WATER RECLAMATION AND CONSERVATION IN A CLOSED ECOLOGICAL SYSTEM

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INTRODUCTION

The essential role that water plays in the balance of life is being emphasized in this symposium. The technologies associated with maintaining closed or semi-closed ecologies become more complex when we attempt to apply them to manned space exploration. Among the many reasons for these complexities, the most obvious are the isolation factors. In planetary exploration men often will find themselves in inaccessible locations for long periods of time; but more significant is the fact that, in space, there are no basic raw materials, external to the ecology, from which the essentials of life can be obtained. On the lunar and planetary surfaces, techniques might be worked out whereby oxygen and water can be obtained from mineral substances but this technology does not help supply the needs of a space crew en route to even the nearest of the planets. A Mars mission, for example, requires over 200 days each way.

LIFE SUPPORT REQUIREMENTS

In addition to an otherwise habitable temperature and humidity environment, man requires three basic supplies: food, oxygen, and water. Table 1 presents the approximate quantities of these necessities that are required by the average man.

Table I.- Man's Daily Balance

Input, lb		Output, lb	
Food	1.50	Humidity water	2.20
Oxygen	1.92	Urine (95% H_2O)	3.24
Water	4.69	Feces (75% H_2O)	.29
		Carbon dioxide	2.24
		Other losses	.14
	8.11		8.11
Additional requirement (not essential to life)			
4.00 lb ←	Wash water	→	4.00 lb

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Of these three essentials, by far the most significant in terms of launch weight is water. Excluding whatever quantity of water may be required for hygienic purposes, the water requirement for drinking amounts to more weight than the combined oxygen and food requirements of man. With the present cost of about $1000 to place 1 pound into orbit, it is imperative that space missions be planned as conservatively as possible without jeopardizing the health and safety of the crew members.

A quick look at the metabolic products of man immediately suggests the feasibility of reducing launch weight by reclaiming a portion of the available water from these waste materials. This reasoning is not as unattractive as it may seem at first. We must all be aware that most of the water we now consume is reclaimed water of a sort. It has indeed been used and reused for centuries and is none the worse for wear. Some of the same processes that occur in nature to purify and reclaim our water can also be employed, in principle, to help balance the ecology onboard a space vehicle. Because of onboard weight and volume limitations, it would not be feasible at the present time, to employ some of the techniques of nature, such as solar evaporation, aeration, percolation through soils, aerobic and anaerobic digestion as well as those processes that employ members of the plant kingdom. A number of natural as well as scientifically devised techniques, however, can be made practical for reclaiming water onboard space vehicles.

WATER-RECLAMATION SYSTEMS

In order for a water-reclamation technique to be practical, it must, in addition to being very reliable, possess these three features:

(1) Act directly on the waste material to yield acceptable water;

(2) Have minimum weight, volume, and power requirements;

(3) Be capable of operation under zero-gravity conditions.

In view of the diverse nature of the waste waters from man, it is not likely that any one system will meet the overall reclamation requirements in space. Water obtained from the dehumidification system has already undergone a phase change and requires only that absorbed odors and entrained particles be removed prior to reuse. A simple multifiltration technique, such as activated charcoal and biological filters, could be employed to do the job. To employ an elaborate phase change system, such as might be required to reclaim water from urine, would be superfluous.

Water-reclamation techniques are generally identified by the basic principle upon which they operate. Figure 1 lists some of the most promising techniques for waste-water management in space. The bars indicate the area of their most competitive application with respect to the management of humidity water, wash water, urine, and feces. Since these as well as other techniques are still being evaluated, no effort has been made to arrange the list in any order of preference. The figure does reflect these findings, however:

(1) It is not likely that multifiltration, as a technique for reclaiming humidity water, will be replaced in the near future.

(2) It is not likely that any direct attempt will be made to recover water from feces in the immediate future.

The vacuum drying process referred to in this figure is just one of the techniques that has been worked out to dispose of fecal matter. A prototype system has been constructed to demonstrate the feasibility of this concept and tests have shown that feces dried in this manner can be stored at room temperature for periods of time in excess of 75 days without contaminating the surrounding atmosphere.

The region of greatest discovery potential relates to techniques that would most advantageously recover water from wash water or urine. In this connection, it is safe to assume that any system that can recover water from urine can also be used to process wash water. Wash water is very similar, chemically, to urine that has been diluted about 25:1 with the inclusion of trace quantities of the cleanser used. Therefore, wash-water reclamation systems would share the same problems associated with the reclamation of urine only to a lesser extent. About 5 percent of urine is dissolved solids, the majority of which are organic in nature, with very objectionable characteristics. The primary constituent is urea. This substance decomposes rapidly at temperatures in excess of about 120° F to produce copious quantities of ammonia. Foul odors, like ammonia, that are soluble in water are extremely difficult to eliminate from a water-reclamation system. By far, the easiest way is to avoid forming such gases if possible. Operating the system at low temperature helps tremendously, but even so, some kind of pretreatment is required. Some of these reclamation techniques are more independent of pretreatment processes than others.

There has generally been one of three approaches to the pretreatment problem: The destruction of urea by chemical or enzymatic means; the fixing or preserving of urea by chemical treatment; or the adsorption of urea by activated charcoal. A common objection to each of these techniques is the fact that expendable materials are required. On medium to long term space missions, their launch-weight penalties may become excessive. The Langley Research Center is investigating an electrolytic approach to pretreatment that not only does not require expendables, but breaks down urea into nitrogen that can be used for leak makeup, carbon dioxide which is a potential source of oxygen, and hydrogen which can be vented overboard.

In this system, raw urine is fed directly into an electrolytic cell. At the anode, chlorides in the urine are converted into chlorine gas. Thus,

$$2\ Cl^- \rightarrow Cl_2 + 2\ e^-$$

At the cathode, water is decomposed to form hydroxide:

$$2\ H_2O + 2\ e^- \rightarrow H_2 + 2\ OH^-$$

The chlorine produced at the anode is allowed to react with water and the hydroxide formed at the cathode to give hypochlorite:

$$Cl_2 + H_2O \rightarrow HOCl + H^+ + Cl^-$$

$$Cl_2 + OH^- \rightarrow HOCl + Cl^-$$

Hypochlorite is, of course, a powerful oxidizer and disinfectant. It can react with urea in this fashion:

$$CO(NH_2)_2 + 3\ OCl^- \rightarrow CO_2 + N_2 + 3\ Cl^- + 2\ H_2O$$

It also decomposes other organic compounds and sterilizes the solution. The above-mentioned reactions may be summarized as follows:

$$CO(NH_2)_2 + H_2O \rightarrow CO_2 + N_2 + 3\ H_2$$

This new technique promises launch-weight savings over prior techniques on space missions lasting longer than about 60 days. The reclamation techniques are variously affected by this new technology. Electrodialysis, for example, is a technique that, by its nature, is dependent upon a pretreatment process that completely removes urea. By conventional methods, such time-dependent weight penalties are prohibitive. Therefore, electrodialysis would not be competitive on certain space missions without this new technology.

At present, there are only a few competitive techniques for the reclamation of wash water and urine in manned spacecraft. They are: multifiltration, distillation, reverse osmosis, and electrodialysis. No attempt has been made to name all the techniques that are being evaluated. Such techniques as freeze drying or photosynthesis are not considered because of their present excessive weight, volume, or power requirements. All techniques listed in figure 1 and others are being evaluated by the Langley Research Center.

These basic techniques are next considered in a little more detail. Multifiltration includes any combination of filter mediums that may be necessary to do the job. Figure 2 is a photograph of a multifiltration system that is capable of processing wash water. It consists of a canister of mixed-bed ion exchange resins in series with an activated charcoal and a particulate filter. This system is, incidentally, the simplest and probably the most reliable of all the reclamation concepts, and there is no obvious reason why it would not work in zero gravity. If the filters are hydrated to begin with, recovery efficiency would be close to 100 percent. Because the filters are expendable, however, the weight penalty of this technique when applied to urine-water recovery does not trade off very well with other techniques and may not be feasible for wash-water reclamation except for missions of short to medium duration.

Distillation as a technique for separating and concentrating pure substances was practiced as early as the 9th century A.D., and it has long been recognized as one of the most effective means of separating water from its contaminants in solution. This technique is indeed the primary process used by nature to close the water cycle. Water evaporates from our oceans and rivers and all moist surfaces; and when moisture laden air is cooled below its dewpoint, this water is returned to us as precipitation. Any means whereby water is evaporated and condensed is distillation, and since there is a change of phase, there are energy changes involved. For every pound of water that is evaporated, approximately 1000 Btu/lb is absorbed. And for every pound of water vapor that condenses, approximately 1000 Btu/lb is released.

An aspect of distillation that is not commonly understood is that it can occur even when water is not visibly boiling. Water can evaporate into any atmosphere in which the relative humidity is less than 100 percent, and water can be obtained from any moist atmosphere either by lowering its temperature or by increasing its partial pressure to its dewpoint.

The energy changes that occur in the natural distillation process affect such a large quantity of atmosphere that great temperature differences are not observed. If, however, operation on a smaller scale and acceleration of the process is required, as for manned spacecraft, heat can be added on one side and dissipated on the other. A very recent technique takes the saturated vapors from the evaporator and compresses them to their dewpoint. This technique has at least one very definite advantage, as follows: Depending upon the degree of compression, it is possible to force condensation to occur at a higher temperature than evaporation. Then if there is a heat-transfer relationship between the evaporator and condenser, the heat of vaporization can be recycled in the system.

Each of the three principles of distillation just mentioned has been modified and incorporated into life-support-system components that would be suitable for use onboard space vehicles.

An integrated life-support system that included provisions for the air evaporation of urine and wash water was delivered to the Langley Research Center in July 1965. The principle of air evaporation is illustrated in figure 3. In this system, air is circulated in a closed loop through an evaporator compartment that contains the waste water or urine in wicks. By using wicks in the evaporator and a cyclone-type cooler-condenser, the system possesses operating capability in zero gravity. Integrating this system into the environmental control loop permits utilization of any waste heat that might be available from other components onboard the space vehicle. The temperature changes do not have to be as high as might be expected in a still that operates at atmospheric pressure. Since the system can be operated until the wicks are dry, it is capable of recovering essentially all the available water from urine. Pretreatment is required, however, and these materials, together with the expendable wicks required, make up a significant time-dependent weight penalty.

The air evaporation technique described here is just one type of heat input still. Others might employ more conventional methods and utilize heat either from the environmental control loop, a radioactive isotope, or electrical resistance heat. Water purity may be controlled by pretreatment or post-treatment, by elaborate entrainment filters, or by pyrolysis of the vapors before condensation.

Figure 4 is a photograph of a phase-change reclamation system that employs the principle of vapor compression distillation. As pointed out previously, since the heat of vaporization is recycled, the only energy required is that necessary to drive the compressor and to rotate the evaporator so as to give the system its zero-gravity operating capability. The system stands about 2 feet high and weighs about 59 pounds. Such a system, if operated on a near continuous basis would be capable of reclaiming approximately 97 percent of all the available water in the urine of 20 men.

Some pretreatment is required in order to obtain acceptable water from this system. The operation is conducted under reduced pressure so that operating temperatures do not exceed about 120° F. By operating in this fashion (at low temperatures), many of the problems associated with the rapid breakdown of urea into ammonia are avoided. Residue removal is accomplished by evaporating to dryness and physically removing a plastic evaporator liner together with its contents. This is certainly one of the most disadvantageous features of the system.

Vapor compression distillation as a technique has been used for a number of years for the desalination of brackish waters. There is a plant in Roswell, N.M., that delivers over 1 000 000 gallons per day. Large systems can be made to operate very efficiently, but when the concept is scaled down to deliver only about 2 or 3 gallons per day, its relative efficiency decreases by approximately a factor of 3. More efficient vapor compressors are needed to make this technique more competitive.

Figure 5 is a block diagram of another reclamation technique, a membrane process called reverse osmosis. This technique utilizes the selective properties of certain semipermeable membranes to separate water from its dissolved salts. In this process, the waste water or urine is placed next to a dialyzing membrane and subjected to a hydrostatic pressure that exceeds the osmotic pressure of the solution. Under these conditions, water will pass through the membrane in a direction opposite to that normally observed in an osmotic experiment where the driving force is the concentration gradient. Since there is no change of phase, this process has the promise of being a very economical technique from the standpoint of energy consumption. Unfortunately, however, most membranes that will pass water will also pass urea; therefore, pretreatment is necessary to remove the urea and other organics in urine in order to obtain a product water of high purity.

Electrodialysis is another membrane process that uses electricity as the driving force. Figure 6 illustrates the mechanism which consists of a series of compartments that are separated by semipermeable membranes having alternate properties. The membranes labeled "C" in the diagram are permeable only to positively charged ions such as sodium. The membranes labeled "A" in the diagram are permeable only to negatively charged ions such as chloride. If a stack of such compartments are placed in a field of dc current, then positively charged ions will tend to migrate toward the cathode, and negatively charged ions will tend to migrate toward the anode. The overall effect is that these ions migrate into adjacent compartments where they are "trapped." By judiciously connecting many such "stacks" in series, one can obtain from the system a concentrate and a dilute stream.

Electrolysis is very economical of electrical power since the power requirements are a function of the quantity of ions in solution and not so much upon the quantity of water that is processed. The disadvantages of electrodialysis as a method of reclaiming water from urine would include the fact that urea and other nonionizable substances cannot be removed by this technique. Therefore, the system is heavily dependent upon pretreatment or post-treatment. techniques.

Figure 7 is a view of an electrodialysis system that is being evaluated at Langley. It includes the electrodialysis stack itself, together with the necessary valving and instrumentation. The circulating pump cannot be seen in this view of the system.

SYSTEM EFFICIENCY

Thus far, a review has been presented of some of the basic water-reclamation techniques, which might be utilized to help close the ecology onboard a space vehicle. These and other techniques are currently being evaluated for this application. The pieces of actual hardware are very different, not only in principle but in terms of their process parameters. Several of these are quite independent of system sizing, they are: recovery efficiency in terms of percent of available water contained in the waste product that is recovered by the system, and recovery cost in terms of watt-hours per pound of water recovered. There has been an effort to establish some ground rules upon which the properties of water-reclamation systems of varying capacities can be compared. One way is to compare them on the basis of their launch-weight requirements per man, for a given mission. Strictly speaking, one would not be justified in scaling the properties of these systems down directly. The parametric equations derived in this fashion would be applicable to a given mission only if they are multiplied by a factor that is equal to the number of men that the system was designed to accommodate for that particular mission. The data submitted herein on the various systems have been reduced directly to a one-man basis for comparative purposes only. These one-man parametric equations were obtained in the following manner.

The system was first sized by taking its hourly process rate and dividing it by 0.162 pound per hour or the amount of urine our one-man system would have to process if it operated 20 hours per day. The base weight was determined by taking the actual system weight, adding a penalty for the use of electrical power at the rate of 0.3 pound per watt or if the system used waste heat, 0.005 pound/Btu/hr. In either case a heat-rejection penalty amounting to

0.01 lb/Btu/hr or 0.034 lb per watt was added. This result was divided by the system size in men. The time-dependent weight penalty for the one-man system was determined by taking the weight of all expendable materials required for the daily operation of the system, dividing by the system size in men, and then adding a recovery inefficiency penalty equal to 100 percent minus the recovery efficiency of the system times 3.08 pounds (the amount of available water in the average urine output of one man). If in the operation of a system, heat exchangers are used, the efficiency of this exchange was taken to be 90 percent unless its true value was known.

Data of this type have been derived for some of the techniques that have been discussed and are presented in figure 8. These curves could be revised somewhat since they are based on technical information that has been published and is presently available. It should be emphasized that the selection of a technique for actual flight use would not be based upon any one property of a system. Actually the choice of technique and extent of reclamation are dictated to a large degree by the nature and type of other systems onboard the craft as well as the intended mission duration.

Figure 9 illustrates some basic factors that influence decisions concerning the use of water-reclamation systems on space missions. Launch weight in pounds per man is plotted against mission duration in days. The water-demand line represents the amount of stored water that would be required, assuming that humidity water is not available for reuse. There would be no need to perform water reclamation on space missions that are of such duration that fuel cells are used for power, since a byproduct of fuel cells is water. The assumption is also made that water derived from these cells can be made fit for human consumption by some practical means. When space missions are of such duration that energy-supply systems other than fuel cells, such as solar cells or nuclear power supplies, are used for power, it becomes obvious from the water-demand curve that, in the interest of minimizing launch weight, some degree of water reclamation must be performed. It can be shown that all need for stored water can be eliminated if there is a system onboard which is capable of reclaiming at least 91.5 percent of the available water from man's waste products. The reason this is possible is that man produces metabolic water from the food he eats. Since some oxygen is also consumed in the production of this metabolic water, when mission durations become long enough that oxygen reclamation systems are included to balance the oxygen cycle, then some water must be decomposed. It would be necessary because man requires about 1.92 pounds of oxygen but there are only 1.63 pounds available from his daily output of carbon dioxide. Therefore, when oxygen reclamation is performed, there is an increased water demand and it becomes necessary to reclaim at least 95 percent of the available water from man's waste products if stored water is to be eliminated. Curves are presented for two hypothetical water-reclamation systems: System A is basically heavier than system B because it pushes the recovery efficiency up to 95 percent or better. Until oxygen reclamation is performed, system B (which can recover 91.5 percent of the available water) is the system of choice from launch-weight considerations. But on missions that require oxygen reclamation, system B would have to be penalized for its lower recovery efficiency. Then it would be more economical to fly with system A.

Looking toward even longer space missions, a need for higher recovery efficiency of water from urine can be shown. On the longer space missions, the amount of atmosphere lost through leaks and from airlock cycling during the transfer of men and materials can become significant. On such missions, if it is desired to eliminate the need for stored water, provide water for electrolysis to balance the oxygen cycle, and make up for atmospheric leakage, it will be necessary to recover all the available water in urine.

CONCLUDING REMARKS

The necessity for water reclamation on manned space missions of medium to long term duration is recognized. Ideally, it would be most desirable to be able to close our ecology in space as effectively and completely as nature closes it here on earth. Biological systems are a vital link in this cycle. However, manned space missions in the immediate future are not of such duration to justify the resulting weight and volume requirements of these biological systems. A number of promising nonbiological techniques are being evaluated and compared. So far as the state of the art is concerned, there are only a few competitive techniques. They are: multifiltration, distillation, reverse osmosis, and electrodialysis. The selection of a flight system can best be made on the basis of its reliability, launch weight, recovery efficiency, recovery cost, and the quantity of expendables required for its operation. It should not be implied, however, that our future space missions will be so marginal that a few or even a hundred pounds one way or the other will spell success or failure. The ultimate goal of high reliability, low weight and power operation, elimination of expendables, and recovery approaching 100 percent has not been achieved. Advanced engineering concepts are being incorpoated into the development of better systems to approach these goals, and it is expected that future research may produce new concepts to further this technology, particularly in the area of zero gravity operation without moving parts and near 100 percent recovery without expendables. Such systems must be acquired in order to have and maintain a closed ecology in space.

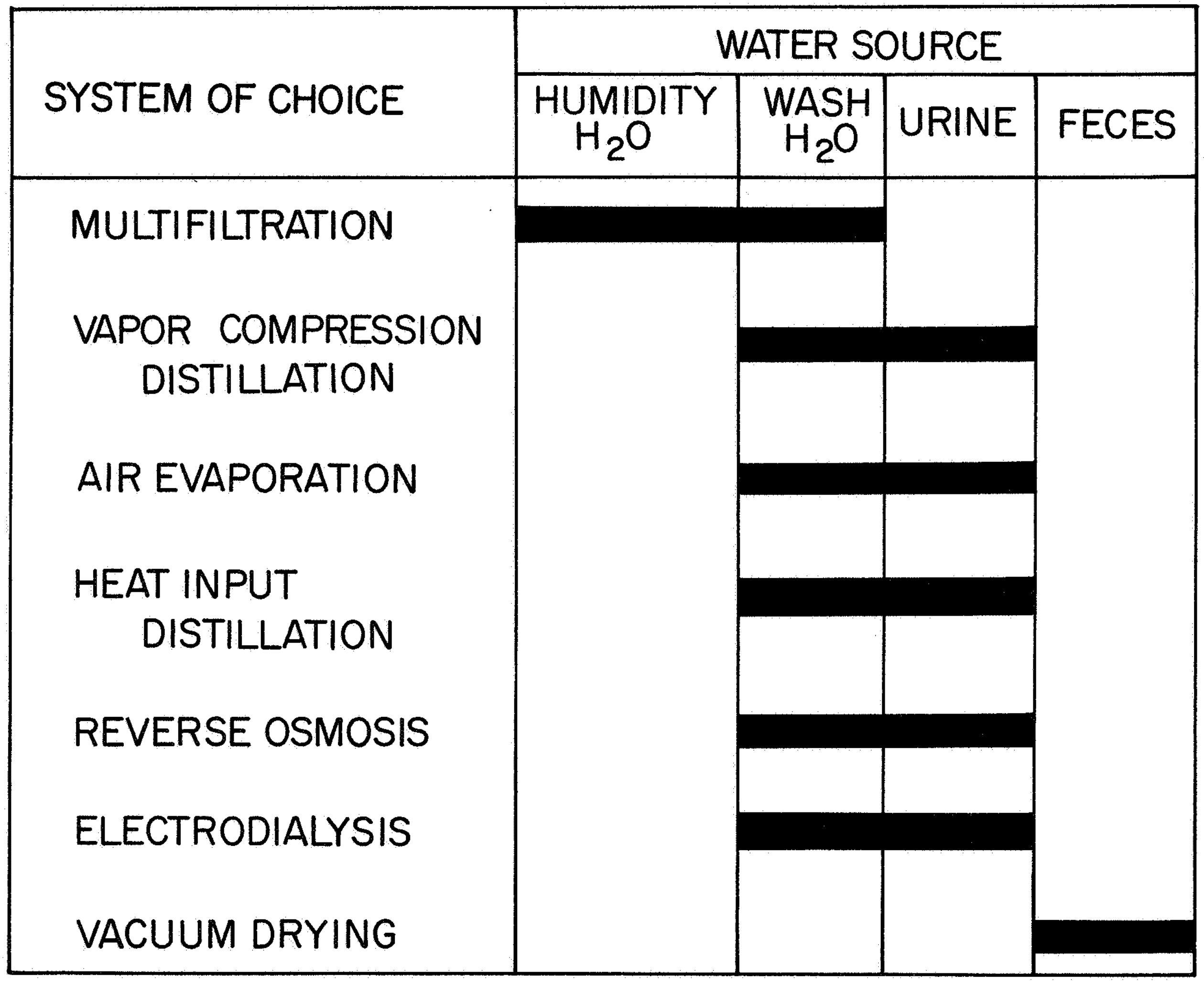


Figure 1.- Water management on manned space missions.

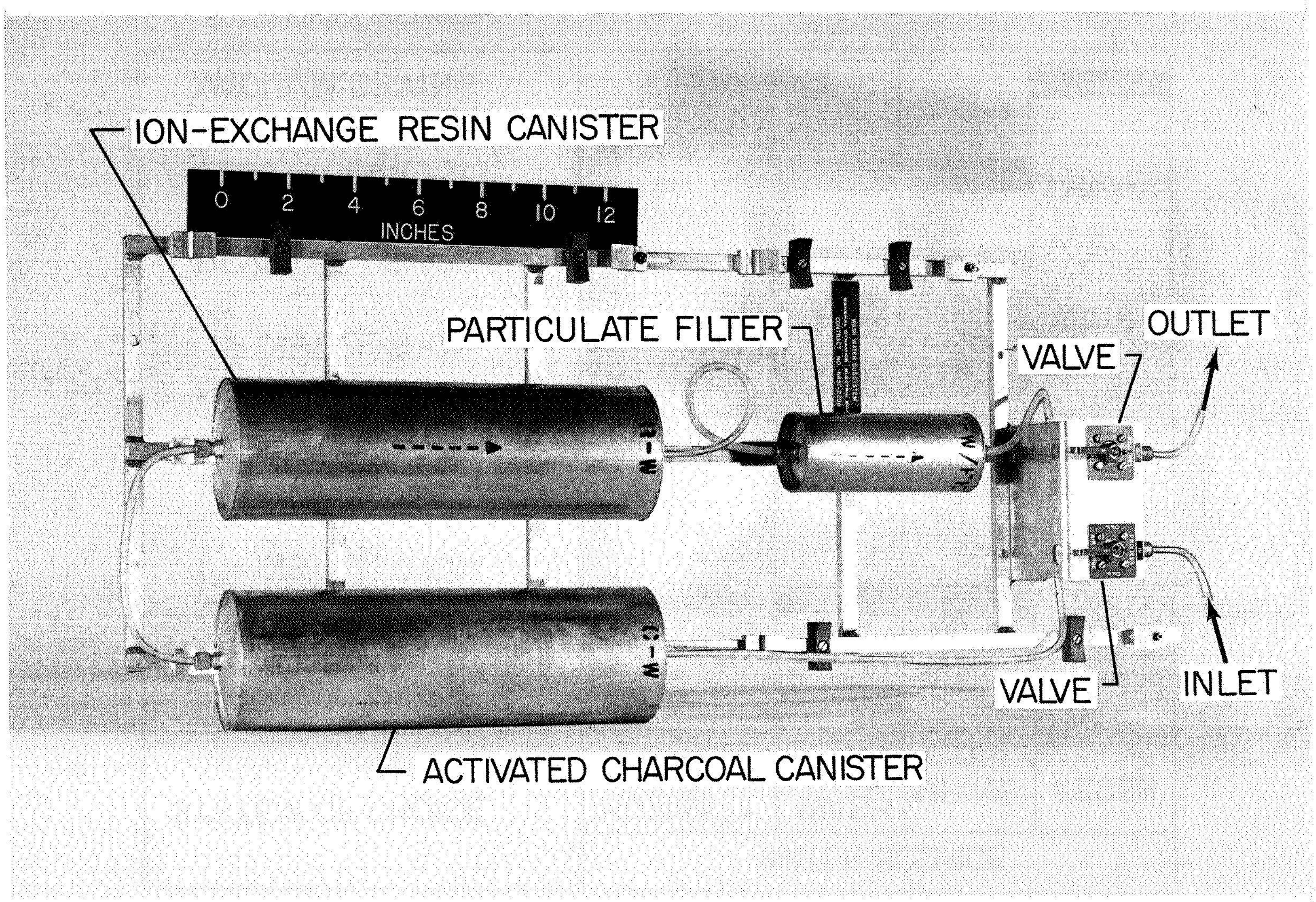


Figure 2.- Wash-water subsystem.

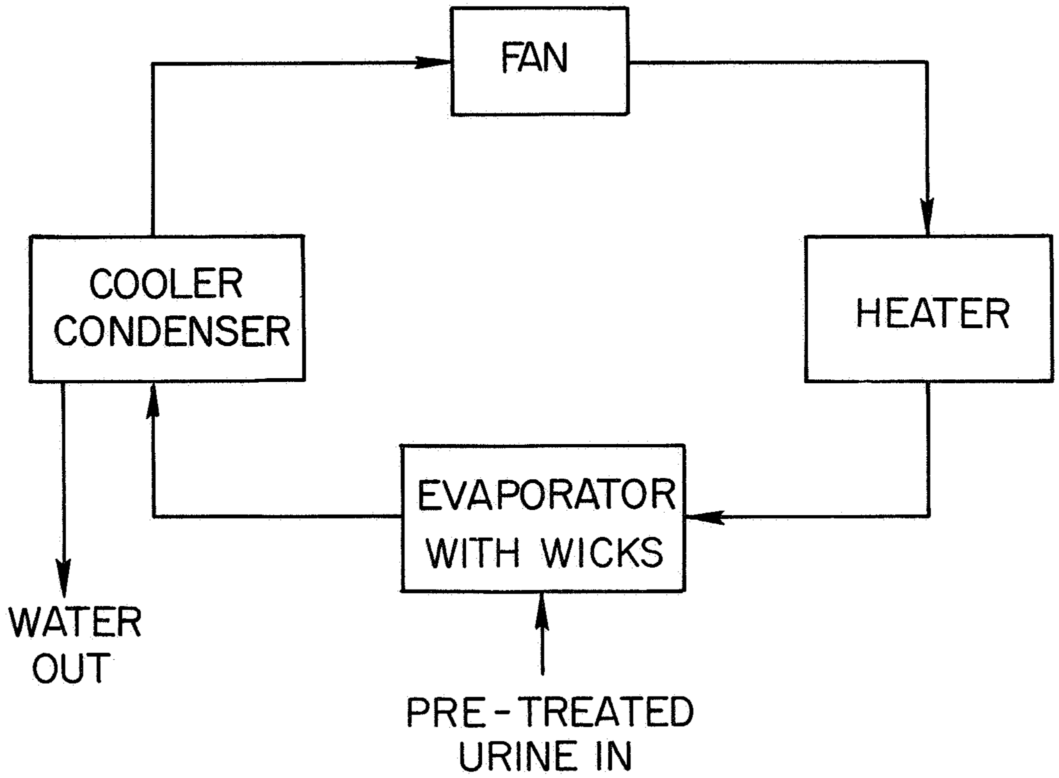


Figure 3.- Air evaporation system.

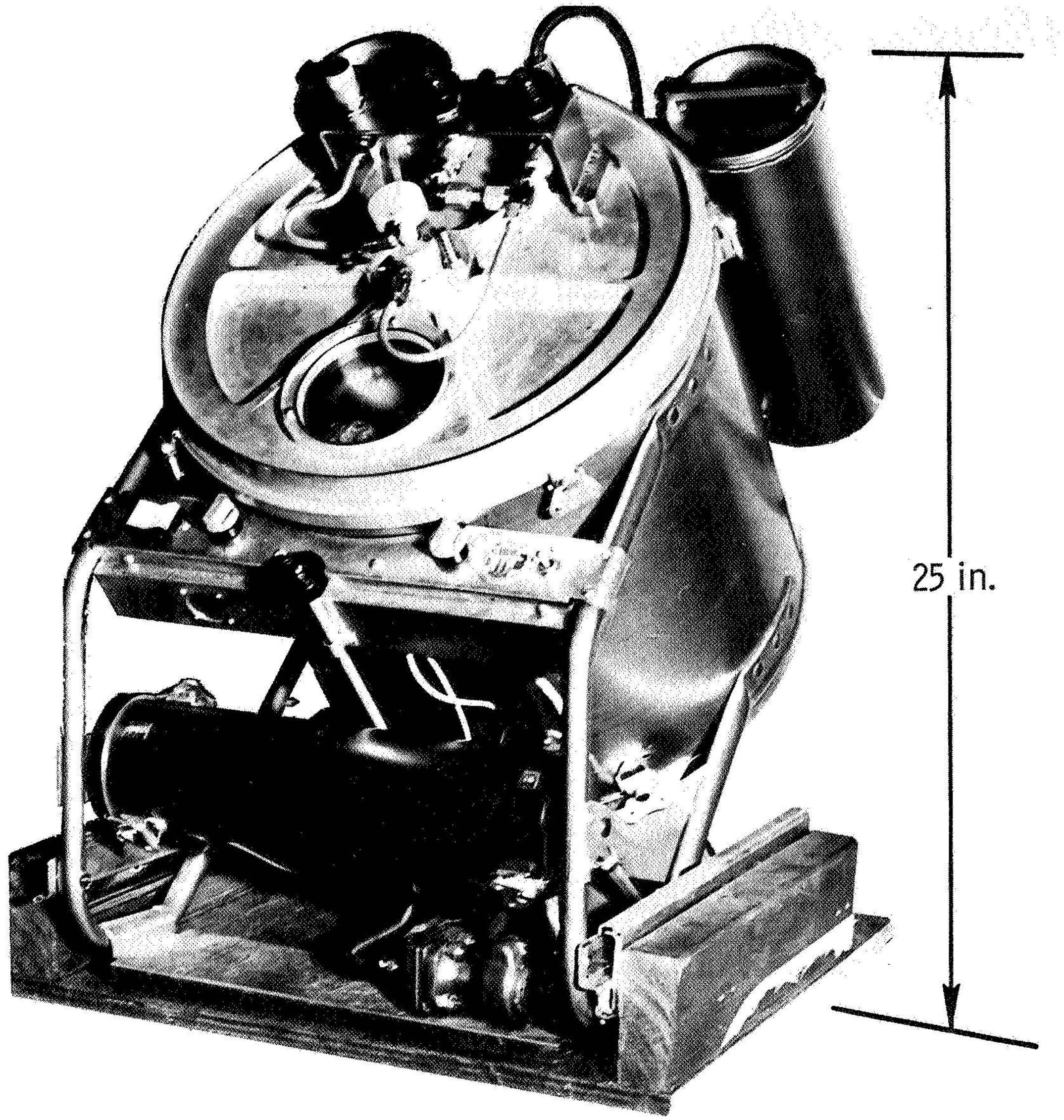


Figure 4.- Vacuum compression distillation system.

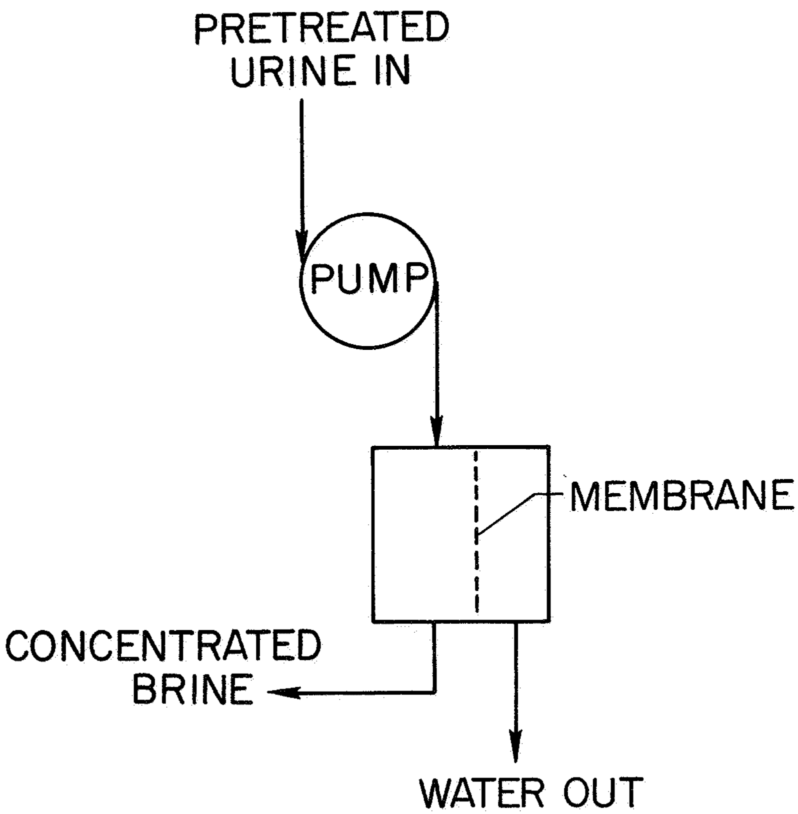


Figure 5.- Reverse osmosis system.

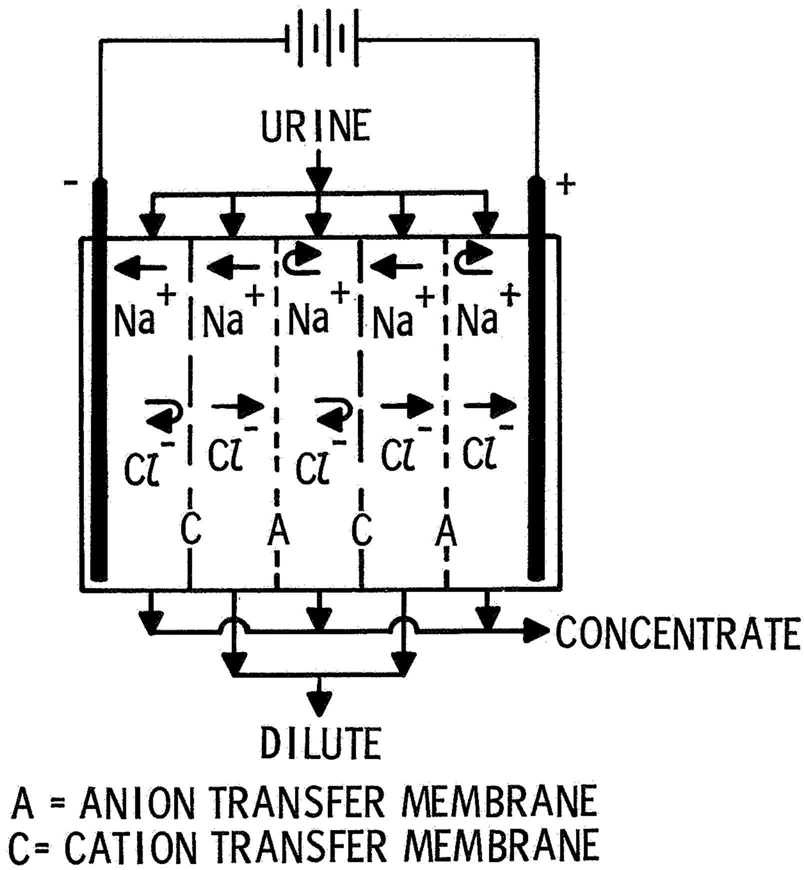


Figure 6.- Electrodialysis cell.

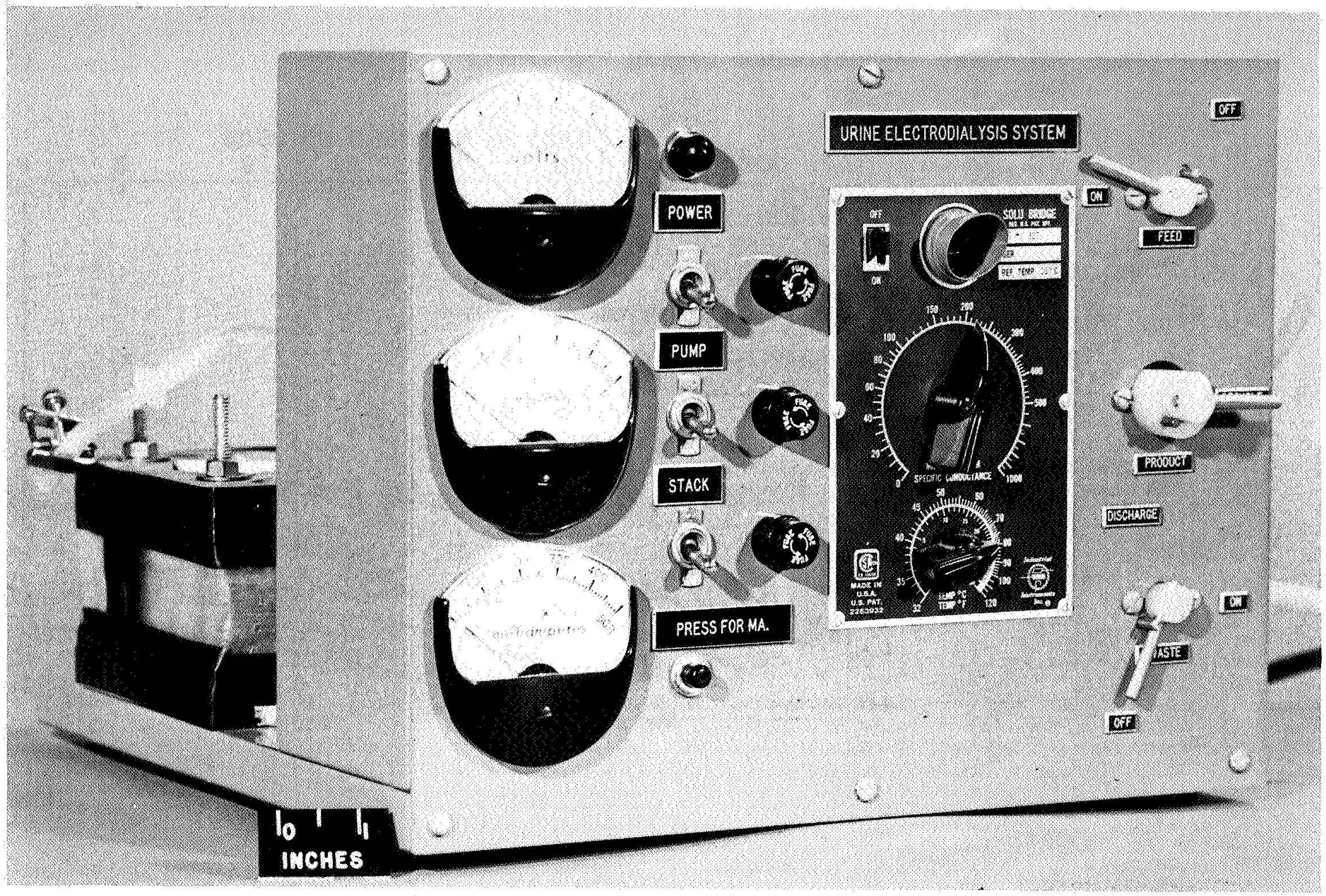
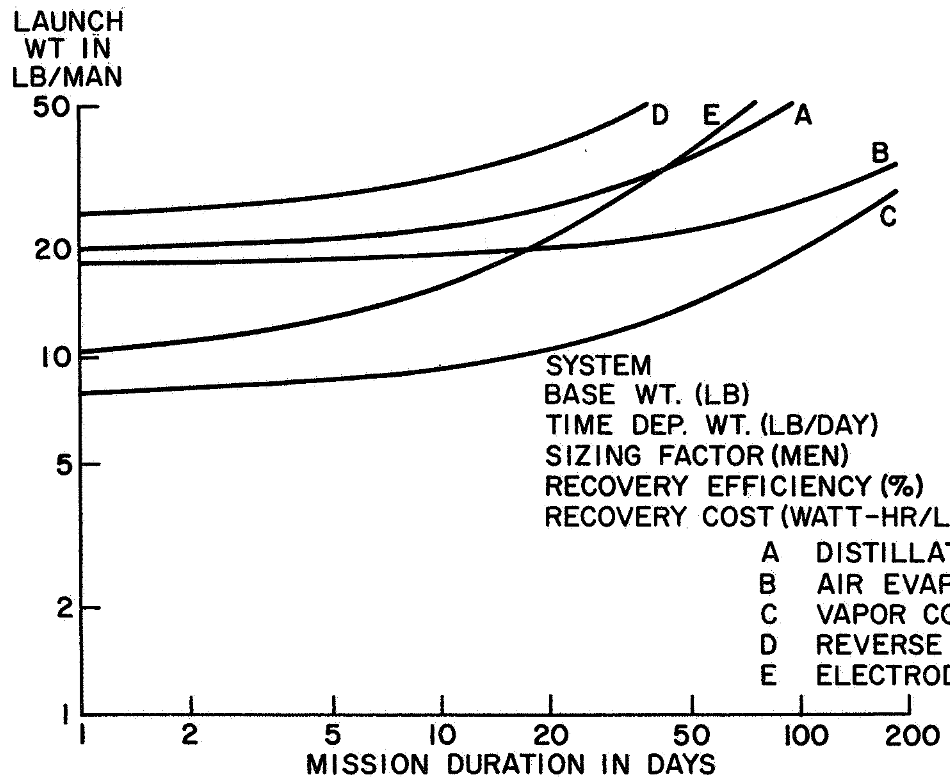


Figure 7.- Electrodialysis urine-reclamation system.



SYSTEM	A	B	C	D	E
BASE WT. (LB)	19.71	18.35	7.95	24.88	10.16
TIME DEP. WT. (LB/DAY)	0.31	0.08	0.11	0.69	0.52
SIZING FACTOR (MEN)	3	8	15	5	13
RECOVERY EFFICIENCY (%)	90	99	97	86	91
RECOVERY COST (WATT-HR/LB)	292	66	38	142	28

A DISTILLATION WITH PYROLYSIS
B AIR EVAPORATION
C VAPOR COMPRESSION DISTILLATION
D REVERSE OSMOSIS
E ELECTRODIALYSIS

Figure 8.- System comparisons.

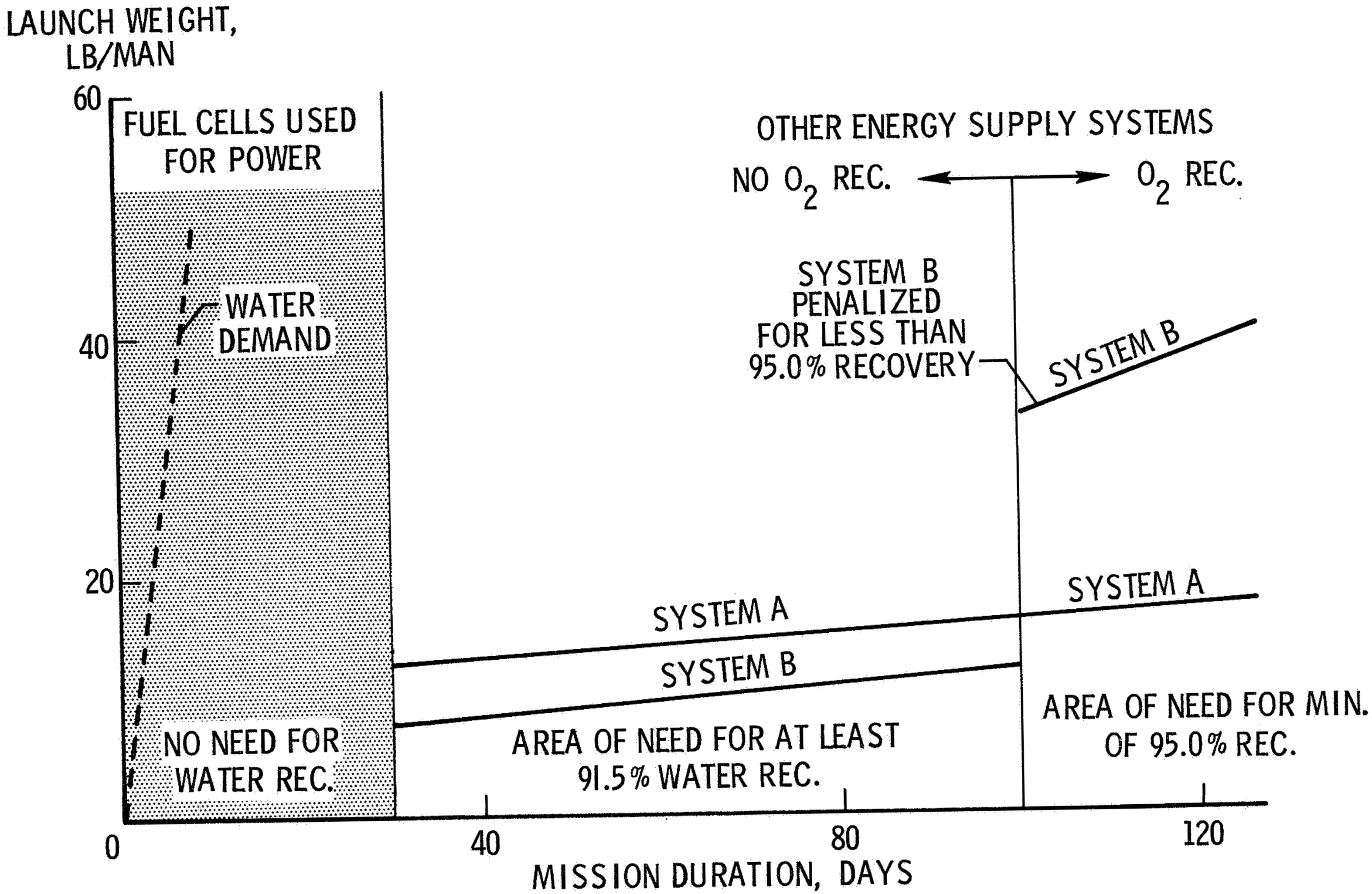


Figure 9.- Significance of water-reclamation systems.

NASA-Langley, 1966