantage for multifiltration. This advantage derives mainly from the basic simplicity of multifiltration, its ability to operate at low pressure,its lack of interfaces with other subsystems and its high safety and adaptability to flight conditions.



MF WEIGHT SUMMARY : SEE TABLE 6-2
RO WEIGHT SUMMARY : SEE TABLE 6-7

Figure 8-6. WEIGHT COMPARISON OF MULTIFILTRATION AND REVERSE OSMOSIS SUBSYSTEMS

Table 8-1 OVERALL ASSESSMENT OF MULTIFILTRATION AND REVERSE OSMOSIS SUBSYSTEMS

	Maximum Points (weighting Factor)	MF Baseline	RO Baseline
A. Comparison Categories (Si)			
1. Safety	20	18	15
2. Operating Complexity	18	17	12
3. Simplicity of Interfacing	12	11	9
4. Adaptability to Flight Conditions	16	15	12
5. Versatility	7	6	5
6. Penalties (10 yrs)	27	20	22
TOTALS (ΣSi)	100	87	75
B. Critical Coefficients (M)			
1. Critical Safety Coefficient (M_{CS})	1.0	.98	.94
2. Critical Performance Coefficient (M_{CP})	1.0	.98	.96
C. Computation of S_{TOTAL}			
$S_{TOTAL} = (M_{CS})(M_{CP})\sum_{i=1}^{6} S_i$	100	89.0	67.7

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