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FEASIBILITY STUDY FOR SMALL GROUP WATER DESALINATION EQUIPMENT

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The ability for small groups of soldiers to desalinate brackish or sea water will reduce their dependence on supply lines. Ten desalination options were reviewed for effectiveness in ~~eight~~ nine scenarios. Each option was rated according to a number of factors such as energy consumption, water recovery, logistics concerns, weight, and simplicity. The importance of each of these factors depended on the scenario being considered. The options which seem most favorable include simple distillation, membrane distillation, and reverse osmosis.

See p iii

EXECUTIVE SUMMARY

A total of 10 options were considered for desalinating brackish or sea water. These options included simple distillation, single-pass membrane distillation, multiple-pass membrane distillation, multiple-effect evaporation, heat pumps, vapor-compression, reverse osmosis without energy recovery, reverse osmosis with energy recovery, electrodialysis, and ion exchange. These desalination options were evaluated in the nine scenarios includ~~ing~~e: using waste heat from vehicles, using power take-off from vehicles, using a trailer mounted unit performing desalination on the move or in a fixed location, stowing a small desalination unit in vehicles to be used when needed, using waste heat at a fixed location, using a dedicated power source for a desalination unit at a fixed location, using waste heat from a microclimate cooling unit, and having a soldier carry the desalination unit.

Each of the 10 options was considered for use in each of the nine scenarios. The appropriate option for each scenario was determined by considering such factors as energy efficiency, water recovery, product purity, logistical support requirements, unit weight and volume, cost, simplicity, controllability, the ability to remove nuclear, biological, and chemical (NBC) agents, and the ability to chill the product water. From this analysis, it was determined that simple distillation, membrane distillation, reverse osmosis, and vapor-compression were viable options. The table below shows which option is recommended for each scenario.

Summary of Desalination Options

2 = Strong Recommendation

1 = Weak Recommendation

0 = Not Recommended

SCENARIO	Simple Distillation	Membrane Distillation	Reverse Osmosis	Vapor-Compression
Fixed Installation, Waste Heat	2	2	0	0
Mobile Vehicle, Waste Heat	2	1	0	0
Trailer Mounted Unit, Dedicated Power Stationary Separation	2	2	2	1
Fixed Installation, Dedicated Power	0	0	2	1
Mobile Vehicle, Power Take-Off	0	0	2	1
Trailer Mounted Unit, Dedicated Power Mobile Separation	2	1	1	1
Vehicle Stowed Unit, Dedicated Power	2	1	2	1
Foot Soldier, Waste Heat	2	1	0	0
Foot Soldier, Dedicated Power	1	1	2	0

Note that vapor-compression is listed as a viable option, but it is not highly recommended since the alternatives are more attractive.

From the analysis conducted in this report, a number of fruitful avenues for future research have become apparent. Each research option would benefit different sized groups of soldiers.

LARGE GROUP (50-800 Soldiers)

1. Develop equipment which allows recovery of waste coolant heat from military generators to be used in membrane distillation.

MEDIUM GROUP (20-50 Soldiers)

1. Develop equipment which allows recovery of waste coolant heat from military generators to be used in simple distillation.

SMALL GROUP (7-20 Soldiers)

1. Develop reverse osmosis units employing energy recovery which can be powered by a Stirling engine or other small mechanical power source.

2. Develop equipment which allows recovery of waste coolant heat from military vehicles to be used in simple distillation.

3. Develop a membrane distillation unit to be heated with a 1950 squad stove. The stove should be modified to have a thermoelectric generator to operate the pumps of the membrane distillation unit.

INDIVIDUAL SOLDIER

1. Develop equipment which allows recovery of waste coolant heat from a Stirling-powered microclimate conditioning unit for use in simple distillation.

2. Modify hand-powered reverse osmosis desalinators to operate using leg muscles rather than arm muscles to increase production rates. Incorporate features that allow greater water recovery from brackish water than from sea water.

The research options for large- and medium-sized groups are included for the sake of completeness. The emphasis of this study is directed towards small groups and individual soldiers.

PREFACE

On 14 September 1982, a Draft Letter of Agreement (DLOA) was issued from the U.S.A. Institute for Military Assistance, Ft. Bragg, NC which describes the need for an Individual/Small Unit Water Purification Device (WPD). The WPD should provide Special Operations Forces (SOF) and other units which operate independently of supply lines with the capability to provide potable drinking water in a nuclear, biological, chemical (NBC) hostile environment. To meet the SOF requirements, the WPD was to be designed to have the following capabilities.

1. Remove particulate matter.
2. Provide drinking water at a minimum rate of one quart per minute.
3. Provide a minimum of 15 quarts per day for 14 days (210 quart capacity).
4. Weigh no more than one pound without water.
5. Neutralize or remove harmful chemicals.
6. Kill or remove harmful biological materials/substances.
7. Remove soluble radioactivity.
8. Provide a method to indicate end of service life.
9. Comply with those provisions of TRADOC Reg. 71-14 (25 Sept. 81) as jointly determined by the combat developer and the new material developer.
10. Operate in climatic environments ranging from hot through severe cold (C-1, AR 70-38).
11. Operate and maintain with ease.
12. Desalinate seawater.

The combat developer and the material developer will initiate actions in accordance with AR 702-3, page 2-3, para. 2.6.b and quantitate reliability, availability and maintainability (RAM) to be included in the requirements document supporting full-scale engineering development, if applicable.

On 4 April 1984, a Draft Operational and Organizational Plan (DOOP) for the Individual/Small Unit Water Purification Device was issued from the U.S.A John F. Kennedy Special Warfare Center (successor agency to the U.S.A. Institute for Military Assistance), Ft. Bragg, NC. In this document, the WPD was applied to two separate devices: one device for purification of fresh water by the individual and a second and separate device for the purification of salt water by a small unit. It is this later requirement which this feasibility study was undertaken.

On 8 February 1984, a new 6.2 work unit (1L162724AH99BG011) Advanced Techniques for Small Group Water Purification was started to address the requirements in the DLOA of 14 September 1982 and the DOOP of 4 April 1984. The first phase of the technical plan for this work unit was to conduct a study to determine the feasibility of meeting the J.F. Kennedy Special Warfare Center requirements with current technology including the treatment of brackish or seawater. This report summarizes the results of this feasibility study which has broad applications not only to the specific requirements in the J.F. Kennedy DLOA/DOOP, but also to the general needs of Army 21.

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1. INTRODUCTION

There are few environmental factors which impart more on the individual soldier's well-being than the availability of an adequate supply of drinking water. The amount of water required to prevent dehydration and promote physical and mental welfare varies with the climate and level of physical activity.[1] Water requirements in a temperate environment at 80°F (27°C) are about 6-14 lb/d (3-6 kg/d) per soldier. In a desert environment at 120°F (49°C), water requirement are 35-50 lb/d (11-23 kg/d) per soldier. These water requirements may be converted to a volume basis as shown in Table 1.

Table 1. Individual Water Requirements Expressed in Common Weight and Volume Units of Measure

Temperate	Desert
6-14 lb/d	35-50 lb/d
1-2 gal/d	4-6 gal/d
3-7 qt/d	17-24 qt/d
3-6 kg/d	11-23 kg/d
3-6 L/d	11-23 L/d

Water may be obtained from the surface or ground and may be classified as fresh (<500 ppm salt), brackish (~10,000 ppm salt) or sea (~35,000 ppm salt) water. It is the purpose of this report to explore methods that may be employed by small units or individuals for desalinating brackish and sea water so that it may be consumed.

The water may require further processing beyond desalination to make it acceptable for safe consumption. It is anticipated that the battlefield of the 21st Century may be contaminated with nuclear, biological, and chemical (NBC) agents. These must be removed prior to consumption of the water. Additionally, it has been determined that water temperature is very important since soldiers may not drink enough water if it is too warm.[2] The proper choice of a desalination method may impact favorably on these additional requirements to decontaminate and chill the water.

The separation of salt from water requires energy. The minimum amount of energy is given by the free energy of mixing

$$G = R\ T \ln \frac{P_{\text{salt water}}}{P_{\text{fresh water}}} \qquad (1)$$

where

G = Gibb's free energy of mixing (Btu/lb mol)

R = gas constant = 1.986 Btu/lb mol ^{o}R

T = temperature (^{o}R)

P = water vapor pressure (psia)

Figure 1 shows the minimum amount of energy to separate a pound of water from salt water as determined from Eqn. 1. For brackish water (1% salt) the minimum energy is about 0.25 Btu/lb (0.6 kJ/kg) and for sea water (3.5% salt), the minimum energy is about 1.0 Btu/lb (2.3 kJ/kg). Although this is a rather small theoretical energy requirement, real processes for separating the water from salt have many inefficiencies involved which can increase the theoretical requirement by thousands of times.

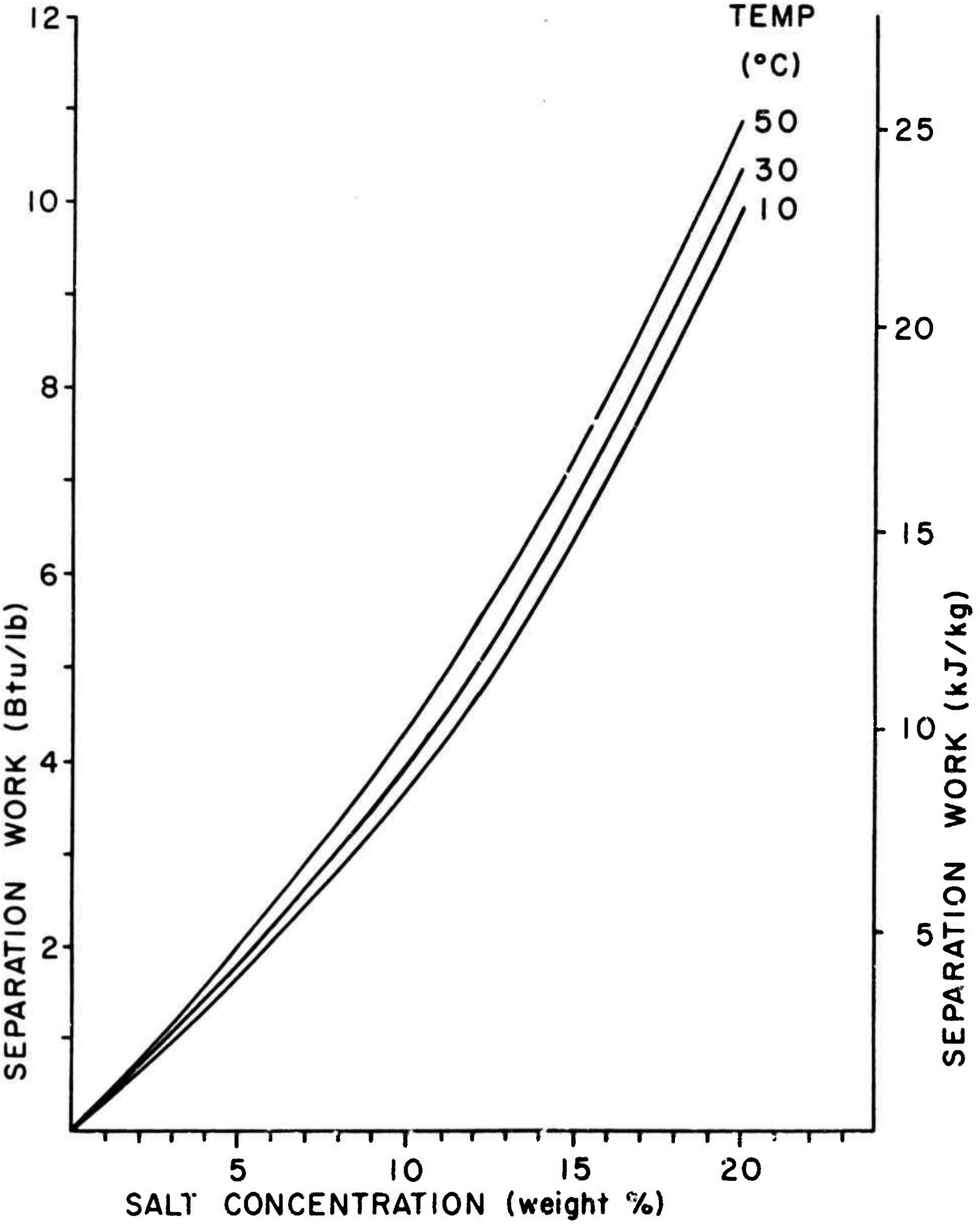

Figure 1. Minimum energy to separate pure water from salt water.

2. OPTIONS

A total of 10 options have been identified for separating water from salt water. These may be classified according to the type of energy used to achieve the separation as shown in Table 2. The following sections briefly describe each of these options.

TABLE 2. Classification of Desalination Options by Energy Source

HEAT

1. Simple distillation
2. Membrane distillation
    a. Single-pass
    b. Multiple-pass
3. Multiple-effect evaporation

MECHANICAL

1. Heat pump
2. Vapor compression
3. Reverse osmosis
    a. without energy recovery
    b. with energy recovery

ELECTRICAL

1. Electrodialysis

CHEMICAL

1. Ion exchange

2.1 Simple Distillation

DESCRIPTION

Fig. 2 shows a schematic of simple distillation. Heat is supplied to the salt water which generates water vapors. These vapors are condensed and collected as potable water.

PERFORMANCE

	Brackish Water	Sea Water
Heat Energy (Btu/lb)	1000	1000
(kJ/kg)	2300	2300
Water Recovery (%)	90-95	80-90
Product Salt Concentration (ppm)	0	0

ADVANTAGES

1. very simple
2. high water recovery

DISADVANTAGES

1. high energy requirement
2. produces hot water

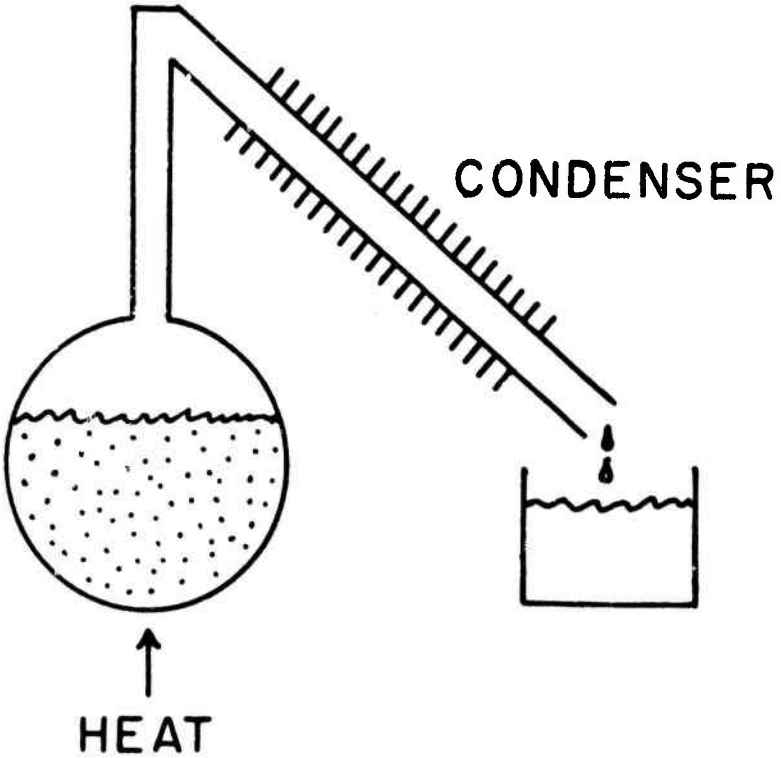

Figure 2. Schematic of simple distillation.

2.2 Membrane Distillation (Single-Pass)

DESCRIPTION

Fig. 3 shows a schematic of a single-pass membrane distillation unit. Salt water flows into the preheater section, through a heater, and out through the post cooler. The energy added in the heater causes the water temperature in the post cooler to be slightly higher than that of the water in the preheater. The hydrophobic membrane* allows hot water vapors generated in the post cooler to pass while preventing liquid water from passing through. These vapors liquefy on the condenser plate thus warming the water in the preheater. The condensate is collected as potable water.

PERFORMANCE

	Brackish Water	Sea Water
Heat Energy (Btu/lb)	80-150	100-200
(kJ/kg)	180-350	230-450
Recovery (%)	8-10	8-10
Product Salt Concentration (ppm)	0	0

ADVANTAGES

1. low energy consumption
2. low grade, waste heat may be used

DISADVANTAGES

1. heavy
2. large volume

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* Available from W.L. Gore & Associates, Membrane Distillation Division, 3773 Kaspar, P.O. Box 1980, Flagstaff, Arizona 86002

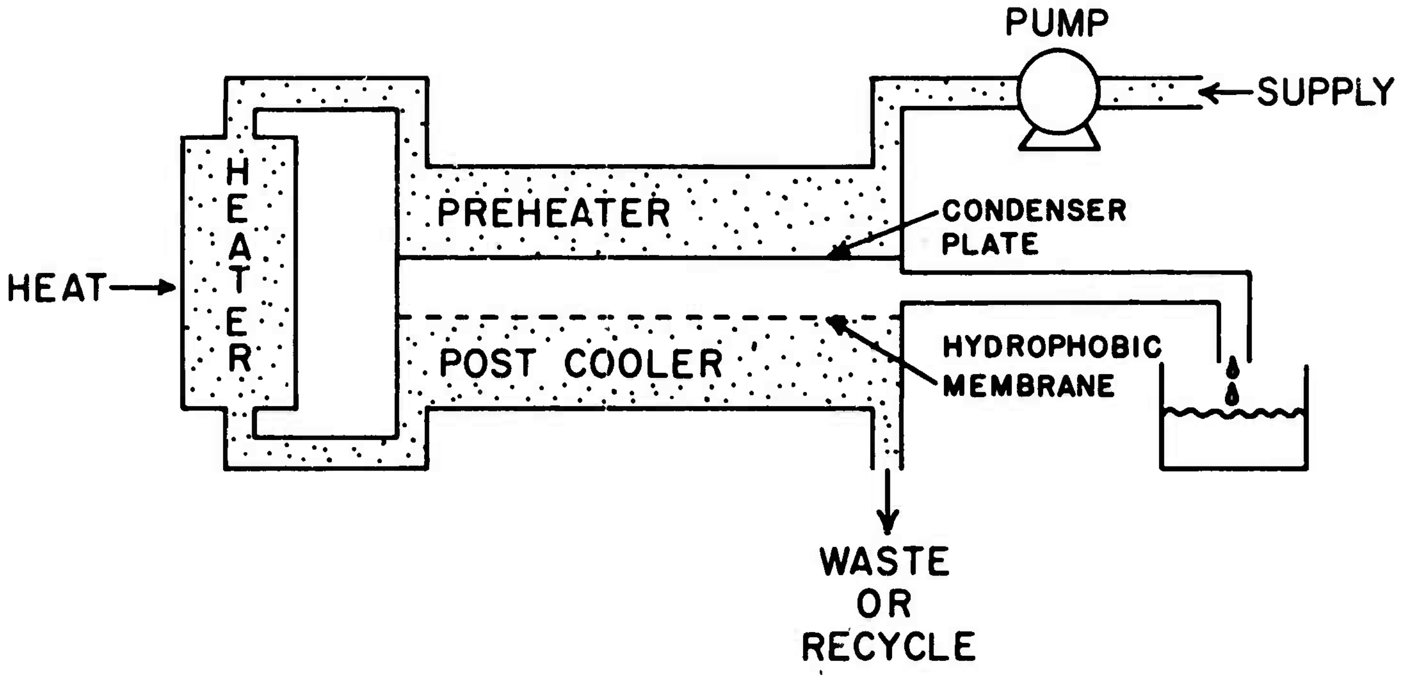

Figure 3. Schematic of single-pass membrane distillation.

2.3 Membrane Distillation (Multiple-Pass)

DESCRIPTION

Fig. 4 shows a schematic of a multiple-pass membrane distillation unit. The technology is identical to single-pass membrane distillation, except that the water flowing out of the post cooler is returned to the supply reservoir. The heat added in the heater is removed from the exit stream so the reservoir does not rise in temperature.

PERFORMANCE

	Brackish Water	Sea Water
Heat Energy (Btu/lb) (kJ/kg)	100-200 230-460	150-300 350-700
Recovery (%)	70-80	40-50
Product Salt Concentration (ppm)	0	0

ADVANTAGES

1. water recovery is higher than single-pass membrane distillation

DISADVANTAGES

1. heat exchange from the exit stream is difficult since the temperature is low

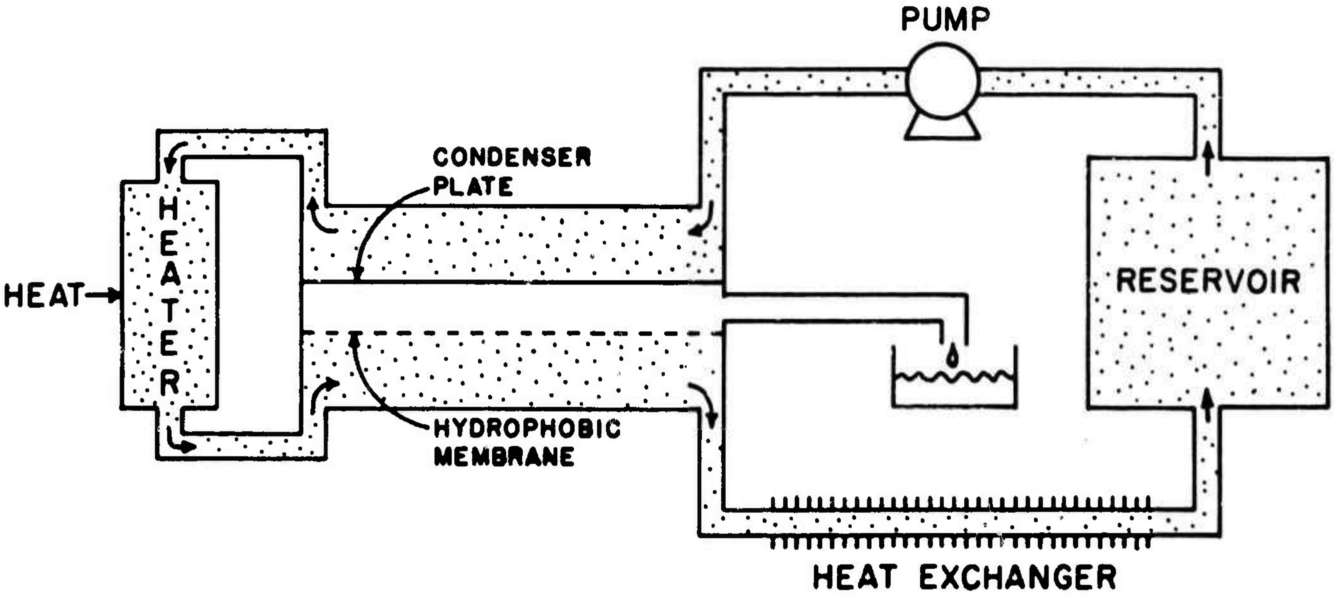

Figure 4. Schematic of multiple-pass membrane distillation.

2.4 Multiple-Effect Evaporator

DESCRIPTION

Fig. 5 shows a schematic of a multiple-effect evaporator. Salt water is circulated through multiple vessels, each at a different pressure. Heat is applied to the vessel with the highest pressure. The vapors which are generated condense by rejecting their latent heat to the adjacent vessel which has a lower pressure (and temperature). This process is repeated in subsequent vessels. The more vessels, the lower the energy requirement.

PERFORMANCE

	Brackish Water	Sea Water
Heat Energy* (Btu/lb)	333	333
(kJ/kg)	770	770
Recovery (%)	90-95	80-90
Product Salt Concentration (ppm)	0	0

ADVANTAGES

1. well proven technology in industrial sizes
2. high water recovery

DISADVANTAGES

1. difficult to control
2. complex
3. large
4. produces warm water

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* assumes three stages

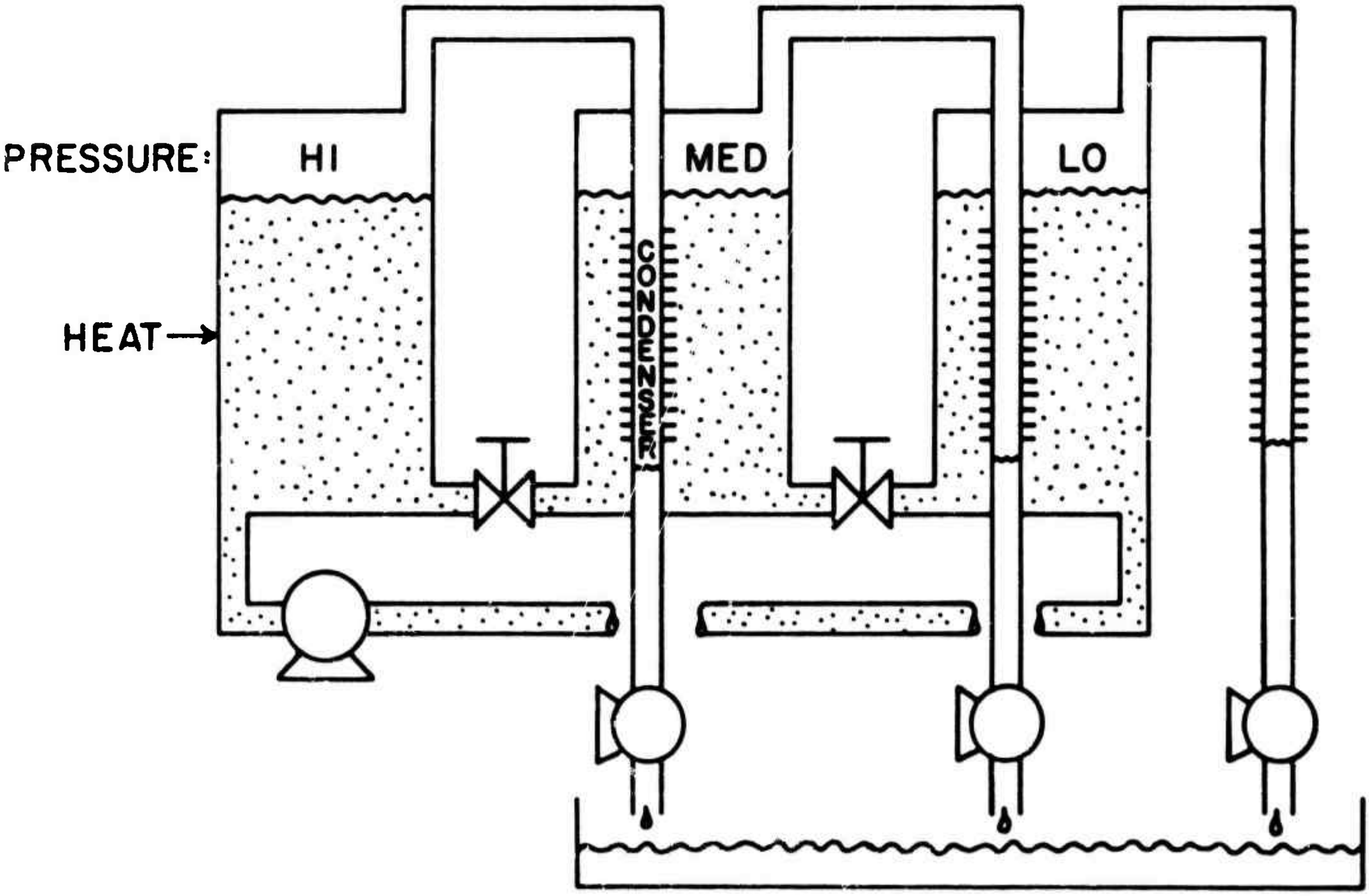


Figure 5. Schematic of multiple-effect evaporator.

2.5 Heat Pump

DESCRIPTION

Fig. 6 shows a schematic of a heat pump system. The condenser of the heat pump is placed in the salt water. The heat from the condenser causes vapors to be generated. The evaporator of the heat pump removes heat from the vapors causing them to condense. A pump on the exit keeps the system pressure low so that the water condenses at a low temperature.

PERFORMANCE

	Brackish Water	Sea Water
Mechanical Energy (Btu/lb)	50-180	60-200
(kJ/kg)	120-400	90-300
Recovery (%)	80-90	70-80
Product Salt Concentration (ppm)	0	0

ADVANTAGES

1. can produce chilled water if condenser heat is rejected to the ambient environment rather that the salt water
2. high water recovery

DISADVANTAGES

1. not as efficient as a vapor-compression system (see next section)
2. more complex than a vapor-compression system

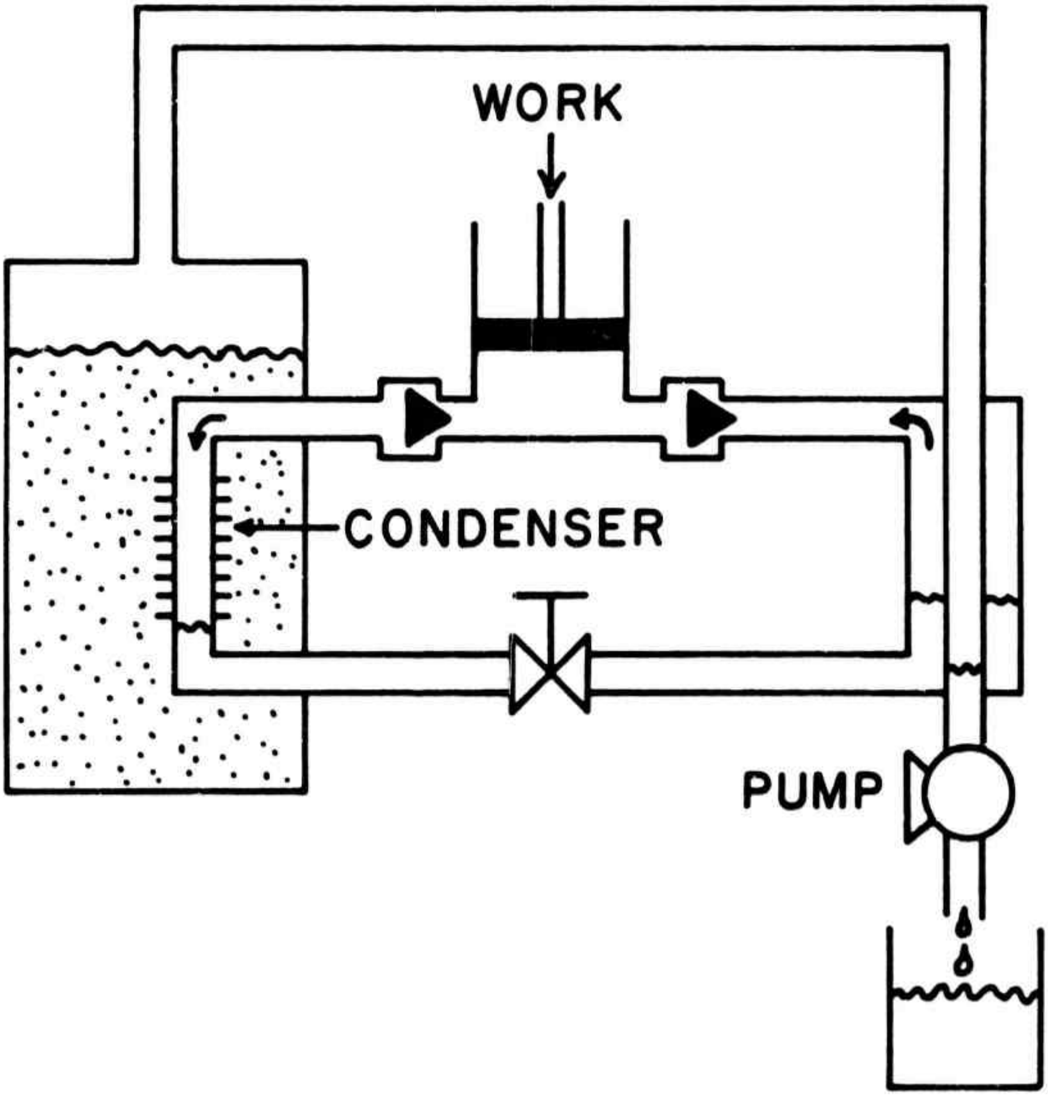


Figure 6. Schematic of heat pump.

2.6 Vapor-Compression

DESCRIPTION

Fig. 7 shows a schematic of a vapor-compression system. A compressor pulls a vacuum on the salt water causing it to generate vapors. These vapors are compressed and liquefy in a condenser. The condenser is placed in the salt water so that the latent heat of condensation causes further water vapors to be generated. A pump on the exit line maintains the system at a low pressure so that evaporation and condensation occur at low temperatures.

PERFORMANCE

	Brackish Water	Sea Water
Mechanical Energy (Btu/lb)	35-120	40-130
(kJ/kg)	80-275	90-300
Recovery (%)	90-95	70-90
Product Salt Concentration (ppm)	0	0

ADVANTAGES

1. high water recovery
2. energy efficient
3. can produce chilled water if pressurized vapors are redirected to a condenser which rejects heat to the ambient environment rather than the salt water

DISADVANTAGES

1. complex mechanical equipment required

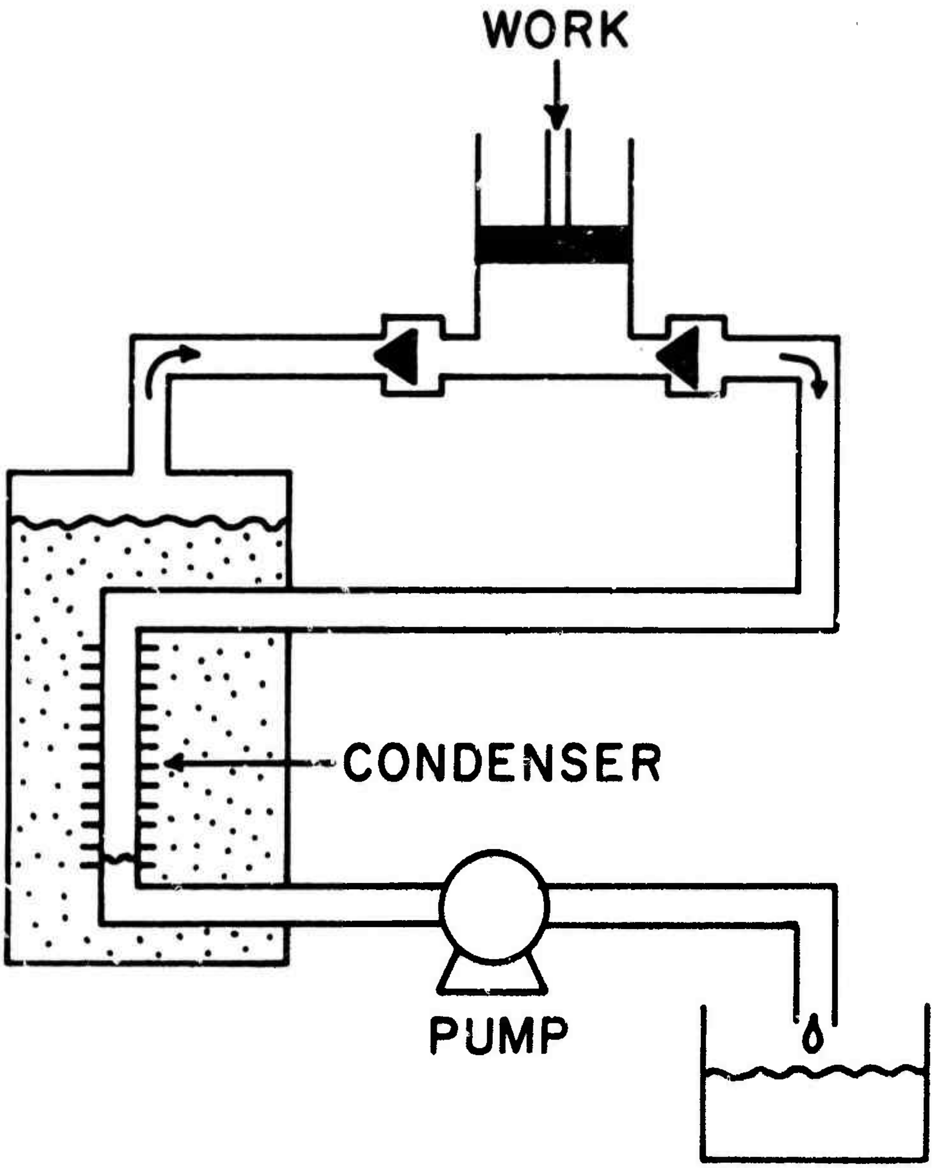


Figure 7. Schematic of vapor-compression.

2.7 Reverse Osmosis (Without Energy Recovery)

DESCRIPTION

Fig. 8 shows a schematic of reverse osmosis desalination where energy recovery is not employed. Salt water is pumped through a semipermeable membrane which allows water to pass through it while rejecting most of the salt. The waste, high-pressure water is throttled through a valve.

PERFORMANCE

	Brackish Water	Sea Water
Mechanical Energy (Btu/lb)	15-20	20-40
(kJ/kg)	35-45	45-90
Recovery (%)	50-75	10-30
Product Salt Concentration (ppm)	150-750	300-1500

ADVANTAGES

1. well developed in large and small sizes
2. low energy requirement

DISADVANTAGES

1. low recovery of water
2. after first use, proper maintenance of membrane in damp condition is critical

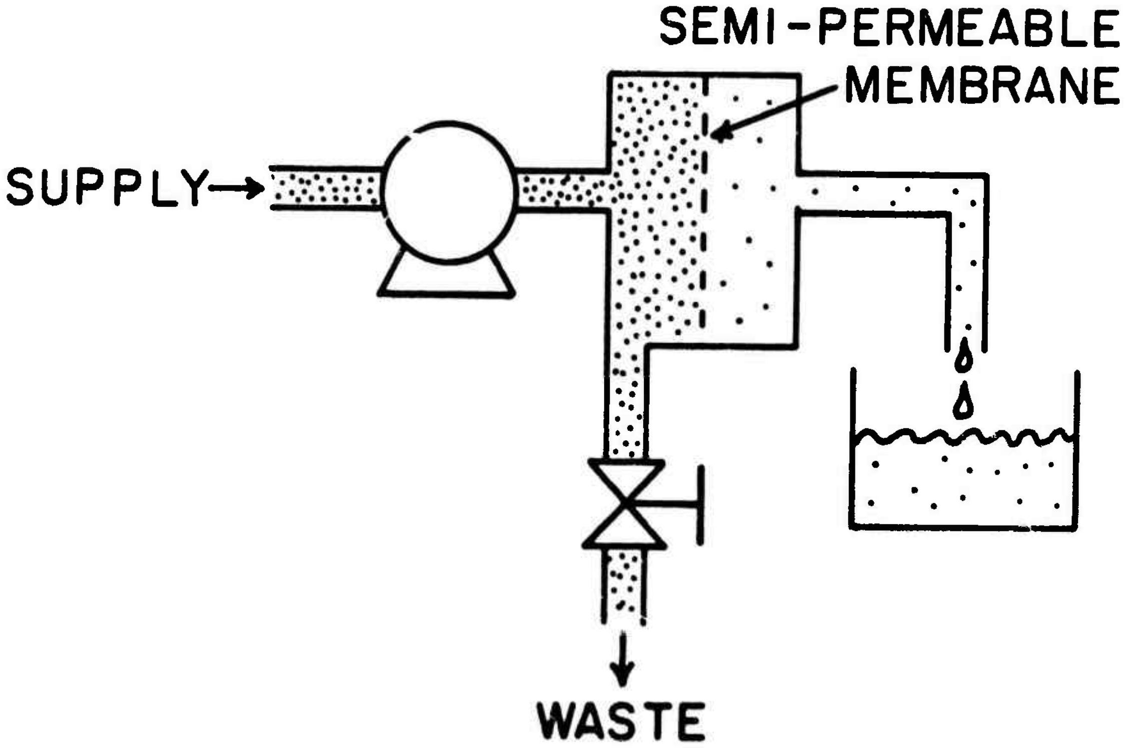


Figure 8. Schematic of reverse osmosis without energy recovery.

2.8 Reverse Osmosis (With Energy Recovery)

DESCRIPTION

Fig. 9 shows a schematic of a reverse osmosis unit with energy recover. Salt water is pumped through a semipermeable membrane which allows water to pass through it while rejecting most of the salt. The waste, high-pressure water is passed through a hydraulic motor which returns mechanical energy back to the pump.

PERFORMANCE

	Brackish Water	Sea Water
Mechanical Energy (Btu/lb)	5-8	8-10
(kJ/kg)	12-20	20-25
Recovery (%)	50-75	10-30
Product Salt Concentration (ppm)	150-750	300-1500

ADVANTAGES

1. very high energy efficiency

DISADVANTAGES

1. energy recovery device adds some complexity and expense
2. energy recovery limits the number of pump suppliers since very few manufacturers incorporate this feature

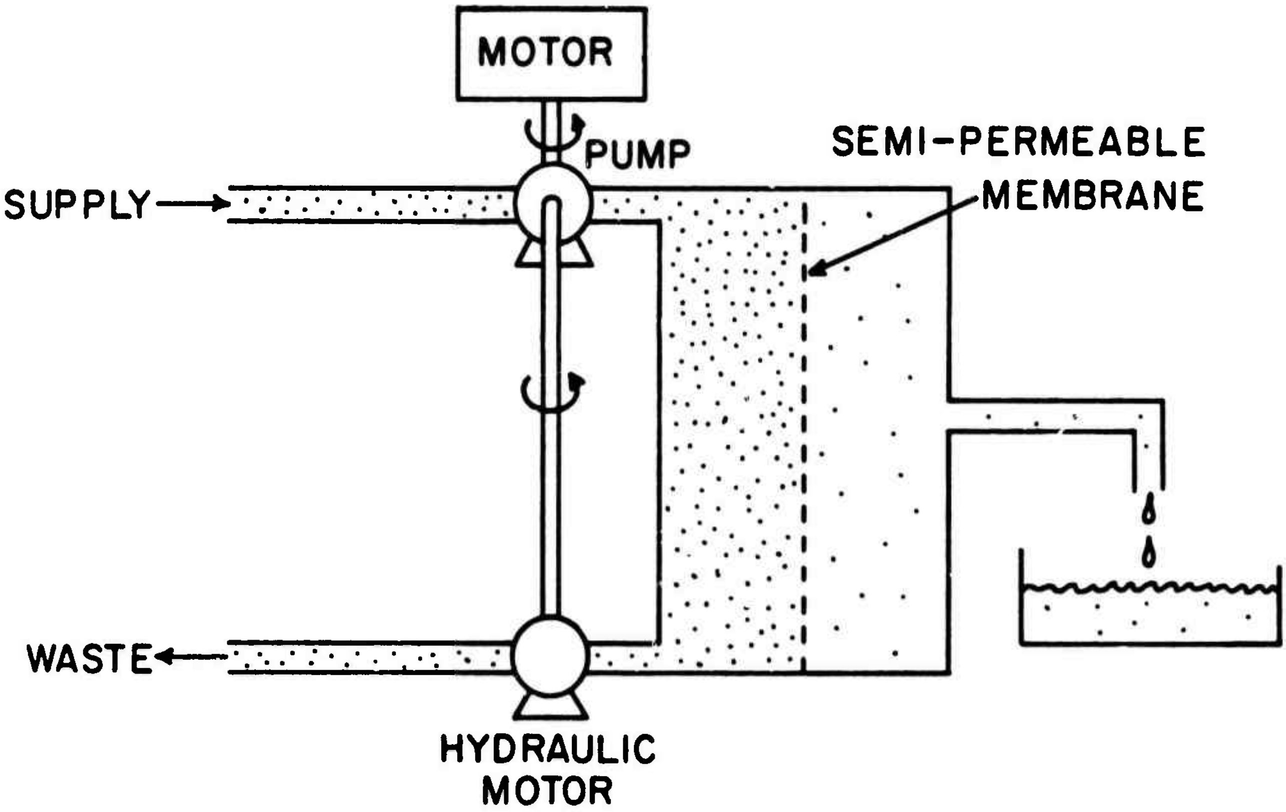


Figure 9. Schematic of reverse osmosis with energy recovery.

2.9 Electrodialysis

DESCRIPTION

Fig. 10 shows a schematic of electrodialysis desalination equipment. Cation- and anion-selective (abbreviated "C" and "A" in Figure 10) membranes are placed between a cathode and an anode. The applied voltage causes the cations to migrate to the cathode and the anions to migrate to the anode. However, cations can pass only through cation-selective membranes and anions can pass only through anion-selective membranes. The net effect is to cause salt to be concentrated in some regions and diluted in other regions.

PERFORMANCE

	Brackish Water	Sea Water
Electrical Energy (Btu/lb)	50-100	300-500
(kJ/kg)	115-230	700-1200
Recovery (%)	40-60	40-60
Product Salt Concentration (ppm)	250-1000	500-1500

ADVANTAGES

1. no moving parts

DISADVANTAGES

1. high energy requirement

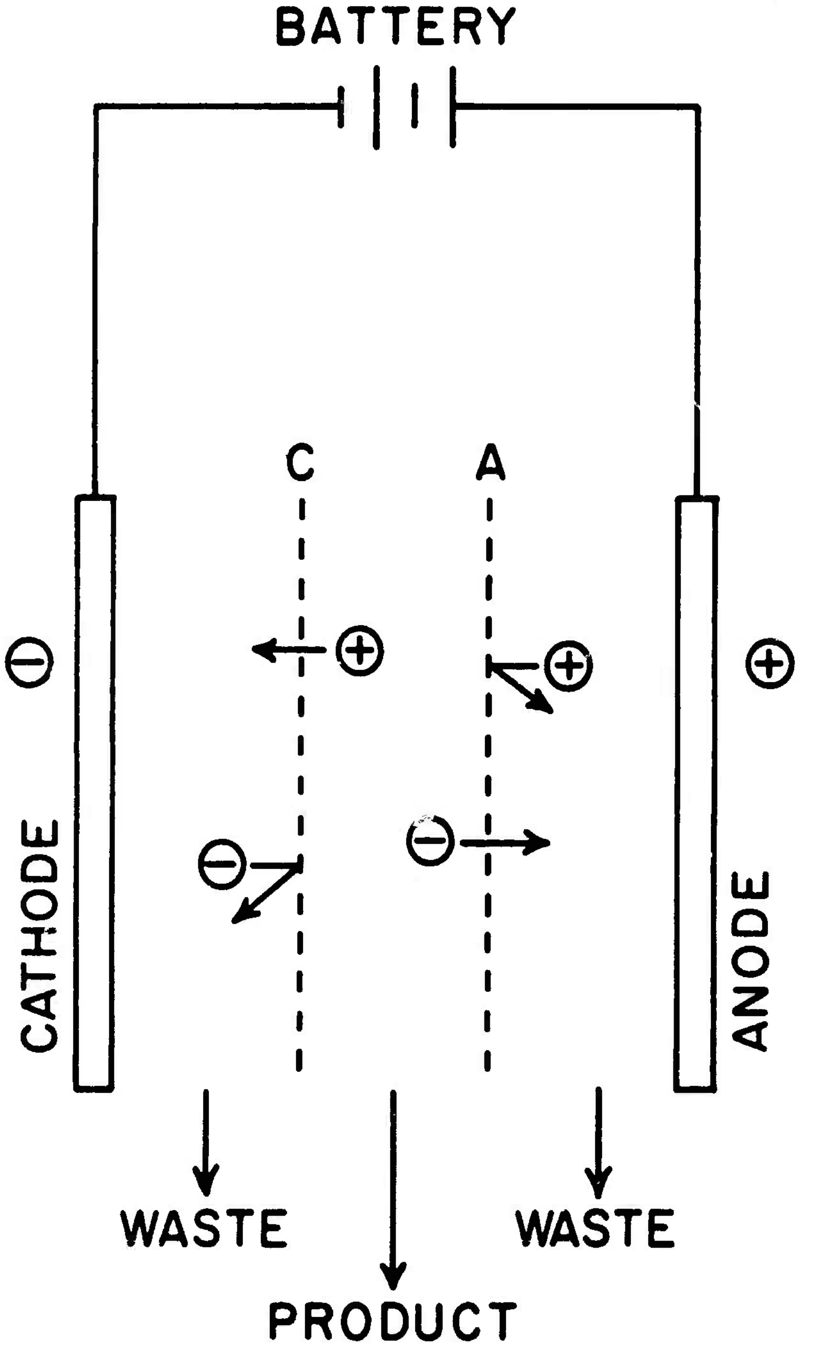


Figure 10. Schematic of electrodialysis.

2.10 Ion Exchange

DESCRIPTION

Fig. 11 shows a schematic of ion exchange desalination equipment. The salt water is passed through a weak base anion exchange resin which exchanges bicarbonate for chloride. In the weak acid cation exchange resin, hydrogen ions are exchanged for sodium ions which causes carbonic acid to be formed. The carbonic acid is adsorbed by the final weak base anion exchanger. To regenerate the system, ammonia is used to regenerate the first weak base anion exchanger and sulfuric acid is used to regenerate the weak acid cation exchanger. The flow is reversed in the next cycle.

PERFORMANCE

	Brackish Water	Sea Water
Water/Regeneration Chemicals (lb/lb)	20-25	5-8
(kg/kg)	20-25	5-8
Recovery (%)	100	100
Product Salt Concentration (ppm)	50-200	100-500

ADVANTAGES

1. no moving parts (if gravity fed)

DISADVANTAGES

1. logistics difficulty is supplying the chemicals

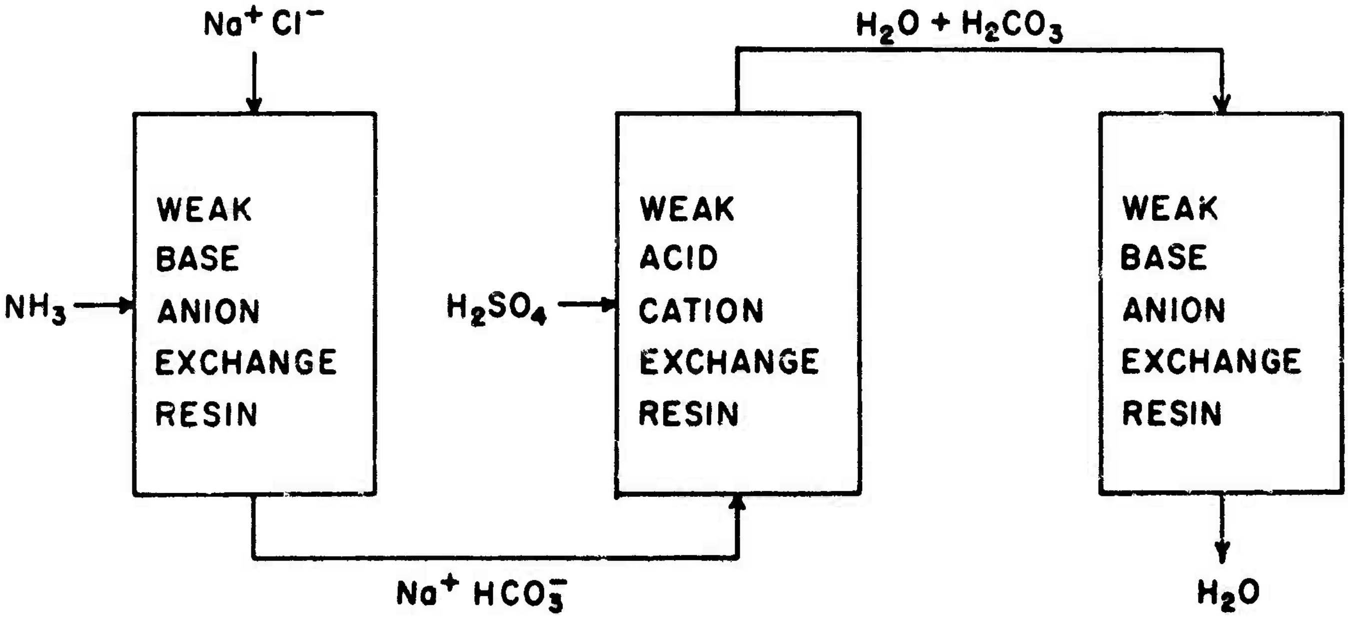


Figure 11. Schematic of ion exchange.

3. SUMMARY

Table 3 shows a summary of the performance of the desalination options. Although each option requires that the energy be in a particular form, the energy may be initially supplied in any form and then converted to the desired form. It was assumed that the conversion efficiencies were as follows:

Electrical to Heat = 100%

Work to Heat = 100%

Electrical to Work = 70%

Work to Electrical = 70%

Heat to Work = 25%

The option with the lowest energy requirement is reverse osmosis with energy recovery. The penalty for this high energy efficiency is that only a fraction of the salt water is recovered as potable water and the salt concentration in the product is fairly high. The Public Health Service recommends that the salt concentration of drinking water not excede 500 ppm.[3] This guideline can be met fairly easily if brackish water is the water source. It may be more difficult to meet if sea water is the water source.

TABLE 3. Performance Comparison of 10 Desalination Options Utilizing Brackish and Sea Water

	Heat (Btu/lb)	Work (Btu/lb)	Elec (Btu/lb)	Recov (%)	Salt (ppm)
Brackish Water					
1. Simple Distillation	1000	1000	1000	92	0
2. Membrane Dist (Single)	115	115	115	9	0
3. Membrane Dist (Multiple)	150	150	150	75	0
4. Multiple-Effect Evap	333	333	333	92	0
5. Heat Pump	460	115	165	85	0
6. Vapor-Compression	312	78	112	92	0
7. RO (w/o Energy Recov)	72	18	26	62	450
8. RO (w/ Energy Recov)	28	7	10	62	450
9. Electrodialysis	428	107	75	50	625
10. Ion Exchange	-	-	-	100	125
Sea Water					
1. Simple Distillation	1000	1000	1000	85	0
2. Membrane Dist (Single)	150	150	150	9	0
3. Membrane Dist (Multiple)	225	225	225	45	0
4. Multiple-Effect Evap	333	333	333	85	0
5. Heat Pump	520	130	185	75	0
6. Vapor-Compression	340	85	121	80	0
7. RO (w/o Energy Recov)	120	30	43	20	900
8. RO (w/ Energy Recov)	36	9	13	20	900
9. Electrodialysis	2284	571	400	50	1000
10. Ion Exchange	-	-	-	100	300

4. EVALUATION OF OPTIONS

There are a number of characteristics of the desalination options that will determine the military usefulness. These characteristics are briefly described below.

1. Energy - It is important to minimize energy consumption because in all likelihood the energy will be supplied from fuel, a precious commodity in battle. The only circumstance where this consumption may not be important is if waste sources of heat are employed.

2. Recovery - It is important that a large fraction of the salt water be converted to potable water if the desalination is performed on the move, such as in a vehicle. This high recovery will minimize the size of storage tanks and the weight that must be carried. If the desalination is performed at the water source, a high recovery will be less important.

3. Purity - The concentration of salt in the water must be low enough that it can be consumed for an extended period of time.

4. Logistics - It is important that the desalination method not impose a logistic burden on the supply chain.

5. Weight - The weight should be minimized for the desalination unit. This factor is very critical if the unit must be carried by a soldier, it is fairly important if it is vehicle mounted, and is less important if it is employed at a fixed installation.

6. Volume - The desalination unit should not take up much space. This criterion is particularly important if the unit is carried by a soldier, fairly important if it is vehicle mounted, and less important if the unit is employed at a fixed installation.

7. Cost - The cost should be minimal to ensure that the desalination unit is widely available. If the unit is to be carried by a soldier, it may be necessary to pay a premium price for the light weight.

8. Simplicity - Simple devices tend to be more reliable, which is important in minimizing maintenance overhead.

9. Control - It is important that the unit be able to function with minimal attention by soldiers since they have many other duties to perform.

10. NBC Removal - It is helpful if nuclear, biological, and chemical (NBC) contaminants are eliminated or reduced through the desalination process. It should be noted that very little is known about the ability of desalination methods to remove NBC contaminants.

11. Chilled Water - Compared to hot water, chilled water is more readily consumed in the quantities necessary to avoid dehydration.[2] Although this factor is not a major consideration, some desalination technologies may more easily lend themselves to producing chilled water than others.

These characteristics can be evaluated for each desalination option by employing a rating scheme. Each option can be assigned a rating as indicated below:

0 = Excellent
1 = Very Good
2 = Good
3 = Fair
4 = Poor
5 = Very Poor
* = Unacceptable

A rating of unacceptable prevents the option from being considered as viable.

A score can be determined for each option by summing the product of the rating and a weight factor.

$$\text{Score} = W_1 R_1 + W_2 R_2 + \ldots + W_{11} R_{11} \qquad (2)$$

where

W = Weight
R = Rating

The weight assigned to each characteristic is determined by the scenario in which the desalination equipment is employed. A number of likely scenarios are described in the following sections.

The "best" solution according to this type of analysis is the one with the lowest score. The solution determined by this method should be viewed only as an option worthy of further study. To verify that the solution is truly workable requires further in-depth analysis.

4.1 Mobile Vehicle, Waste Heat

Some of the energy released from the combustion of fuel in motor vehicles is converted into work which propels the vehicle. The remaining energy is lost as heat. Some of the heat exits in the exhaust, some is lost to the water that cools the engine, and some is lost directly to the air that contacts the hot engine. Figure 12 shows an energy balance for some common military vehicles.[5] Between 28% and 35% of the energy is converted to work. The remaining energy is lost as heat. In diesel engines (which power the HMMWV, 5-Ton, and M2/M3), approximately 25% of the energy is lost to the engine coolant: the remaining heat is lost in the exhaust (about 30%) and by direct heating of air which contacts the engine (about 15%)[4]. The turbine engine which powers the M1 tank has a different energy split with much more energy being lost out the exhaust (about 50%) and much less being lost to the coolant (about 8%).

The heat which is lost directly to the air is not recoverable. However, the heat in the coolant and the exhaust can be recovered for use in separating water from salt. Table 4 shows the weighting scheme for using waste heat from a mobile vehicle to perform the separation. Energy usage is not important. however, there is a high premium placed on a high recovery in order to minimize the amount of water which must be carried while the vehicle is moving. There is also a fairly high premium placed on a small volume and weight.

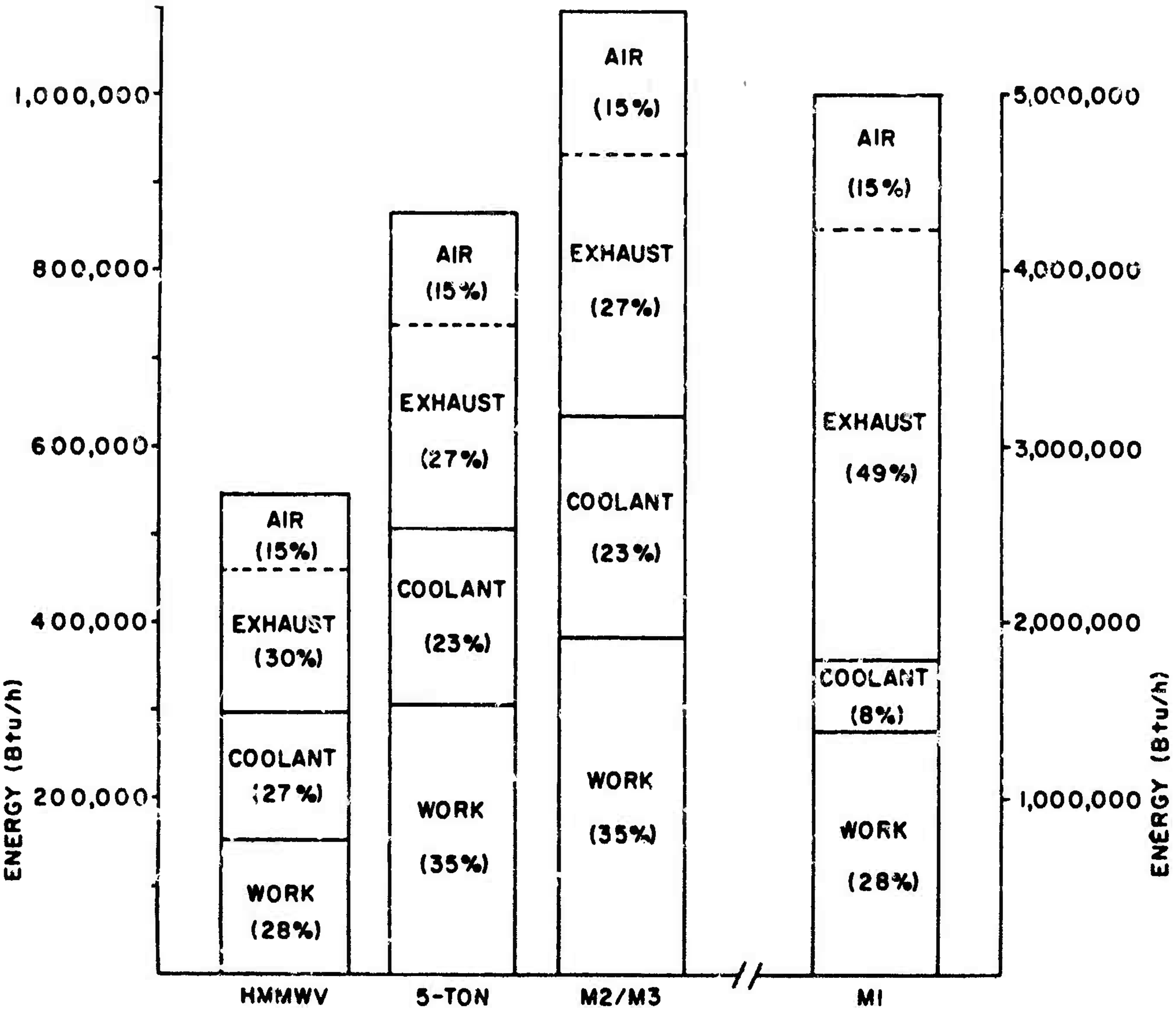


Figure 12. Energy balance in four military vehicles.

TABLE 4. Scores for Desalination Options in a Mobile Vehicle, Waste Heat Scenario

WEIGHT	Simple Distillation	Membrane Dist (Single)	Membrane Dist (Multiple)	Multiple-Effect Evap	Heat Pump	Vapor-Compression	RO (w/o Energy Recov)	RO (w/ Energy Recov)	Electrodialysis	Ion Exchange
0 Energy	5	2	2	3	*	*	*	*	*	0
5 Recovery	0	5	3	2	1	1	4	4	3	0
1 Purity	0	0	0	0	0	0	3	3	4	1
2 Logistics	0	0	0	0	0	0	1	1	1	*
3 Weight	2	4	4	5	5	5	2	2	2	2
3 Volume	2	4	4	5	2	2	1	1	2	1
3 Cost	1	3	3	5	5	5	2	2	3	1
4 Simplicity	1	2	3	5	4	5	1	2	3	0
4 Control	1	3	4	*	3	3	1	1	3	0
2 NBC Removal	3	3	3	3	3	3	3	3	4	5
2 Chilled Water	5	5	5	5	0	0	5	5	5	5
Number Unaccept	0	0	0	1	1	1	1	1	1	1
Score	39	94	92	91	75	79	64	68	84	33

Weight: 5 Very Important; 1 Unimportant

Rating: 0 Excellent; 5 Very Poor; * Unacceptable

Score: see equation (2)

From the analysis presented in Table 4, the option which appears the best is simple distillation. Membrane distillation is feasible, but many penalties must be paid, particularly the increased weight, size, complexity, and cost.

To recover the heat from the coolant for use in simple distillation requires a simple liquid/liquid heat exchanger. This is pictured in Figure 13. Some or all of the coolant which normally flows to the radiator would be diverted to the liquid/liquid heat exchanger where the salt water is distilled.

If waste heat were recovered from the exhaust, a gas/liquid heat exchanger would be required. This is pictured in Figure 14. If the exhaust temperature is reduced to 212°F (100°C) or cooler, water vapors resulting from the combustion of the fuel will condense. For every two gallons of fuel burned, approximately one gallon of water is generated. This water must be purified before it can be consumed. Bend Research, Inc. of Bend, Oregon is exploring this technology for the Tank and Automotive Command of Warren, Michigan.

The maximum power ratings for some military vehicles are indicated in Table 5. The percentage of maximum power used in normal operations is also indicated.

Figure 15 shows the maximum amount of water that could be desalinated from simple distillation using waste engine heat. It is assumed that the engine is operating at the percentage of maximum power indicated in Table 5. For diesel engines (HMMWV, 5-Ton, and M1/M2), the maximum amount of water which can be distilled using waste coolant heat is about 150 - 250 lb/h (70-115 kg/h).

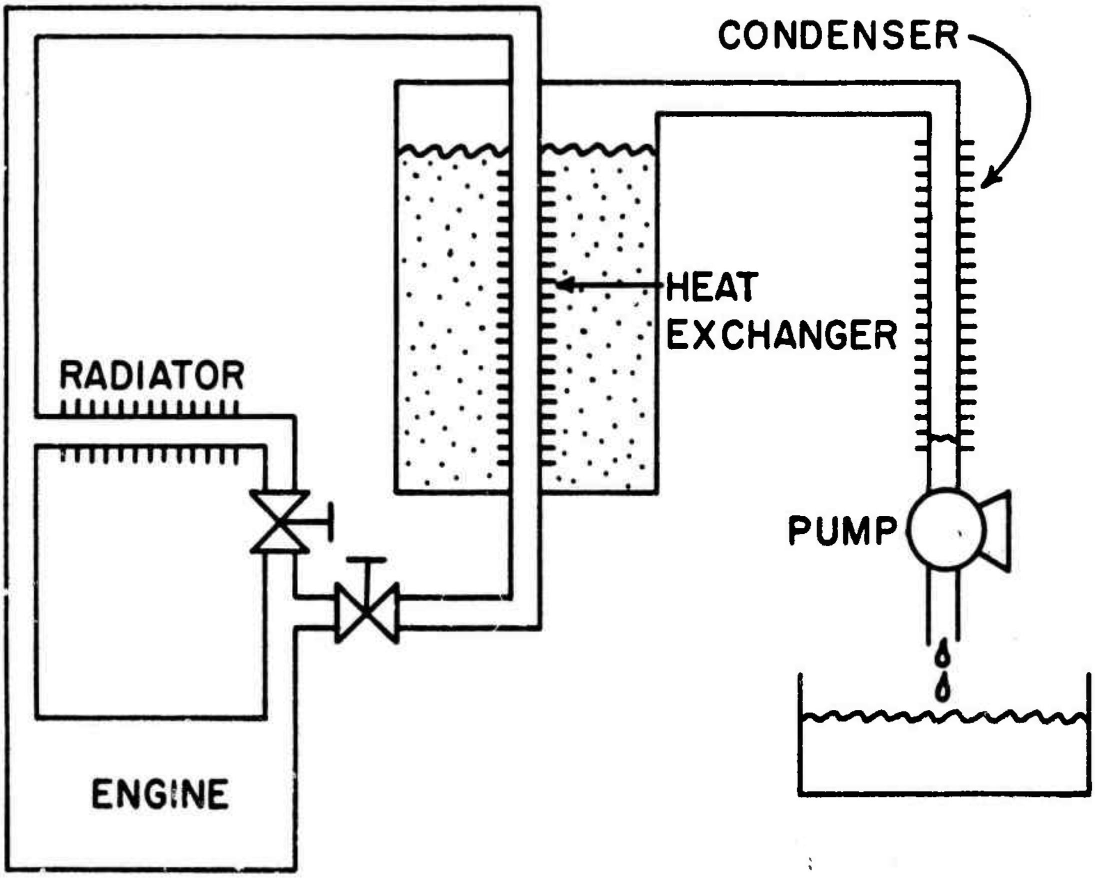


Figure 13. Simple distillation using waste coolant heat.

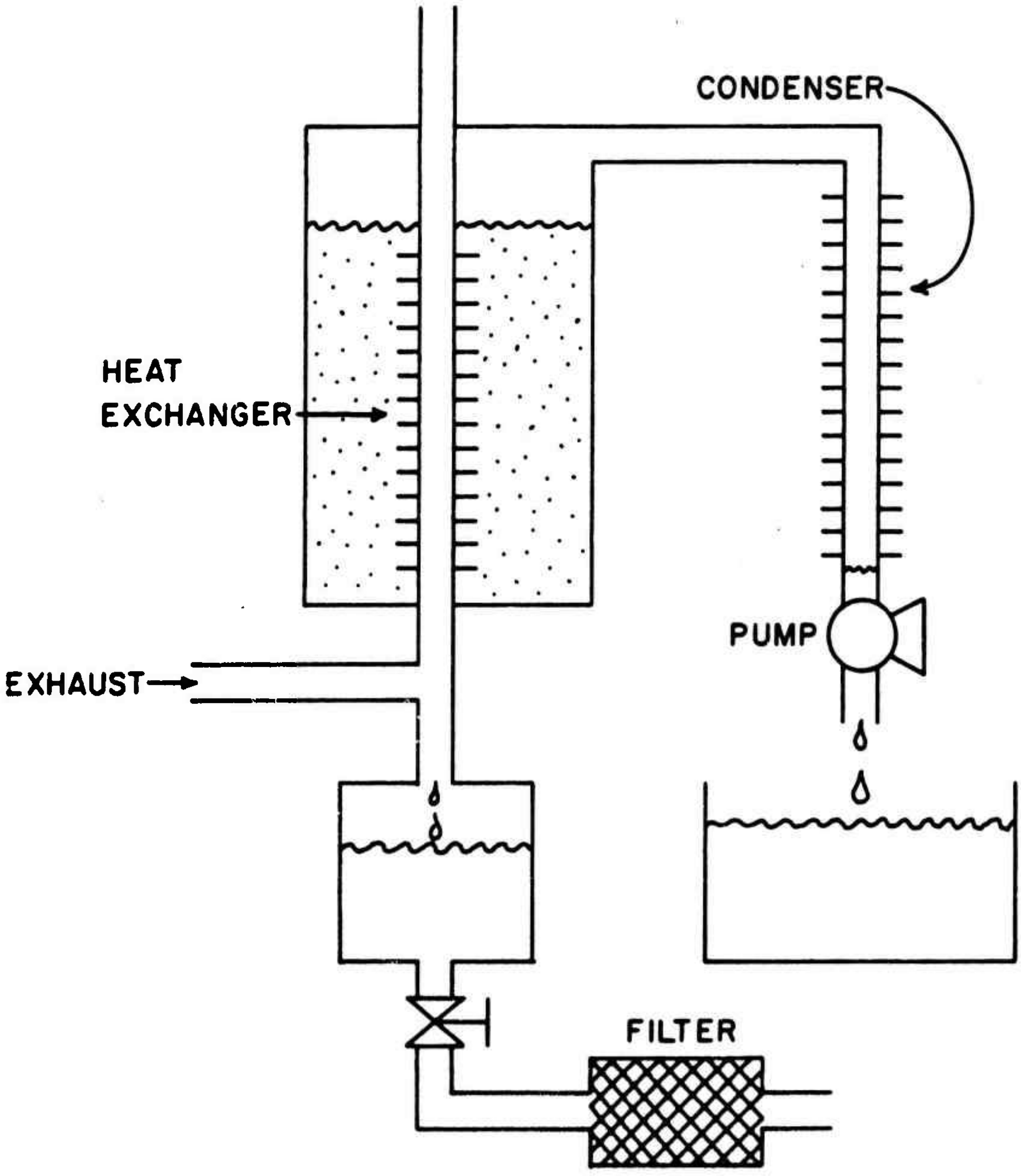


Figure 14. Simple distillation using waste exhaust heat.

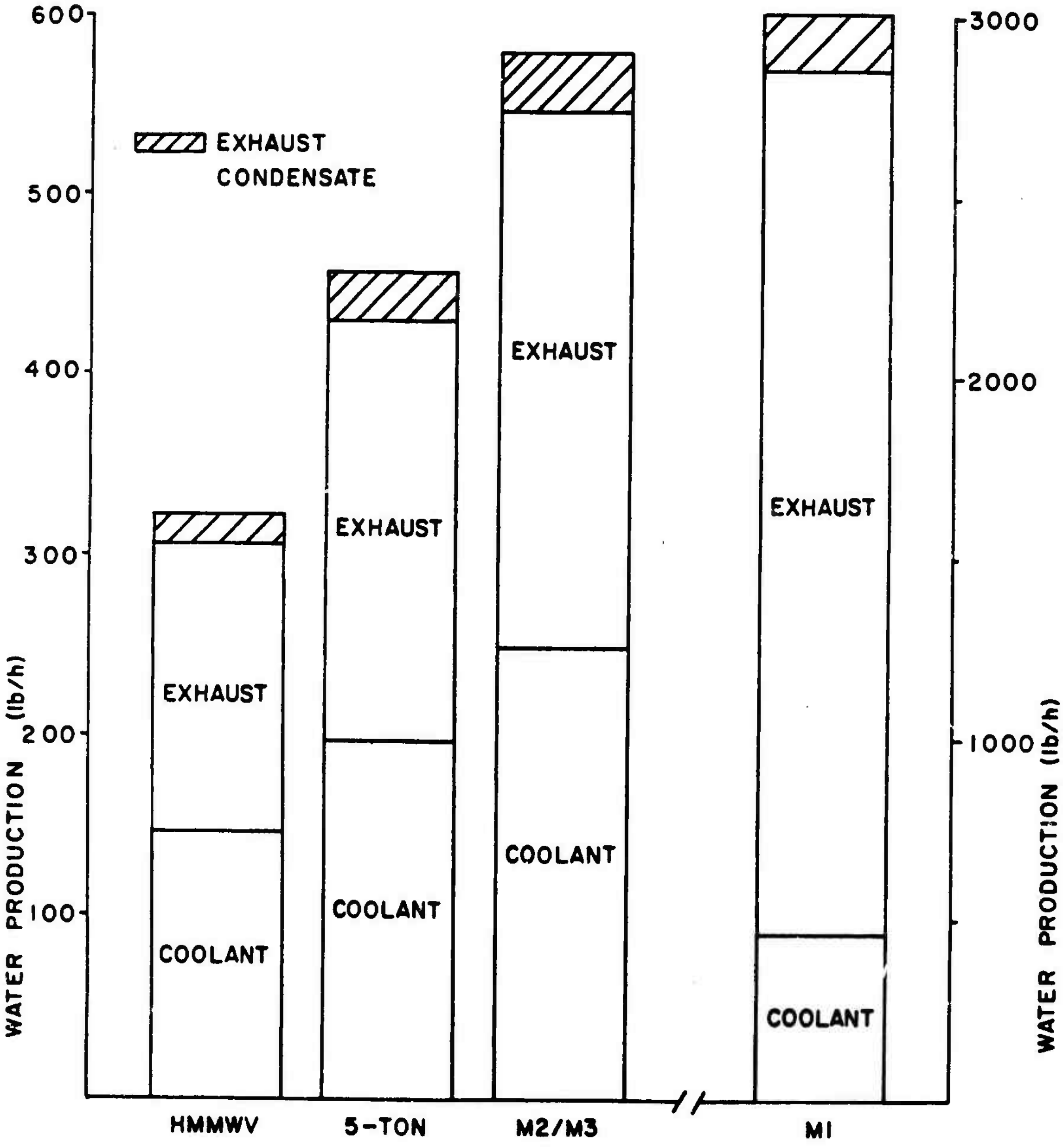


Figure 15. Maximum amount of water that can be desalinated using waste engine heat in simple distillation for four vehicles.

TABLE 5. Power Output of Four Military Vehicles

Vehicle	Maximum Power (hp)	Maximum Power (kW)	Percentage of Max Power (%)
HMMWV (High Mobility Multipurpose Wheeled Vehicle)	150	111	40
5-Ton Truck	240	179	50
M2/M3 (Infantry Fighting Vehicle/Cavalry Fighting Vehicle)	500	373	30
M1 (Abrams Tank)	1500	1119	36

A similar amount of water could be generated by using the waste heat from the exhaust. In addition, about 15-35 lb/h of water could be recovered from the exhaust condensate. From the turbine engine of the M1 tank, approximately 400 lb/h of water could be distilled using waste coolant heat and about 2500 lb/h could be distilled using waste exhaust heat. About 160 lb/h of water could be condensed from the exhaust. Because of the greater simplicity of using liquid/liquid heat exchangers compared to liquid/gas heat exchangers, it is recommended that only the waste heat in the coolant be employed for distillation.

Rather than simple distillation, membrane distillation could be employed to desalinate water. Figure 16 shows a schematic arrangement that uses waste heat from the engine coolant and Figure 17 shows a schematic arrangement that uses waste heat from the vehicle exhaust. Figure 18 shows the maximum amount of water that could be generated using single-pass membrane distillation

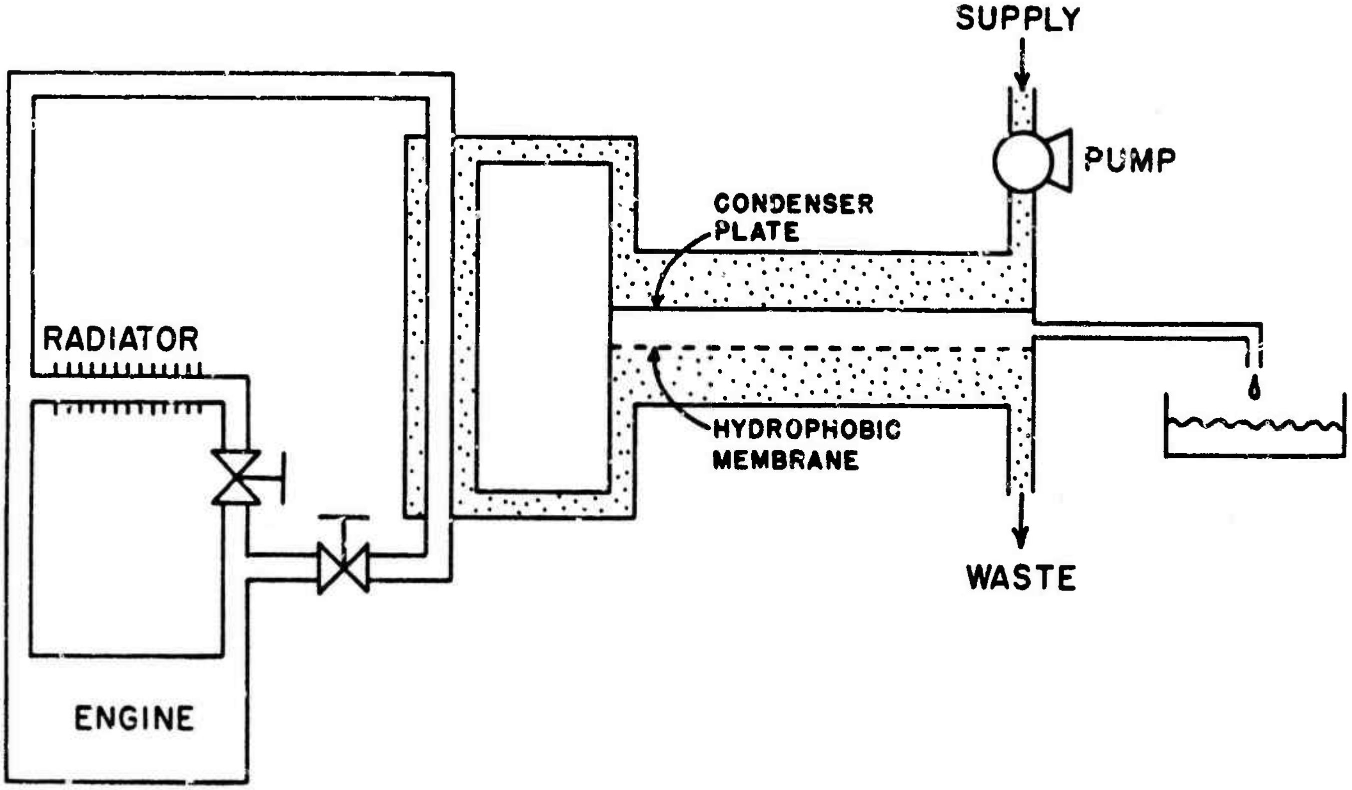


Figure 16. Schematic of membrane distillation employing waste heat from the engine coolant.

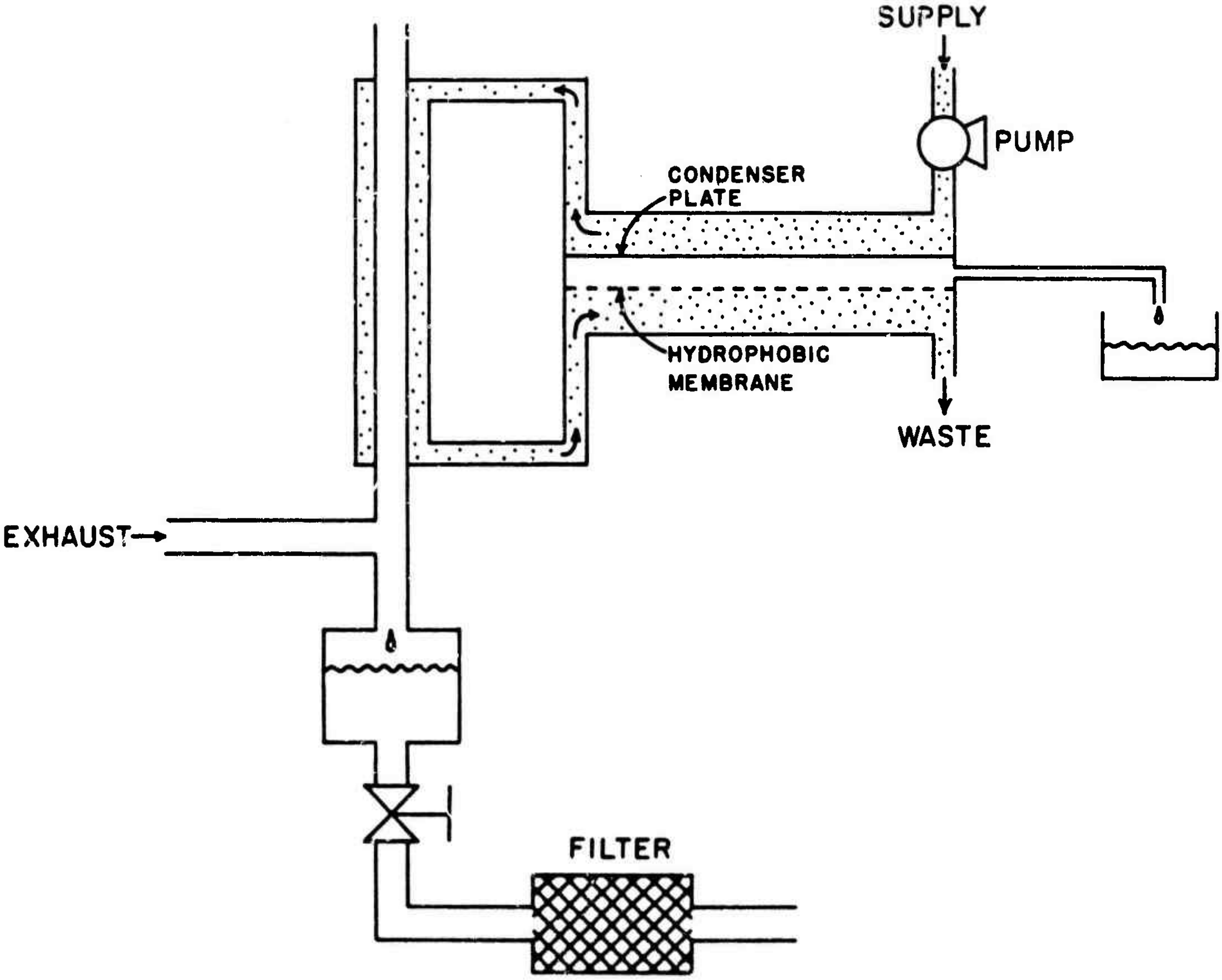


Figure 17. Schematic of membrane distillation employing waste exhaust heat.

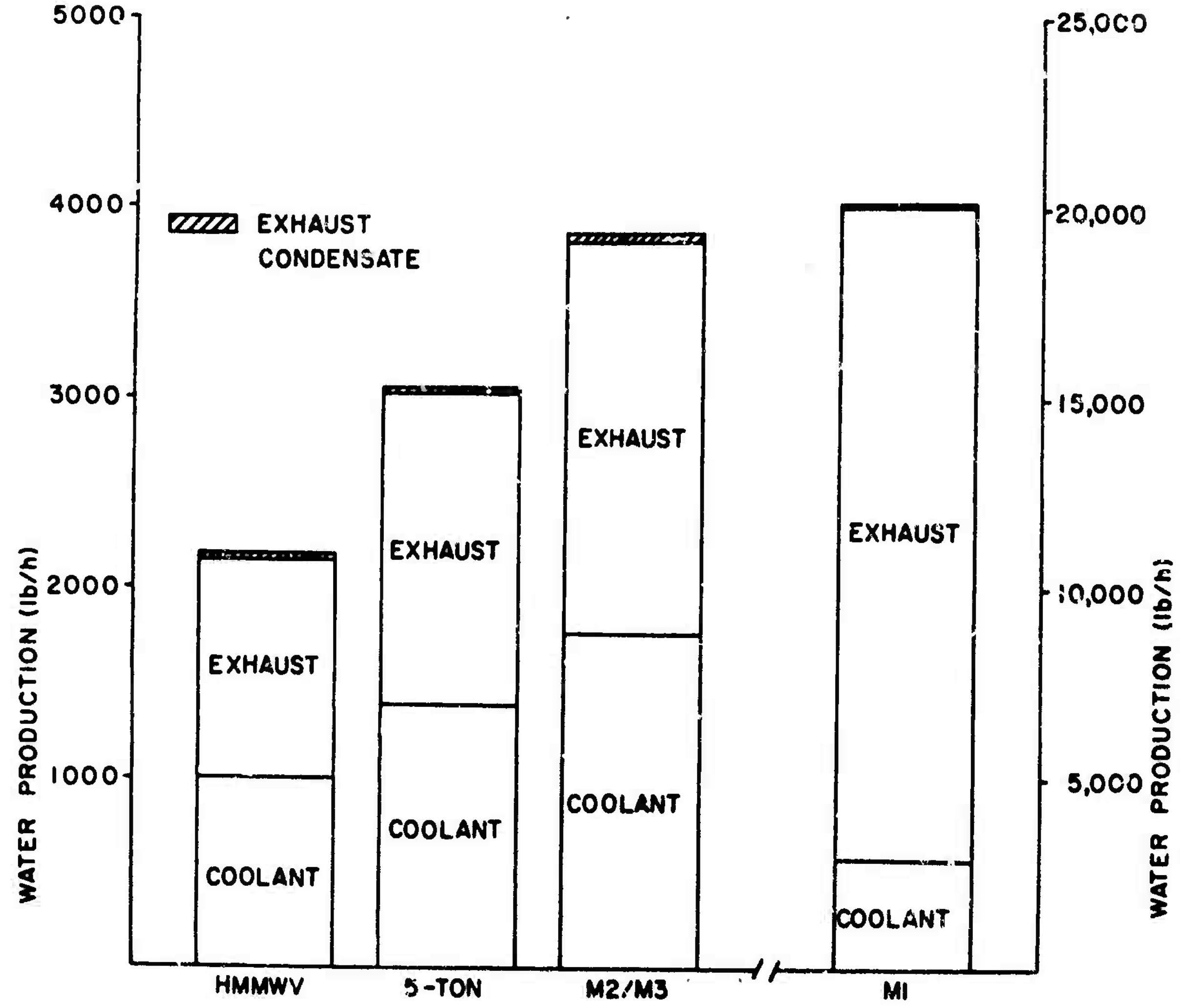


Figure 18. Maximum water production employing single-pass membrane distillation with energy supplied from waste engine heat from four vehicles.

with energy supplied from waste vehicle heat. The diesel engines (HMMWV, 5-Ton, and M2/M3) are able to produce between 1000 and 1800 lb/h of potable water using waste coolant heat. A similar amount of water could be produced from the waste heat in the exhaust. The exhaust condensate would supply between 15 and 35 lb/h of potable water. The turbine engine (M1 tank) could generate about 2900 lb/h from waste coolant heat. About 17,000 lb/h could be generated from waste exhaust heat. An additional 160 lb/h of water could be condensed from the exhaust.

The amount of water that could be produced from membrane distillation far exceeds the requirements for small groups of soldiers. The membrane unit would require additional space, weight, and expense compared to simple distillation. Further, a larger water supply storage tank would be required since the water recovery for membrane distillation is much less than that for simple distillation. For these reasons, it is recommended that simple distillation be pursued if it is desired to desalinate water using waste heat from vehicle engines.

4.2 Mobile Vehicle, Power Take-Off

It is possible to use some of the mechanical power produced by vehicles to power a desalination apparatus. The power take-off may be in the form of shaft power or electrical power. It will probably be easier to use electrical power since shaft power is less accessible. Also, the drive shaft is rotating at various speeds as the vehicle accelerates and decelerates, which will make control of the desalination device more difficult. In contrast, electrical power is easily regulated for smooth control of the desalination apparatus.

Table 6 shows the score for the various options. Energy efficiency is given a high priority since there is not a great excess of electrical power available on most vehicles. A high recovery is also very important in order to reduce the amount of water which must be carried to a minimum. A low weight and volume are fairly important, although not critical. Simplicity and ease of control are important since the device may have to be operated unattended.

Of the four which received no unacceptable ratings, reverse osmosis appears to be the best. It is unclear whether the additional capital expense of putting in energy recovery is justified. This must be analyzed for the specific vehicle which is being considered. If there is not a great deal of excess electrical power available, then energy recovery is necessary.

TABLE 6. Scores for Desalination Options in a Mobile Vehicle, Power Take-off Scenario

WEIGHT	Simple Distillation	Membrane Dist (Single)	Membrane Dist (Multiple)	Multiple-Effect Evap	Heat Pump	Vapor-Compression	RO (w/o Energy Recov)	RO (w/ Energy Recov)	Electrodialysis	Ion Exchange
4 Energy	*	*	*	*	4	3	1	0	*	0
5 Recovery	0	5	3	2	1	1	4	4	3	0
1 Purity	0	0	0	0	0	0	3	3	4	1
2 Logistics	0	0	0	0	0	0	1	1	1	*
3 Weight	2	4	4	5	5	5	2	2	2	2
3 Volume	2	4	4	5	2	2	1	1	2	1
3 Cost	1	3	3	5	5	5	2	2	3	1
4 Simplicity	1	2	3	5	4	5	1	2	3	0
4 Control	1	3	4	*	3	3	1	1	3	0
2 NBC Removal	3	3	3	3	3	3	3	3	4	5
2 Chilled Water	5	5	5	5	0	0	5	5	5	5
Number Unaccept	1	1	1	2	0	0	0	0	1	1
Score	39	94	92	91	91	91	68	68	84	33

Weight: 5 Very Important; 1 Unimportant

Rating: 0 Excellent; 5 Very Poor; * Unacceptable

Score: see equation (2)

4.3 Trailer Mounted Unit, Dedicated Power Source

There may be difficulty in mounting desalination equipment directly on a vehicle due to space and power limitations. It may then be necessary to mount the equipment on a trailer which is towed by the vehicle and powered by an independent, dedicated power source.

The trailer may desalinate while the vehicle is moving or it may be placed near the source of water and desalinate while it is stationary. The weight assigned to the various characteristics depends on whether the desalination is conducted while the unit is stationary or moving.

Table 7 shows the score for desalination on the move. High recovery is very important since this will reduce the size of the supply storage vessels. In addition, simplicity and easy control are important since the unit must work reliably while unattended. Simple distillation would appear to be the best approach if heat is used as the energy source and reverse osmosis (with or without energy recovery) is a good choice if mechanical power is available.

Table 8 shows the score for desalination while the trailer is stationary. In this case, recovery is less important since it would be located near the water source. Simplicity and ease of control are also less important since it would be possible to have an operator attend to it. In this case, simple distillation is also a very attractive option. However, the disadvantages of membrane distillation are less severe, so it becomes a viable option. If mechanical energy were used as the source of power,

TABLE 7. Scores for Desalination Options in a Trailer Mounted Unit (Mobile), Dedicated Power Scenario

WEIGHT	Simple Distillation	Membrane Dist (Single)	Membrane Dist (Multiple)	Multiple-Effect Evap	Heat Pump	Vapor-Compression	RO (w/o Energy Recov)	RO (w/ Energy Recov)	Electrodialysis	Ion Exchange
3 Energy	5	2	2	3	4	3	1	0	*	0
5 Recovery	0	5	3	2	1	1	4	4	3	0
1 Purity	0	0	0	0	0	0	3	3	4	1
2 Logistics	0	0	0	0	0	0	1	1	1	*
2 Weight	2	4	4	5	5	5	2	2	2	2
2 Volume	2	4	4	5	2	2	1	1	2	1
3 Cost	1	3	3	5	5	5	2	2	3	1
4 Simplicity	1	2	3	5	4	5	1	2	3	0
4 Control	1	3	4	*	3	3	1	1	3	0
2 NBC Removal	3	3	3	3	3	3	3	3	4	5
2 Chilled Water	5	5	5	5	0	0	5	5	5	5
Number Unaccept	0	0	0	1	0	0	0	0	1	1
Score	55	92	90	90	80	81	64	65	80	30

Weight: 5 Very Important; 1 Unimportant

Rating: 0 Excellent; 5 Very Poor; * Unacceptable

Score: see equation (2)

TABLE 8. Scores for Desalination Options in a Trailer Mounted Unit (Stationary), Dedicated Power Scenario

WEIGHT	Simple Distillation	Membrane Dist (Single)	Membrane Dist (Multiple)	Multiple-Effect Evap	Heat Pump	Vapor-Compression	RO (w/o Energy Recov)	RO (w/ Energy Recov)	Electrodialysis	Ion Exchange
3 Energy	5	2	2	3	4	3	1	0	*	0
1 Recovery	0	5	3	2	1	1	4	4	3	0
1 Purity	0	0	0	0	0	0	3	3	4	1
2 Logistics	0	0	0	0	0	0	1	1	1	*
2 Weight	2	4	4	5	5	5	2	2	2	2
2 Volume	2	4	4	5	2	2	1	1	2	1
3 Cost	1	3	3	5	5	5	2	2	3	1
3 Simplicity	1	2	3	5	4	5	1	2	3	0
3 Control	1	3	4	*	3	3	1	1	3	0
2 NBC Removal	3	3	3	3	3	3	3	3	4	5
2 Chilled Water	5	5	5	5	0	0	5	5	5	5
Number Unaccept	0	0	0	1	0	0	0	0	1	1
Score	48	67	71	77	69	69	46	46	62	30

Weight: 5 Very Important; 1 Unimportant

Rating: 0 Excellent; 5 Very Poor; * Unacceptable

Score: see equation (2)

then reverse osmosis appears to be the most attractive.

Both simple distillation and membrane distillation will require a burner to supply the heat. Fig. 19 shows a schematic of a burner supplying heat to a membrane distillation unit. Two common burners are the 1950 Squad Stove and the M2 Burner. The 1950 Squad Stove is rated at 5,500 Btu/h (5.8 MJ/h) and requires about 0.15 to 0.2 gal/h (0.7 to 0.9 L/h) of gasoline. The M2 Burner is rated at 64,000 Btu/h (67 MJ/h) and requires about 1.5 to 2 gal/h (6.8 to 9.0 L/h) of gasoline. Improvements are planned to fit the M2 Burner with thermoelectric elements which will allow it to generate 25-30 W of electricity to power auxiliaries.

Figure 20 shows the amount of water which could be produced from the 1950 Squad Stove and the M2 Burner using simple distillation or membrane distillation. The 1950 Squad Stove would generate about 5.5 lb/h (2.5 kg/h) of water through simple distillation and about 38 lb/h (17 kg/h) of water through membrane distillation. About 10-15 W of electrical power would be required to operate the pump that circulates water through the membrane distillation system. Advanced zinc/nickel batteries have energy densities of 32 W h/lb (70 W h/kg)[6]; thus batteries would be consumed at a rate of about 0.3-0.5 lb/h (0.14-0.23 kg/h).

The M2 Burner would generate 64 lb/h (29 kg/h) of water through simple distillation and about 450 lb/h (200 kg/h) of water through membrane distillation. About 125-150 W of electrical power would be required to operate the pump that circulates water through the membrane distillation system. Advanced zinc/nickel batteries would be consumed at a rate of

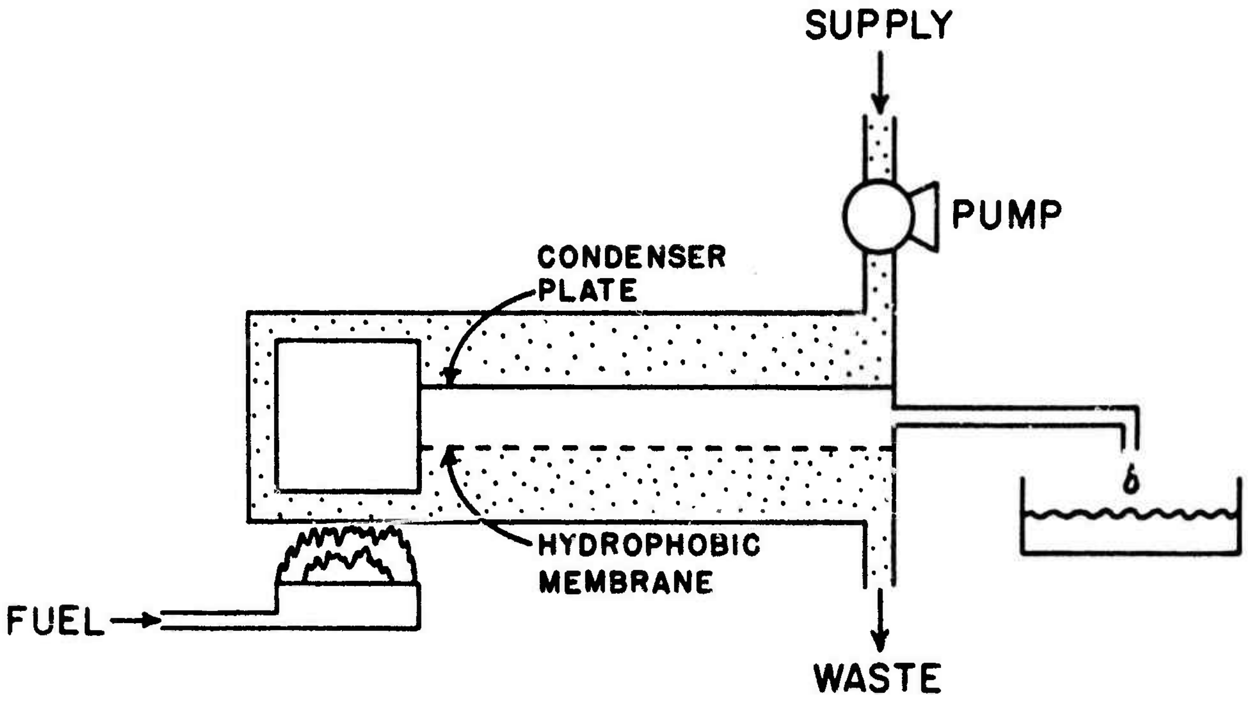


Figure 19. Burner-powered membrane distillation unit.

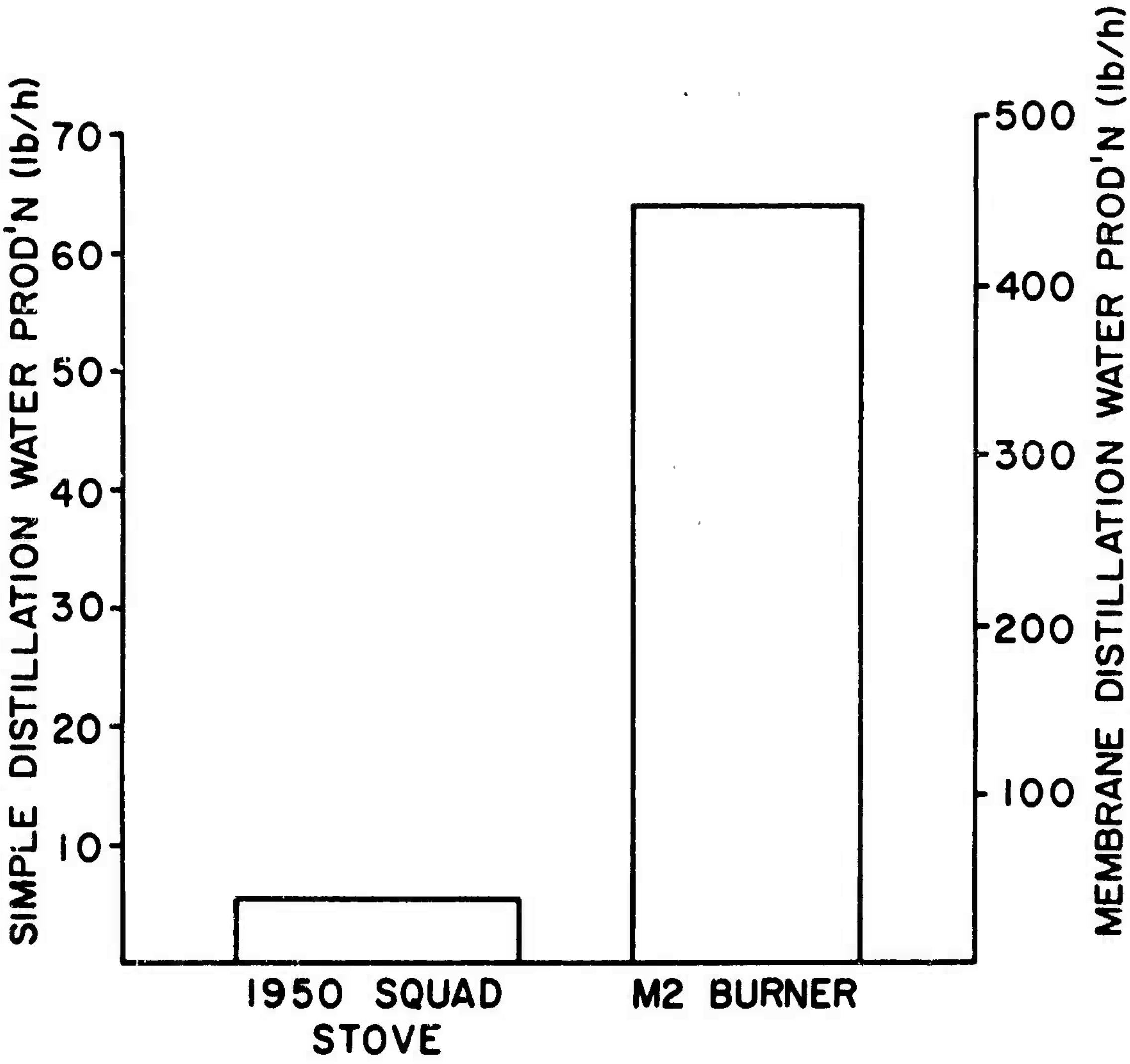


Figure 20. Water production from trailer mounted distillation equipment using standard burners.

4-4.7 lb/h (1.8-2.1 kg/h). As an alternative to batteries, the number of thermoelectric elements planned for the M2 Burner could be increased to generate the required amount of electricity.

If reverse osmosis were employed, it is possible to power the pump directly by a small internal combustion engine or to power it with a standard generator. For control purposes and the ability to use "off-the-shelf" technology, it would be desirable to power electric pumps with standard generators. Figure 21 shows the water production rates from standard generators in the 0.5 kW to 5 kW range. The water production rates are 170-1700 lb/h (75-750 kg/h) if energy recovery is employed and 65-650 lb/h (30-300 kg/h) if energy recovery is not employed.

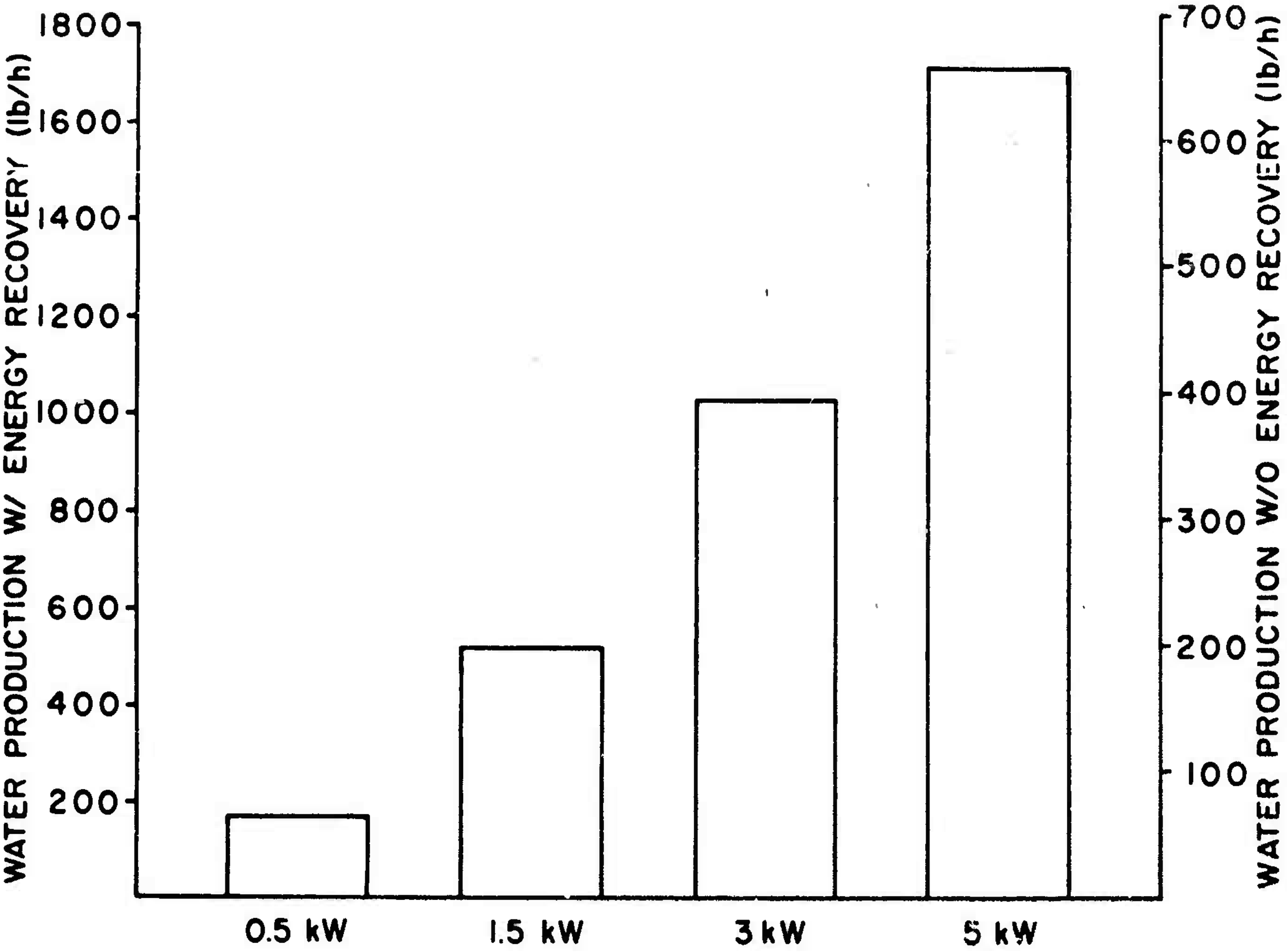


Figure 21. Water production from trailer mounted reverse osmosis unit.

4.4 Vehicle Stowed Unit, Dedicated Power Source

Since water desalination may not be required on a continuous basis, it may be desirable to develop a small, portable unit which could be stowed in a storage compartment of a vehicle. It would be used only when water is not available from other sources. A dedicated power source would provide the energy for the desalination.

Table 9 shows the rating scheme for this scenario. Of prime importance is volume since the storage compartment may be fairly small. Weight is also important since the unit should be easily moved around. Lastly, a high recovery is important since the unit may be used on the move. If heat is used for power, simple distillation appears to be the best approach. If mechanical power is used, then reverse osmosis (with or without energy recovery) appears to be viable. The main disadvantage of reverse osmosis is its low recovery of water. This disadvantage could be overcome using vapor-compression or a heat pump, but as Table 9 shows, there is a price to be paid for this high water recovery. A vapor-compression or heat pump unit will require more energy, be more complex, and weigh more than a reverse osmosis unit.

Figure 22 shows a schematic of a reverse osmosis unit (with energy recovery) powered by a Stirling engine. The Stirling engine is described in more detail in Appendix A. The engine is being developed primarily for microclimate conditioning of an individual soldier, so it incorporates a refrigerant compressor. The schematic shown in Fig. 22 shows that this compressor could be used to operate a vapor-compression refrigeration circuit in

TABLE 9. Scores for Desalination Options in a Vehicle Stowed Unit, Dedicated Power Scenario

WEIGHT	Simple Distillation	Membrane Dist (Single)	Membrane Dist (Multiple)	Multiple-Effect Evap	Heat Pump	Vapor-Compression	RO (w/o Energy Recov)	RO (w/ Energy Recov)	Electrodialysis	Ion Exchange
3 Energy	5	2	2	3	4	3	1	0	*	0
5 Recovery	0	5	3	2	1	1	4	4	3	0
1 Purity	0	0	0	0	0	0	3	3	4	1
2 Logistics	0	0	0	0	0	0	1	1	1	*
5 Weight	2	4	4	5	5	5	2	2	2	2
5 Volume	2	4	4	5	2	2	1	1	2	1
3 Cost	1	3	3	5	5	5	2	2	3	1
4 Simplicity	1	2	3	5	4	5	1	2	3	0
4 Control	1	3	4	*	3	3	1	1	3	0
2 NBC Removal	3	3	3	3	3	3	3	3	4	5
2 Chilled Water	5	5	5	5	0	0	5	5	5	5
Number Unaccept	0	0	0	1	0	0	0	0	1	1
Score	62	116	114	120	101	102	73	74	92	39

Weight: 5 Very Important; 1 Unimportant

Rating: 0 Excellent; 5 Very Poor; * Unacceptable

Score: see equation (2)

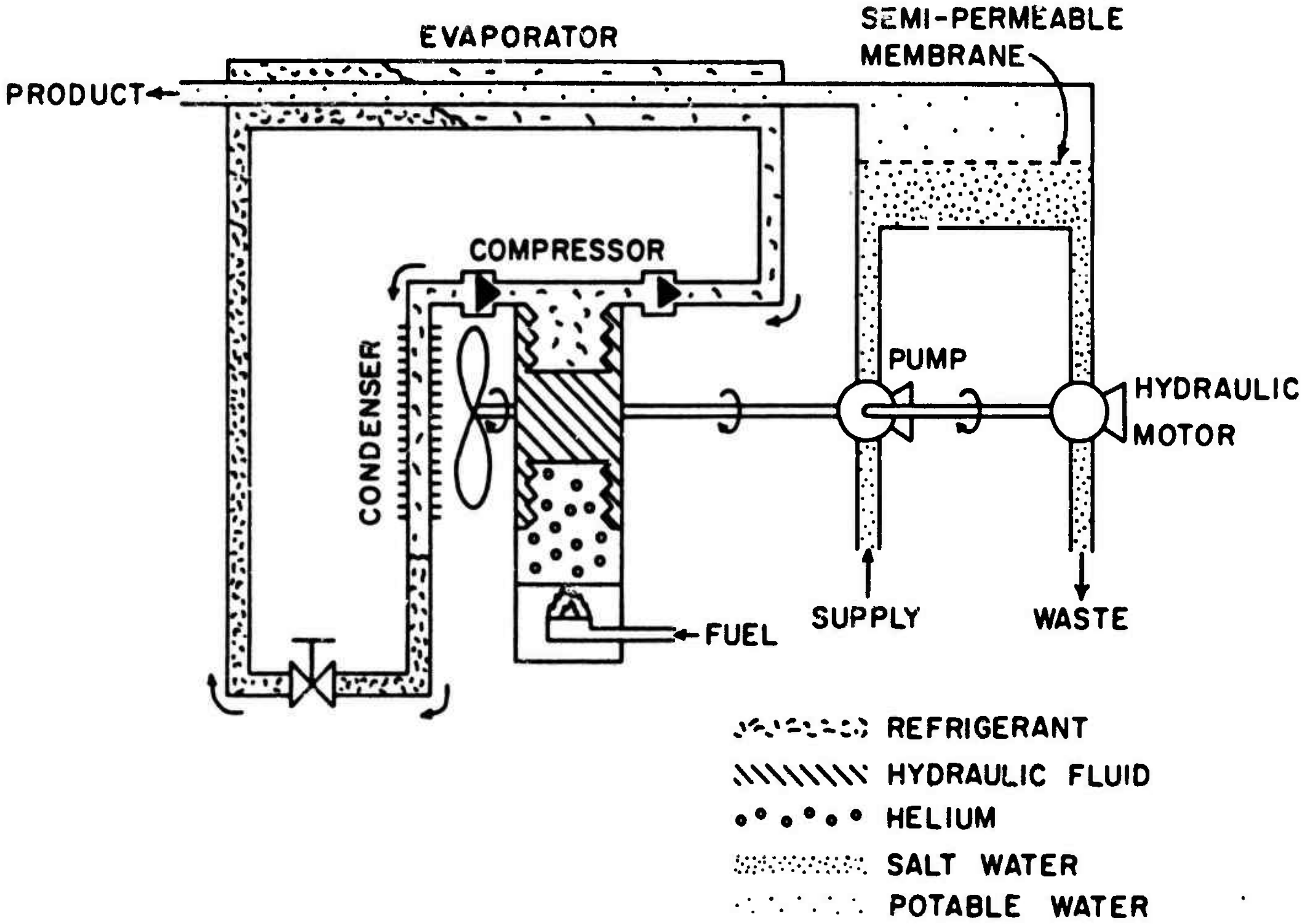


Figure 22. Stirling-powered reverse osmosis unit and water chiller.

order to cool the product water.

Figure 23 shows the amount of water which could be produced from the Stirling-powered reverse osmosis unit with energy recovery. If no energy is diverted to the refrigeration compressor, it would be possible to produce water at a rate of 88 lb/h (40 kg/h). The production rate could drop as low as 26 lb/h (12 kg/h) if desert water at 120°F (49°C) water were cooled to 70°F (21°C), which is the maximum temperature for palatable water.

Figure 24 shows a schematic of how the Stirling engine described in Appendix A may be used to power a compressor used in a vapor-compression desalination device. The compressor creates a vacuum on the salt water which causes water vapors to be generated. The compressor then increases the pressure of the vapors so that they may be condensed. The heat of condensation is rejected to the salt water in order to supply the required heat of vaporization. A pump placed on the exit line allows the whole system to operate at sub-atmospheric pressure in order that boiling can occur at a temperature well below 212°F (100°C).

Figure 25 shows that the amount of water which can be produced from the maximum power output of the Stirling engine. The water production is determined by the salt concentration in the waste stream and the temperature difference between the salt water and the condensate. Figure 25 shows that a wastewater salt concentration of 15% corresponds to water recovery of 75% from sea water and 95% from brackish water. The temperature difference between the salt water and condensate should be relatively small - about 5-10°C (9-19°F) - since the processes of

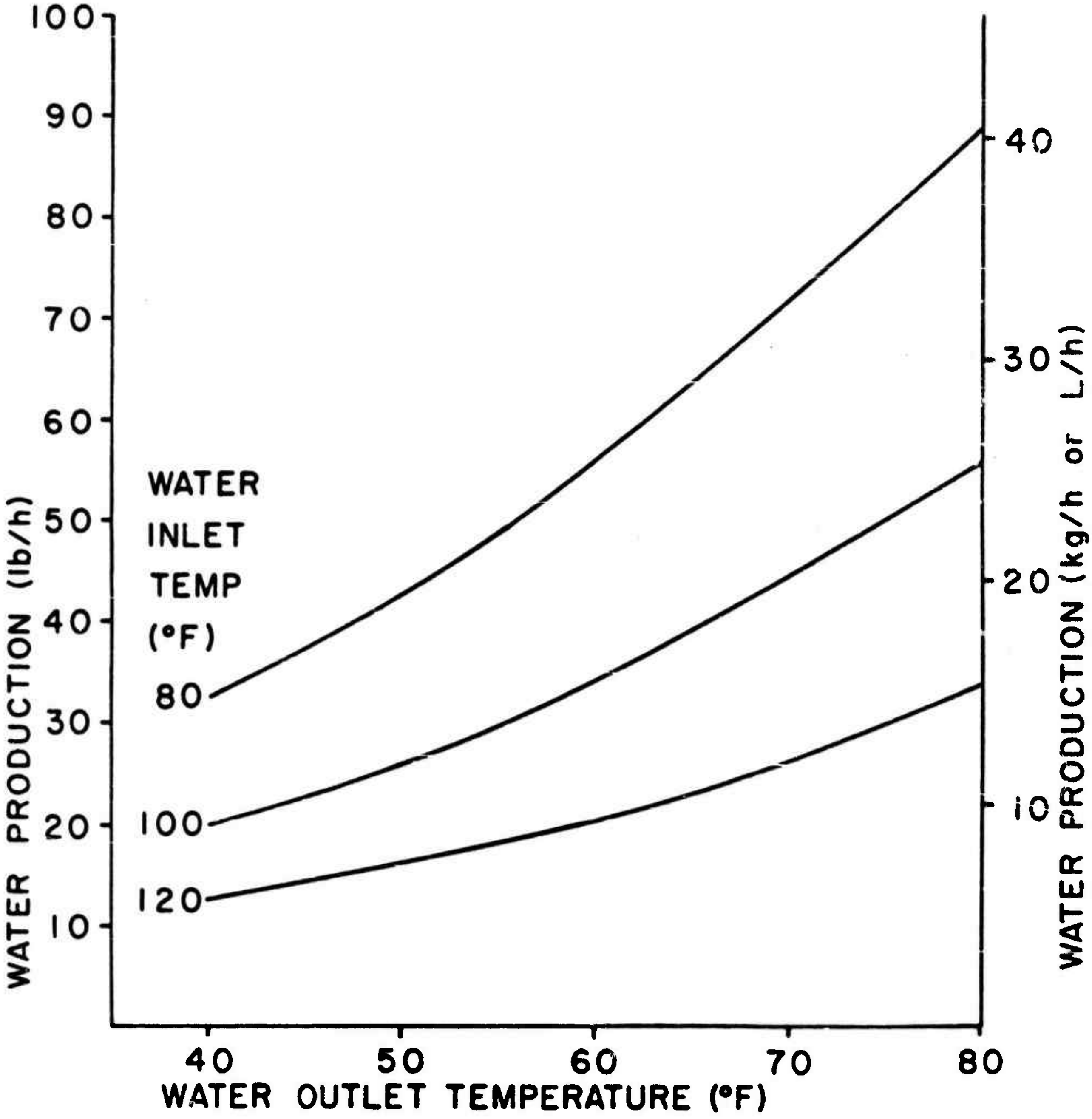


Figure 23. Water production using a Stirling-powered reverse osmosis unit and water chiller.

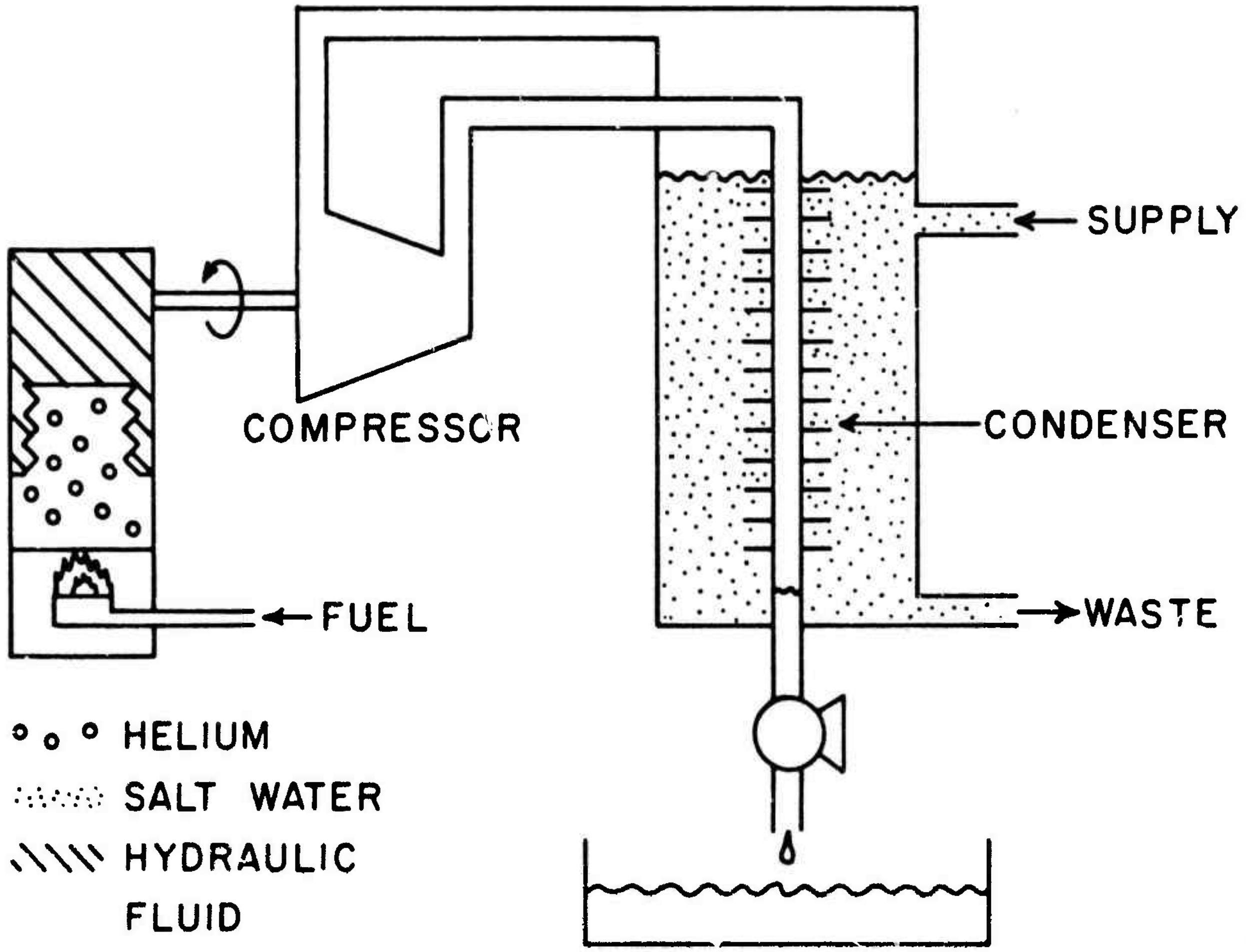


Figure 24. Schematic of Stirling engine powered vapor-compression desalination unit.

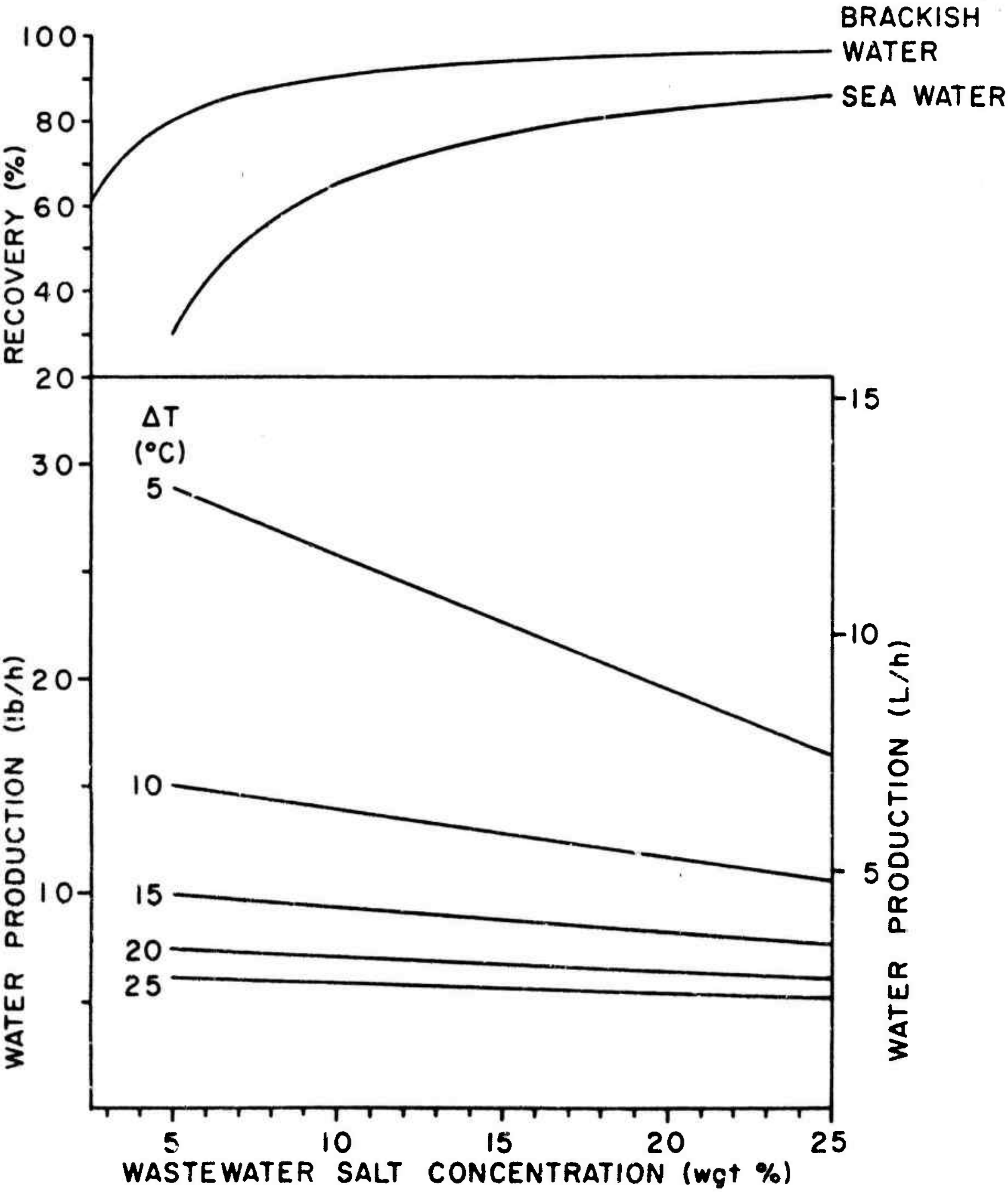


Figure 25. Water production and water recovery from salt water using a Stirling-powered vapor-compression desalinator.

boiling and condensation have such high heat transfer coefficients. Under these conditions (15% salt in wastewater, 5-10°C temperature difference) the water production rate is 13-23 lb/h (6-10 kg/h).

A heat pump (see Fig. 6) could be operated using the compressor of the Stirling engine described in Appendix A. Heat pumps are less efficient than vapor-compressors because of the irreversibilities associated with the need for two heat exchangers in heat pump systems rather than the one required for vapor-compression systems. Heat pumps typically require 50% more energy than vapor-compression systems operating under the same conditions. Thus it is expected that the Stirling engine operating at full power would be able to produce only 8-14 lb/h (3.5-6.5 kg/h).

4.5 Fixed Installation, Waste Heat

Fixed installations, such as command posts and communications centers, generate waste heat from electric generators. It is possible to use this waste heat to desalinate water.

Table 10 shows the rating scheme used for this scenario. Energy efficiency is important only in that there may be a limited supply of heat available. No additional fuel must be burned to provide the energy. Recovery is not important since it is assumed that the desalination equipment would be located near the site of the salt water. Weight and volume are not critical since the device is stationary.

The only options that may be considered are simple distillation and membrane distillation since all the other options received unacceptable ratings. The heat energy may be derived from the exhaust or the coolant. If the exhaust is cooled below 212°F (100°C), water derived from the combustion products of the fuel may be condensed and collected (see Figs. 14 and 17).

Military generators range in size from 0.5 kW to 60 kW.[7] The smaller generators are typically powered by gasoline and the larger ones are powered by diesel fuel. In the future, it is anticipated that all generators will be powered by diesel fuel since diesel-powered units are much more efficient. Figure 26 shows the amount of water which could be produced from gasoline-powered generators assuming that simple distillation or membrane distillation is employed. Not enough data were available to calculate the exact amount of heat which is lost to the exhaust

TABLE 10. Scores for Desalination Options at a Fixed Installation, Waste Heat Scenario

WEIGHT	Simple Distillation	Membrane Dist (Single)	Membrane Dist (Multiple)	Multiple-Effect Evap	Heat Pump	Vapor-Compression	RO (w/o Energy Recov)	RO (w/ Energy Recov)	Electrodialysis	Ion Exchange
2 Energy	5	2	2	3	*	*	*	*	*	0
1 Recovery	0	5	3	2	1	1	4	4	3	0
1 Purity	0	0	0	0	0	0	3	3	4	1
2 Logistics	0	0	0	0	0	0	1	1	1	*
1 Weight	2	4	4	5	5	5	2	2	2	2
1 Volume	2	4	4	5	2	2	1	1	2	1
3 Cost	1	3	3	5	5	5	2	2	3	1
3 Simplicity	1	2	3	5	4	5	1	2	3	0
3 Control	1	3	4	*	3	3	1	1	3	0
2 NBC Removal	3	3	3	3	3	3	3	3	4	5
2 Chilled Water	5	5	5	5	0	0	5	5	5	5
Number Unaccept	0	0	0	1	1	1	1	1	1	1
Score	39	57	61	64	50	53	40	43	58	27

Weight: 5 Very Important; 1 Unimportant

Rating: 0 Excellent; 5 Very Poor; * Unacceptable

Score: see equation (2)

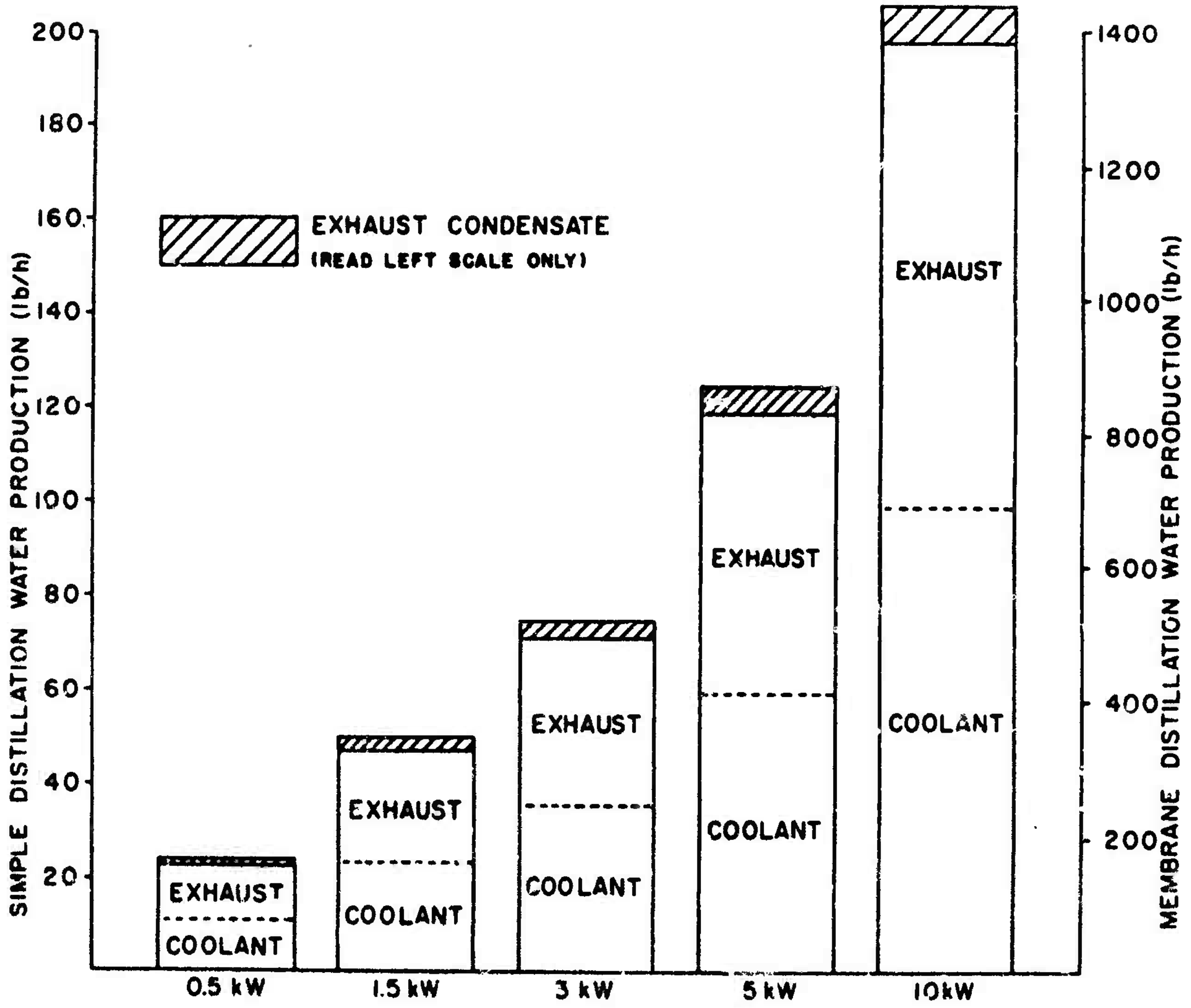


Figure 26. Maximum water produced from gasoline-powered generators using waste heat.

and coolant, so these should be regarded as estimates. A 0.5 kW generator could produce 22.5 lb/h (10.2 kg/h) of water through distillation of which 50% is from the coolant heat and 50% is from exhaust heat. If membrane distillation were employed, as much as 158 lb/h (72 kg/h) of water could be produced, of which 50% is produced from the exhaust and 50% from the coolant. A 10 kW generator could produce up to 198 lb/h (90 kg/h) by simple distillation and 1382 lb/h (628 kg/h) by membrane distillation.

Figure 27 shows the amount of water which could be produced from diesel-powered generators. A 5 kW generator can produce up to 44 lb/h (20 kg/h) by simple distillation and 310 lb/h (141 kg/h) by membrane distillation. A 60 kW generator can produce up to 448 lb/h (204 kg/h) by simple distillation and 3132 lb/h (1424 kg/h) by membrane distillation.

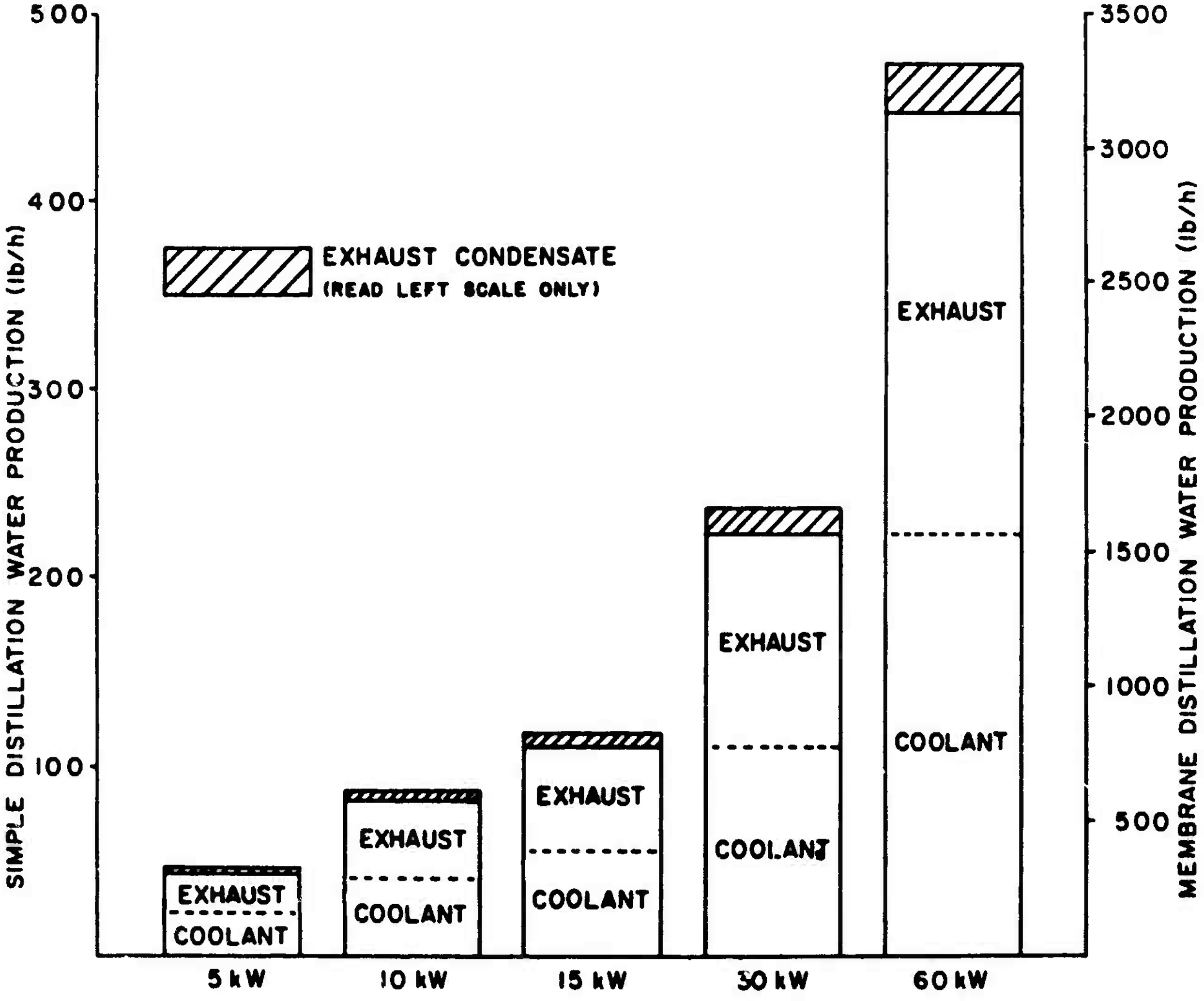


Figure 27. Maximum water produced from diesel-powered generators using waste heat.

4.6 Fixed Installation, Dedicated Power Source

Fixed installations, such as communications centers and command posts, may use pallet-mounted desalination equipment. Such equipment would have a dedicated source of power, such as a burner or engine, to provide the separation energy.

Table 11 shows the analysis of the various options. Energy is rated fairly high since waste energy is not being utilized. Recovery is not considered important since it is assumed that the unit will be placed near the water source. Weight and volume are not considered important since it is assumed the device will not have to be moved frequently. Simplicity and control are not extremely important since it is possible to have an operator attend the equipment.

Table 11 shows that a number of options are possible. Simple distillation or membrane distillation would probably be the method of choice if heat is used to supply the energy. The final choice between these two options would depend primarily on the importance assigned to efficient energy utilization and high water recovery. Simple distillation is favored if a high water recovery is required due to significant water transportation costs. Membrane distillation is favored if a greater premium is placed on energy use than that shown in Table 11.

A similar choice exists if mechanical energy is supplied. If a very high premium is placed on energy efficiency, then reverse osmosis is the method of choice. If high recovery is greatly valued, then vapor-compression or heat pumps would be

TABLE 11. Scores for Desalination Options at a Fixed Installation, Dedicated Power Scenario

WEIGHT		Simple Distillation	Membrane Dist (Single)	Membrane Dist (Multiple)	Multiple-Effect Evap	Heat Pump	Vapor-Compression	RO (w/o Energy Recov)	RO (w/ Energy Recov)	Electrodialysis	Ion Exchange
3	Energy	5	2	2	3	4	3	1	0	*	0
1	Recovery	0	5	3	2	1	1	4	4	3	0
1	Purity	0	0	0	0	0	0	3	3	4	1
2	Logistics	0	0	0	0	0	0	1	1	1	*
1	Weight	2	4	4	5	5	5	2	2	2	2
1	Volume	2	4	4	5	2	2	1	1	2	1
3	Cost	1	3	3	5	5	5	2	2	3	1
3	Simplicity	1	2	3	5	4	5	1	2	3	0
3	Control	1	3	4	*	3	3	1	1	3	0
2	NBC Removal	3	3	3	3	3	3	3	3	4	5
2	Chilled Water	5	5	5	5	0	0	5	5	5	5
	Number Unaccept	0	0	0	1	0	0	0	0	1	1
	Score	44	59	63	63	62	62	43	43	58	27

Weight: 5 Very Important; 1 Unimportant

Rating: 0 Excellent; 5 Very Poor; * Unacceptable

Score: see equation (2)

favored. If energy efficiency is very highly valued, then reverse osmosis is the method of choice.

4.7 Foot Soldier, Waste Heat

If foot soldiers are equipped with a microclimate conditioning device (see Appendix A), there will be a source of waste heat that could be used to desalinate water.

Table 12 shows the scoring used for this scenario. Although the energy is from a waste source, it may be in a limited supply. Thus, energy efficiency was given a moderately important rating. Recovery is very important since the weight of unrecovered water places an unnecessary weight burden on the soldier. Simple logistics is important since foot soldiers may not have easy access to supply lines. A low weight and volume are extremely important since the soldier is already overburdened. Simplicity and ease of control are important since the soldier needs a highly reliable device that does not divert his attention from his more important duties. From these considerations, Table 12 shows that simple distillation and membrane distillation are the only options that are feasible, with simple distillation being more highly favored.

Waste heat could be recovered from the Stirling engine which powers the microclimate conditioning unit. The heat could be used in a simple distillation apparatus as shown in Figure 13. Alternatively, the waste heat could be used in a membrane distillation apparatus as shown in Figure 16. When the Stirling engine operates at full power, it produces about 600 W (2050 Btu/h) of waste heat. If simple distillation were employed, this waste heat could produce about 2 lb/h (0.9 kg/h) of potable water. If membrane distillation were employed, about 14 lb/h (6.4 kg/h) of potable water could be produced.

TABLE 12. Scores for Desalination Options of a Foot Soldier, Waste Heat Scenario

WEIGHT	Simple Distillation	Membrane Dist (Single)	Membrane Dist (Multiple)	Multiple-Effect Evap	Heat Pump	Vapor-Compression	RO (w/o Energy Recov)	RO (w/ Energy Recov)	Electrodialysis	Ion Exchange
3 Energy	5	2	2	3	*	*	*	*	*	0
5 Recovery	0	5	3	2	1	1	4	4	3	0
1 Purity	0	0	0	0	0	0	3	3	4	1
4 Logistics	0	0	0	0	0	0	1	1	1	*
5 Weight	2	4	4	5	5	5	2	2	2	2
5 Volume	2	4	4	5	2	2	1	1	2	1
1 Cost	1	3	3	5	5	5	2	2	3	1
5 Simplicity	1	2	3	5	4	5	1	2	3	0
5 Control	1	3	4	*	3	3	1	1	3	0
2 NBC Removal	3	3	3	3	3	3	3	3	4	5
2 Chilled Water	5	5	5	5	0	0	5	5	5	5
Number Unaccept	0	0	0	1	1	1	1	1	1	1
Score	62	115	115	115	86	91	70	75	94	37

Weight: 5 Very Important; 1 Unimportant

Rating: 0 Excellent; 5 Very Poor; * Unacceptable

Score: see equation (2)

4.8 Foot Soldier, Dedicated Power Source

A foot soldier operating independently of supply lines may be required to carry equipment with him to desalinate "pick-up" water. Such equipment may be powered by the soldier himself or by an independent power source.

Table 13 shows the rating scheme for desalination equipment which is carried by a foot soldier. High energy efficiency is extremely important since the soldier can deliver only a limited supply of work to the desalination equipment. If a nonhuman source of power - such as a burner or small engine - is going to be used, it must also be extremely efficient since the soldier must carry the fuel and energy conversion device. A high recovery is extremely important since the soldier may have to perform the desalination while on the move. Low weight and volume are important since the soldier is already overburdened. Cost is considered less important since a premium may have to be paid for light weight and low volume. The device must be simple for good reliablity. It must be easy to control so that the soldier is not diverted from his other more important duties.

By the analysis presented in Table 13, a number of options appear to be promising. If heat is used as the energy source, simple distillation or membrane distillation are possible. If mechanical energy is to be used, reverse osmosis appears to be the best alternative.

If simple distillation is used, the simplest approach is to attach a condenser to the canteen. The standard burner, which uses trioxane tablets for fuel, would be employed. The tablets

TABLE 13. Scores for Desalination Options of a Foot Soldier, Dedicated Power Scenario

WEIGHT	Simple Distillation	Membrane Dist (Single)	Membrane Dist (Multiple)	Multiple-Effect Evap	Heat Pump	Vapor-Compression	RO (w/o Energy Recov)	RO (w/ Energy Recov)	Electrodialysis	Ion Exchange
5 Energy	5	2	2	3	4	3	1	0	*	0
5 Recovery	0	5	3	2	1	1	4	4	3	0
1 Purity	0	0	0	0	0	0	3	3	4	1
4 Logistics	0	0	0	0	0	0	1	1	1	*
5 Weight	2	4	4	5	5	5	2	2	2	2
5 Volume	2	4	4	5	2	2	1	1	2	1
1 Cost	1	3	3	5	5	5	2	2	3	1
5 Simplicity	1	2	3	5	4	5	1	2	3	0
5 Control	1	3	4	*	3	3	1	1	3	0
2 NBC Removal	3	3	3	3	3	3	3	3	4	5
2 Chilled Water	5	5	5	5	0	0	5	5	5	5
Number Unaccept	0	0	0	1	0	0	0	0	1	1
Score	72	119	119	121	106	106	75	75	94	37

Weight: 5 Very Important; 1 Unimportant

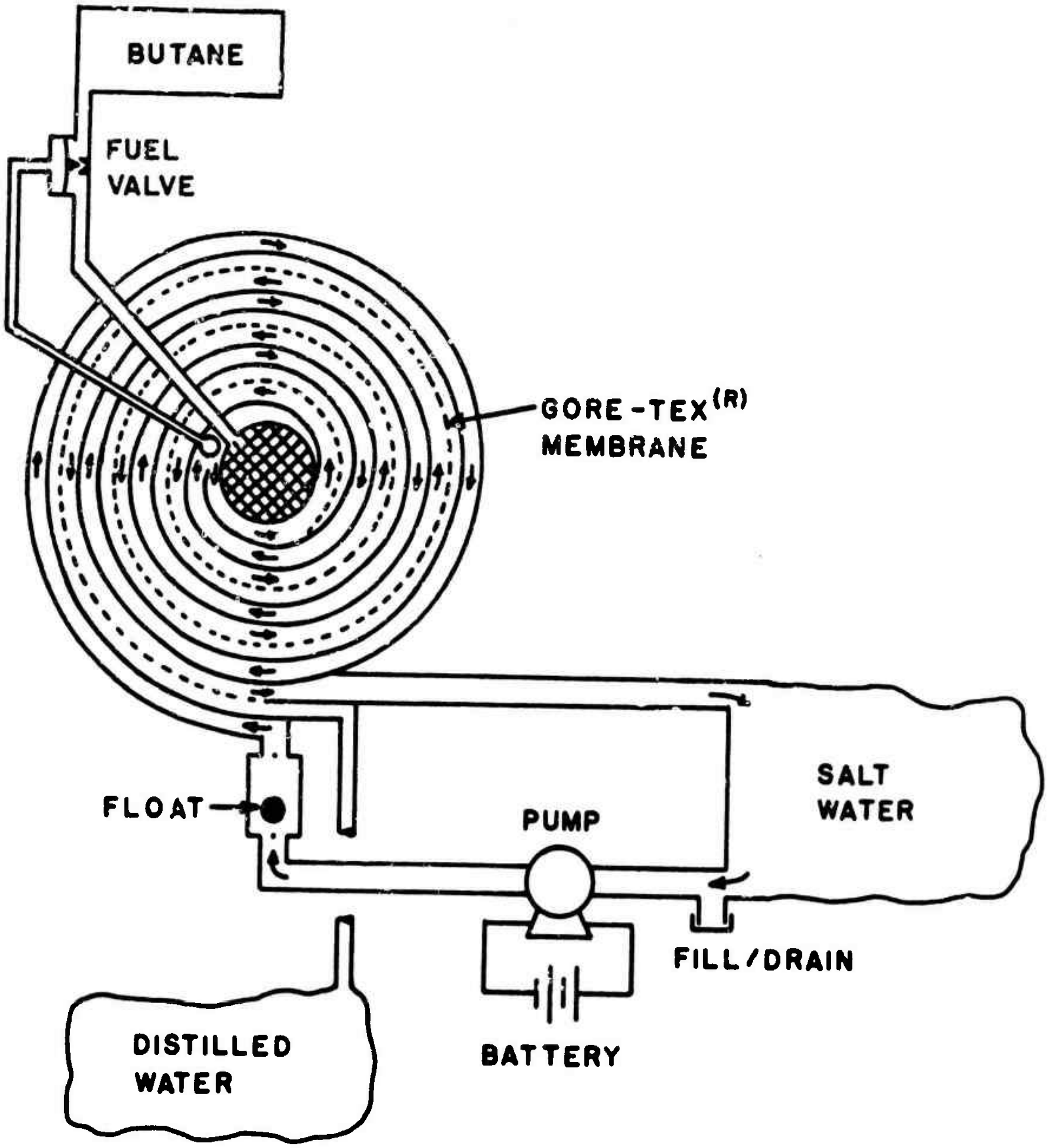
Rating: 0 Excellent, 5 Very Poor; * Unacceptable

Score: see equation (2)

have an energy density of 6790 Btu/lb (15,744 kJ/kg) which is about a third that of diesel or gasoline fuels. Allowing for inefficiencies in the transfer of heat from the fuel tablet to the water, about three pounds of water would be produced from a pound of trioxane tablets. As a rough estimate, such a water distillation device would weigh 3-5 lb (1.4-2.3 kg).

Membrane distillation will improve the yield of water from fuel. Further improvements will be achieved by replacing trioxane with a fuel having a higher energy density, such a hydrocarbon. Ideally, diesel fuel would be used. However, diesel fuel is extremely difficult to burn in small burners. An alternative would be to burn butane in a catalytic burner. This technology has been well developed for use in butane powered hair curlers manufactured by Gillette. Catalytic burners could be developed for fuels commonly available on the battlefield, but great care would have to be taken to remove sulfur from the fuel to prevent poisoning of the catalyst.

Figure 28 shows a scheme where a catalytic burner is employed using butane as a fuel. The rate of fuel addition is controlled by a thermal feedback sensor. The salt water would be pumped from a salt water storage container and cycled through the membrane distillation unit. The distilled water which passed through the membrane is collected in a separate container. Unrecovered salt water is returned to the supply container for recycling. It is assumed that there is enough surface area in the supply container to allow the water to cool a bit before it is recycled. The salt concentration will continue to rise as distilled water is removed from the salt water. To inform the



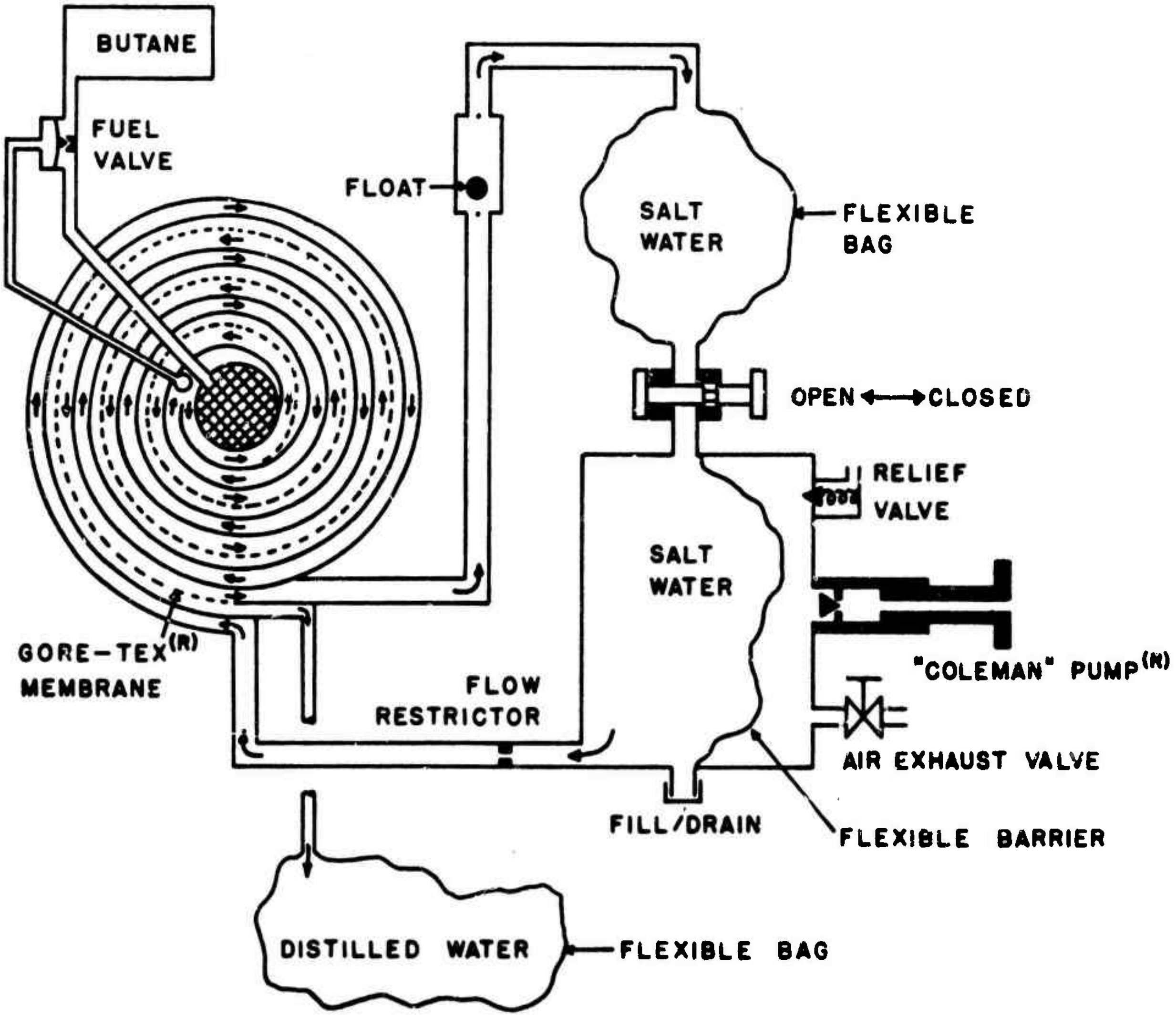
The use of registered trade names does not constitute official endorsement or approval of the use of such items.

Figure 28. Portable membrane distillation unit with battery-powered circulation pump.

soldier when to discontinue the desalination, a float in a site glass will be used. The density of the float will correspond to the density of salt water which is too concentrated for further productive desalination. The water circulation pump is powered by batteries. Approximately 100 pounds of water could be produced from a pound of batteries, so the weight of batteries should not be excessive. It does represent a logistics burden, however.

To avoid the need for batteries to power the water circulation pump, it is possible to devise a hand-operated pump. Such a concept is shown in Figure 29. The supply water would be stored in a rigid container which has a flexible wall dividing it. A simple "Coleman" type hand-pump would be used to pressurize one side of the rigid container. The soldier would know when to stop pumping when air is lost through the relief valve. Unrecovered water is collected in a bag which is at ambient pressure. When the supply bag is empty and the collection bag is full, air pressure would be relieved through the air exhaust valve so that the supply bag and collection bag are at the same pressure. Then the contents of the collection bag would then be transferred to the supply bag by simply opening a valve.

The elimination of the battery-operated pump has introduced greater complexity and the need for more attention by the soldier. Also, control of the hand-operated pump unit would probably be more difficult. It would appear that a battery-powered pump is preferrable to a hand-operated pump. Such a unit would probably weigh 5-10 lbs (2.3-4.5 kg).



The use of registered trade names does not constitute official endorsement or approval of the use of such items.

Figure 29. Portable membrane distillation unit with hand-pump for water circulation.

A reverse osmosis unit should incorporate energy recovery to reduce the energy requirements to a bare minimum. Figure 30 shows a schematic of a reverse osmosis unit which is powered by hand. Exiting wastewater flows through a hydraulic motor to reduce the energy supplied by the soldier. For illustration purposes only, Figure 30 shows the pump is powered by a rotary crank. A commercially available unit manufactured by Seagold Industries Corporation (4008 Myrtle Street, Burnaby, B.C. Canada, V5C 4G2) actually uses a hand-operated lever rather than a crank. This device has been successfully tested by the Navy[8] for use in life rafts. It produces 13 lb/h (6 kg/h) and weighs 11.6 lb (5.3 kg). It requires about 30 W (0.04 hp) of mechanical power to operate it. Humans are between 10% and 30% efficient in converting chemical energy to mechanical energy,[9] so between 70 W and 300 W (240-1025 Btu/h) of metabolic heat will be released during the desalination process. This heat release must be added to the baseline metabolic heat of 100 W (340 Btu/h). Therefore, the soldier must eliminate between 170 and 400 W (580-1365 Btu/h) of heat while performing the desalination. In the desert at 120°F (49°C), a soldier eliminating 170 W (580 Btu/h) of heat will require approximately 5 lb/h (2.3 kg/h) of water. A soldier eliminating 400 W (1365 Btu/h) of metabolic heat in the same desert will require approximately 6.5 lb/h (3 kg/h) of water.[1] Thus, under the worst conditions, the soldier can produce more water than he requires for cooling. However, it must be remembered that he will be spending little time performing the duties of a soldier since so much time will be required to

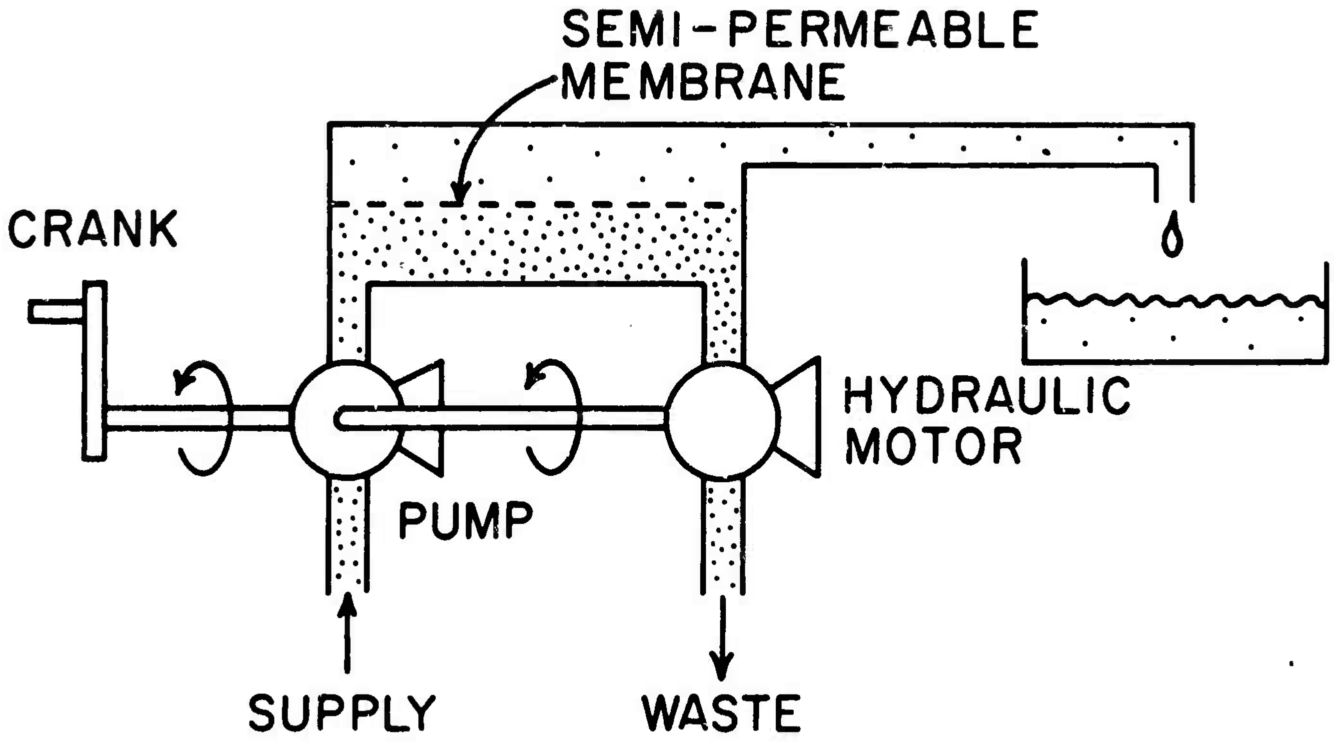


Figure 30. Hand-powered reverse osmosis unit.

desalinate the water. To reduce the time neeeded for desalinating water requires a unit which desalinates at a much higher rate. Such a unit would have to be operated by leg muscles which are able to supply more power than arm muscles.

As an alternative to hand-powered reverse osmosis desalination, it is possible to power the pump electrically. This is shown schematically in Fig. 31. The electrically powered version of the Seagold unit requires 50 W of electrical power to produce 13.2 lb/h (6 kg/h). The device weighs 29 lb (13 kg). If the electrical energy were supplied from a battery, it would require about 1.6 lb/h (0.7 kg/h) of state-of-the-art zinc/nickel batteries to operate it.[6] Thus, only 8.5 pounds of water can be produced from a pound of batteries. This places a great burden on the logistics system.

As an alternative to using batteries, it is possible to convert sunlight to electricity to power the desalination unit. On a clear day, solar radiation at 40° north latitude ranges from an average of 242 to 353 Btu/h ft^2 (763 to 1114 W/m^2) during the nine primary hours of sunshine.[10] To convert the sunlight to 50 W of electricity with photovoltaics (15% efficiency) requires approximately 3.2 to 4.7 ft^2 (0.3 to 0.44 m^2) of surface area if it is optimally placed relative to the incident radiation. Since optimal placement is difficult to achieve and clouds may be present, it would be wise to triple the area to about 12 ft^2 (1.1 m^2)

Recently, a patent has been granted for solar collectors that can theoretically convert solar light to electricity with a 60%-80% efficiency.[11] The principle is based on employing

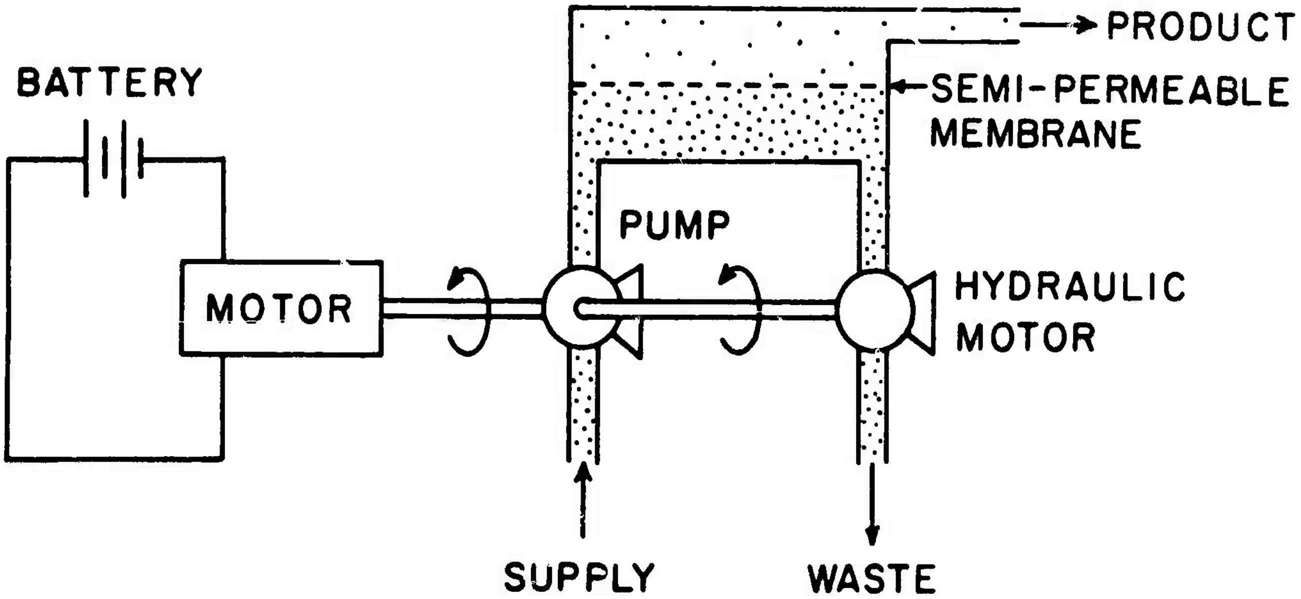


Figure 31. Electrically powered reverse osmosis unit.

miniature antennas which are comparable in dimensions to the wavelength of light. These antennas will be deposited on a glass surfaces much like conductive surfaces are placed on semiconductor chips. Very rapid response diodes are being developed to convert the oscillating current in the antennas to direct current. This four-fold increase in efficiency would reduce the required area to about 3 ft^2 (0.3 m^2). This corresponds to a square which is 1.7 ft (0.5 m) on a side. If this technology can be successfully developed, it is anticipated that these highly efficient solar collectors will be on the market in 1986 or 1987.

All of the small reverse osmosis units currently on the market have been developed to recover drinking water from sea water. Because of the high salt content of sea water, the units have been designed to recover only 10% of the water from the feed water. If brackish water were the feed instead of sea water, it would be possible to recover 30-60% of the water. To achieve this greater water recovery would require modification of the commercial reverse osmosis pumps.

5. CONCLUSIONS

The analyses conducted in Chapter 4 indicate that four options are viable - simple distillation, membrane distillation, reverse osmosis, and vapor-compression. The first two options require a source of heat and the latter two require a source of mechanical energy. The appropriate option depends on the scenario in which the desalination is going to be conducted.

Table 14 summarizes the various scenarios discussed in Chapter 4 in order of preference when ease of desalination is considered the main goal. The order is based on the following considerations:

1. use of waste heat is highly desirable since is does not require the development of special burners;
2. it is desirable to perform the desalination in a fixed location rather than on the move due to the difficulty in moving storage vessels and desalination equipment;
3. it is undesirable to have the individual soldier perform the desalination because of the substantial weight penalty associated with the desalination equipment.

The first consideration is consistent with military goals. The use of waste heat reduces the logistics burden on the petroleum supply system. The second two considerations, however, conflict with military goals. Militarily, it is more desirable to be able to desalinate on the move since high mobility is an asset in war. Similarly, it would be desirable to give each soldier his own desalination equipment to make him independent of supply lines.

TABLE 14. Summary of Desalination Options

2 = Strong Recommendation

1 = Weak Recommendation

0 = Not Recommended

SCENARIO	Simple Distillation	Membrane Distillation	Reverse Osmosis	Vapor-Compression
Fixed Installation, Waste Heat	2	2	0	0
Mobile Vehicle, Waste Heat	2	1	0	0
Trailer Mounted Unit, Dedicated Power, Stationary Separation	2	2	2	1
Fixed Installation, Dedicated Power	0	0	2	1
Mobile Vehicle, Power Take-Off	0	0	2	1
Trailer Mounted Unit, Dedicated Power Mobile Separation	2	1	1	1
Vehicle Stowed Unit, Dedicated Power	2	1	2	1
Foot Soldier, Waste Heat	2	1	0	0
Foot Soldier, Dedicated Power	1	1	2	0

Because of these conflicts with military goals, the final choice (or choices) of desalination approaches will be a compromise between the military goals and the desalination goals.

As shown in Table 14, the most desirable scenario is to use the waste heat from generators to desalinate the water since it satisfies all of the considerations listed above. The least desirable scenario is to have a foot soldier perform the desalination with a dedicated power source since it satisfies none of the considerations listed above. After each scenario listed in Table 14 is a column for the four desalination options. If the desalination option is strongly recommended for that scenario, a "2" is placed in the column. If the desalination option is only weakly recommended, a "1" is placed in the column. If the option is not recommended, a "0" is placed in the column.

If heat is to provide the energy required for separation, simple distillation is highly recommended because of its simplicity and ability to recover almost all the water from the salt water. Unfortunately, there is a very high energy price to be paid for these benefits. The energy cost of simple distillation can be reduced with membrane distillation, but contains the penalties of greater size and complexity and the inability to recover all the water from the salt water.

If work is to provide the energy required for separation, reverse osmosis is highly recommended primarily because of its low energy requirements. Unfortunately, the price to be paid is low recovery of potable water from the salt water. This limitation can be overcome with a vapor-compression system, but the complexity and cost of vapor-compression is probably not warranted considering the other options available.

Many of the desalination options discussed interface with existing military equipment such as vehicles, generators, and a Stirling engine that is being developed. Tables 15, 16, and 17 show the maximum number of soldiers who could be supported assuming simple distillation, membrane distillation, and reverse osmosis are interfaced with these pieces of equipment. It is assumed that the soldier is performing heavy work in a desert and requires 50 lb/d (23 kg/d) of water.

The number of hours per day vehicles operate was determined from the mission profile for the vehicles.[5] It is assumed that the vehicles are operating at the percentage of maximum power indicated in Table 5. Only coolant heat should be recovered since the vehicle modifications required to recover exhaust heat would be too extensive.

Generator use varies widely depending on the end-user, but generators typically operate 24 hours per day.[7] The data presented in Tables 15 and 16 are the <u>maximum</u> number of people who could be supported by using waste heat from generators that operate at 100% of rated capacity. This number should be discounted by an appropriate factor to account for the fact that end-users do not always use the full power output of the generator. Typically generators produce only 60% of their rated capacity.[7] The data presented for the Stirling engine also assumes that the engine is operating at 100% of full power.

Examination of Tables 15, 16, and 17 shows that there is a wide range in the number of people who can be supported by the

TABLE 15. Maximum Potential for Simple Distillation Interfaced with Existing or Planned Equipment

Approach	Water Prod'n (lb/h)	Usage (h/d)	Water Prod'n (lb/d)	Number Soldiers Supported
HMMWV, Coolant Heat	144	8	1,152	23
5-Ton, Coolant Heat	198	15	2,970	59
M2/M3, Coolant Heat	251	4	1,004	20
M1, Coolant Heat	410	4	1,640	33
0.5 kW Gen, Gasoline, Coolant Heat	11	24	264	5.3
1.5 kW Gen, Gasoline, Coolant Heat	24	24	576	12
3 kW Gen, Gasoline, Coolant Heat	35	24	840	17
5 kW Gen, Gasoline, Coolant Heat	59	24	1,416	28
10 kW Gen, Gasoline, Coolant Heat	99	24	2,376	48
5 kW Gen, Diesel, Coolant Heat	22	24	528	11
10 kW Gen, Diesel, Coolant Heat	42	24	1,008	20
15 kW Gen, Diesel, Coolant Heat	56	24	1,344	27
30 kW Gen, Diesel, Coolant Heat	112	24	2,688	54
60 kW Gen, Diesel, Coolant Heat	224	24	5,376	108
M2 Burner	64	24	1,536	31
1950 Squad Stove	5.5	24	132	2.6
Stirling Engine, Coolant Heat	2	10	20	0.4

TABLE 16. Maximum Potential for Membrane Distillation Interfaced with Existing or Planned Equipment

Approach	Water Prod'n (lb/h)	Usage (h/d)	Water Prod'n (lb/d)	Number Soldiers Supported
HMMWV, Coolant Heat	1000	8	8,000	160
5-Ton, Coolant Heat	1386	15	20,790	416
M2/M3, Coolant Heat	1757	4	7,028	141
M1, Coolant Heat	2870	4	11,480	230
0.5 kW Gen, Gasoline, Coolant Heat	79	24	1,896	38
1.5 kW Gen, Gasoline, Coolant Heat	165	24	3,960	79
3 kW Gen, Gasoline, Coolant Heat	248	24	5,952	119
5 kW Gen, Gasoline, Coolant Heat	414	24	9,936	199
10 kW Gen, Gasoline, Coolant Heat	691	24	16,584	332
5 kW Gen, Diesel, Coolant Heat	155	24	3,720	74
10 kW Gen, Diesel, Coolant Heat	292	24	7,008	140
15 kW Gen, Diesel, Coolant Heat	392	24	9,408	188
30 kW Gen, Diesel, Coolant Heat	783	24	18,792	376
60 kW Gen, Diesel, Coolant Heat	1566	24	37,584	752
M2 Burner	448	24	10,752	215
1950 Squad Stove	39	24	936	19
Stirling Engine, Coolant Heat	14	10	140	2.8

TABLE 17. Maximum Potential for Reverse Osmosis Interfaced with Existing or Planned Equipment

Approach	Water Prod'n (lb/h)	Usage (h/d)	Water Prod'n (lb/d)	Number People Supported
0.5 kW Generator	171	24	4,104	82
1.5 kW Generator	512	24	12,288	246
3 kW Generator	1024	24	24,576	492
5 kW Generator	1707	24	40,968	819
Stirling Engine (No Water Chilling)	88	24	2,112	42
Stirling Engine (w/ Water Chilling)	26	24	624	13
Seagold, Hand-Powered	13	2	26	0.5
Seagold, Battery-Powered	13	24	312	6.2
Seagold, Solar-Powered	13	9	117	2.3

various options discussed. As many as 819 people can be supported using a 5 kW generator to power reverse osmosis equipment or as few as 0.4 people can be supported using waste heat from a Stirling engine to provide the energy for simple distillation. It should be noted that the waste heat from a Stirling engine can produce 20 lb (9 kg) of water during 10 hours of operation by employing simple distillation. Although this amount of water would not be sufficient for a soldier who does not have microclimate cooling, it would be sufficient for a soldier who does have microclimate cooling.

Specific recommendations for future research are as follows.

LARGE GROUP (50-800 Soldiers)

1. Develop equipment which allows recovery of waste coolant heat from military generators to be used in membrane distillation.

MEDIUM GROUP (20-50 Soldiers)

1. Develop equipment which allows recovery of waste coolant heat from military generators to be used in simple distillation.

SMALL GROUP (7-20 Soldiers)

1. Develop reverse osmosis units employing energy recovery which can be powered by a Stirling engine or other small mechanical power source.
2. Develop equipment which allows recovery of waste coolant heat from military vehicles for use in simple distillation.

3. Develop a membrane distillation unit to be heated with a 1950 squad stove. The stove should be modified to have a thermoelectric generator to operate the pumps of the membrane distillation unit.

INDIVIDUAL SOLDIER

1. Develop equipment which allows recovery of waste coolant heat from a Stirling-powered microclimate conditioning unit for use in simple distillation.
2. Modify hand-powered reverse osmosis desalinators to operate using leg muscles rather than arm muscles to increase production rates. Incorporate features that allow greater water recovery from brackish water than from sea water.

Note that although waste heat from vehicles could produce more water than would be consumed by a small group, space limitations on vehicles would preclude production of large amounts of potable water for consumption by large groups.

This document reports research undertaken at the US Army Natick Research and Development Command and has been assigned No. NATICK/TR-85/042 in the series of reports approved for publication.

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APPENDIX A - STIRLING ENGINE

A Stirling engine is being developed under contract DAAK60-83-C-0054 with the Joint Center for Graduate Study operated by the University of Washington. The engine is being designed to power a portable microclimate conditioning unit, which can provide cooling or heating to individual soldiers.

A schematic of the engine is shown in Fig. 32. Heat is supplied to the hot end of the cylinder by combustion of fuel in a burner. The cylinder is filled with helium, which can be shuttled from the hot end of the cylinder to the cold end by movement of the displacer. When the helium is at the hot end of the cylinder, the helium pressure rises causing the power bellows to expand. The expanding power bellows displace hydraulic fluid which causes the power piston to move downward. As it moves downward, it displaces hydraulic fluid which causes the compressor to compress. Thus, there is a hydraulic coupling between the power bellows and the compressor.

As the power piston moves downward, it also causes a crank to rotate. The rotating crank allows the engine to generate mechanical shaft power. If the shaft power levels are low, a magnetic coupling (as shown in Fig. 32) should suffice to transmit the torque through the housing wall. For high power levels, a rotating shaft seal would be required.

The rotating crank powers a leakage make-up pump which supplies the small amounts of hydraulic fluid required to replenish losses past the power piston.

The rotating crank also causes a master piston to move up

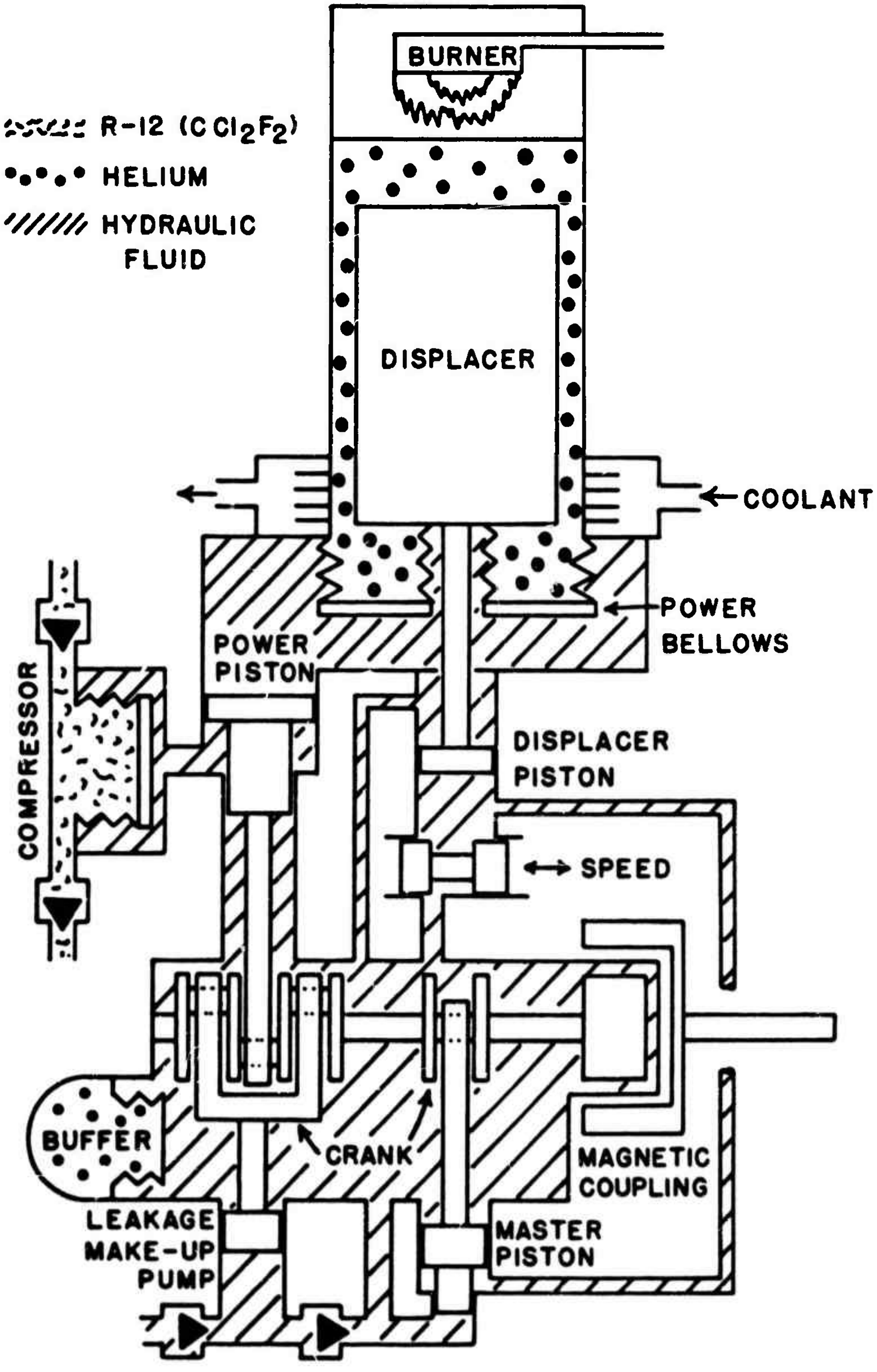

Figure 32. Schematic of Stirling engine.

and down. The master piston crank is 90° out of phase with the power piston crank. As the master piston moves up and down, it displaces hydraulic fluid which causes the displacer piston to move up and down. The degree of coupling between the master piston and the displacer piston is determined by the position of the speed control spool valve. If the speed control spool valve closes the opening to the buffered region, the displacer moves directly with the master piston. This makes the displacer move 90° out of phase with the power bellows, which corresponds to the condition for maximum torque. If the torque is higher than that taken up by the load, the system will accelerate. The speed control spool valve will open automatically allowing some of the fluid which is displaced by the master piston to throttle into the buffered region. This reduces the degree of coupling between the master piston and displacer piston. The displacer no longer moves 90° out of phase with the power bellows and the amplitude is reduced. Both of these effects act to reduce the torque output of the system. At an appropriate setting of the speed control spool valve, the system will run at a constant 60 Hz (3600 rpm).

Coolant flows through the cold end of the cylinder to take away the heat which is generated when the cold helium is compressed as the power piston moves in the upward direction. The energy required for this compression is stored in the inertia of the rotating components. The energy required to compress the cold gas is much less than the energy produced during the expansion of the hot gas. At full power, the net work produced by the engine is 235 W (0.32 hp). The amount of heat which must be removed from the engine at full power is 600 W (2050 Btu/h).