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SUMMARY REPORT

ON

WORK ORDER NO. 10,
TASK ORDER NO. TT

May 21, 1961

INTRODUCTION

The Sponsor is interested in the potential development of a moisture condenser for use by individual untrained personnel in arid or desert areas of the world. This interest stems from a need to provide potable water for individual consumption in quantity and quality such as to enable a person to withstand the rigors of prolonged travel or of survival in such areas. It was our understanding that no suitable device or apparatus was (or is) available for this purpose, i.e., that no unit has been developed for use by an individual in obtaining from the air the quantity of water required to satisfy a human being's daily minimum requirements. On even the hottest and driest days, the air masses in desert areas reportedly represent a suitable source of water, providing, of course, that the water can be condensed and collected in a satisfactory manner.

Any equipment provided for this purpose should be small, lightweight, simple, and durable. A weight of 2.2 pounds and a size of about 6 x 6 x 12 inches were indicated as design goals in the consideration of an appropriate device.

Accordingly, an effort under Work Order No. 10, Task Order No. TT, was initiated, to investigate the practicability of developing a specialized moisture condenser of the type described herein. The proposed method of attack was to evolve ideas regarding devices which might serve the purpose; and to evaluate them, at least in preliminary fashion, from the viewpoint of possibly providing the basis for a subsequent development effort aimed toward achieving a unit which would embody the desired characteristics.

This report summarizes the results of the effort performed under Work Order No. 10, Task Order No. TT, during the period February 22 through May 21, 1961.

SUMMARY AND CONCLUSIONS

A number of methods have been considered for providing potable water to a desert traveler. None of those considered seems to be capable of meeting the weight and size goals as specified. Further, it presently seems doubtful that any system would be able to meet these goals, particularly the weight. However, if some increase in weight and size can be tolerated, the following three approaches appear to be very promising:

(1) The use of solid or liquid desiccants, with solar regeneration.

(2) A large, flat collector which would cool itself by radiating to the sky at night.

(3) A reciprocating compressor-expander with a rotating cylinder block, which would extract the water by centrifugal action immediately after it condensed in the expansion process.

Of these, the system with the smallest potential gross weight is probably the compressor-expander; it has been estimated that such a system would weigh about 8 pounds without a prime mover, and that an appropriate solar-energy-operated prime mover would weigh about 4 pounds. However, the exploitation of this method or of that based on the use of a desiccant would entail considerable developmental effort, as compared to the relatively small effort which would be needed to develop a suitable large, flat collector.

METHOD OF PROCEDURE

The problem presented for study was to consider methods of providing drinking water to a man traveling alone and on foot through the desert. It was specified that:

(a) The equipment should provide 2 quarts of water per day for 21 consecutive days.

(b) Any equipment provided should preferably weigh no more than 2.2 pounds and fit in a space about 6 x 6 x 12 inches.

(c) The equipment should be durable and easily operable by a man of average intelligence and mechanical skill.

In the absence of a definite environmental specification, it was assumed that the atmosphere contained 0.005 pound of water per pound of dry air, during the daytime and nighttime. Further, daytime temperatures were assumed to reach a peak of about 95 to 100 F, with long-period averages of about 90 F; nighttime temperatures were taken to be a constant 78 F.

The method of attack used for this program was to present the problem in general terms to selected members of our technical staff representing a variety of interests in the fields of chemistry, chemical engineering, physics, biosciences, and mechanical engineering. As a result, a number of approaches were suggested; these were subsequently screened to select those which seemed most promising in view of the specified requirements. The most promising ideas were then evaluated in some detail, in order to estimate how closely they would permit approaching the required performance and weight. Since the program did not provide for a thorough design study, evaluations were based on estimates of performance and weight that were detailed enough to permit only an approximate classification. For example, if a system depended on the use of a chemical, the required weight of the chemical was calculated and used as an indication of the minimum attainable weight of the system.

Table 1 summarizes the results of the study.

DISCUSSION OF RESULTS

The methods suggested for collecting water in the desert can be catalogued in five groups:

(1) Condensation of moisture from the air on a cold surface

(2) Absorption or adsorption of atmospheric moisture by suitable chemicals

(3) Extraction of moisture from the air by compression, cooling, and expansion

TABLE 1. PERTINENT METHODS OF COLLECTING WATER FROM SURROUNDINGS, PARTICULARLY FROM AMBIENT AIR

Method	Description	Estimated Minimum Weight	Remarks
ondensation on a cold surface	(a) Intermittent-absorption refrigeration system	Probably 50 to 60 pounds	-
	(b) Collector radiating to the sky at night	About 20 to 25 pounds	Probably not effective every night because of dependence on clear sky an negligible wind
dsorption	Silica gel system with cyclic concentration and solar regeneration	28 pounds of desiccant, plus a fairly simple apparatus	Would require considerable developmental effort
bsorption	Liquid desiccants, such as lithium chloride solutions, with solar regeneration	4 pounds of desiccant, plus the required equipment	Would require some method circulating desiccant to e pose large surface area to the air during absorption; some desiccant might be lo by evaporation; would involve considerable develo mental effort
ompression-expansion systems	Rotating-block compressor-expander with regenerative cooling of compressed air and centrifugal extraction of condensed water	About 8 pounds for compressor-expander, without prime mover; additional 4 pounds estimated for solar-energy-operated prime mover	Would require considerabl developmental effort
ombustion processes	Combustion of hydrogen with condensation of water vapor produced	9 pounds of hydrogen, plus combustion and condensing equipment	Very bulky; difficult to handle

TABLE 1. (Continued)

Method	Description	Estimated Minimum Weight	Remarks
[M]iscellaneous methods	Extraction from soil or rocks, by solar distillation	Possibly about 5 pounds for soil; somewhat heavier for rocks	Depends on availability of the appropriate kind of soil or rock; there is no experience with such system that could be used as a basis for estimating effectiveness

(4) Chemical reactions in which water is one of the products

(5) Miscellaneous methods.

These are discussed in some detail in the following.

<u>Condensation on a Cold Surface</u>

The collection of moisture from the desert air by using a cold exposed surface for condensation has some obvious limitations. With the assumed climatic conditions, the dew point of the air would be approximately 40 F; an appropriate cold surface would have to be appreciably below 40 F in order to collect much moisture. Below 32 F, the moisture would collect as ice, tending to insulate the collector from the air and to reduce the rate of collection. The low moisture content of the air would require the use of large collecting surfaces or a long collecting period in order to provide the required quantity of water. The use of a conventional compression refrigeration system would necessitate equipment of considerable weight, including a prime mover to drive the compressor.

The applicability of an intermittent-absorption refrigeration system, which would operate from solar energy, was analyzed. Units of this basic type were sold commercially many years ago as residential refrigerators which required no electricity. Basically, this type of system consists of two interconnected containers; one holds a solution of a refrigerant in an absorbent, which could be ammonia and water, for example, and the other is empty. To start the cycle, the container which holds the solution is heated. The heating drives off part of the refrigerant, which passes to the second container and condenses. When a suitable quantity of refrigerant is thus transferred to the second container and condensed, the heat source is removed. The first container then cools, the pressure in the system drops, and the refrigerant begins to evaporate from the second container; as evaporation occurs, the refrigerant passes to the first container and is absorbed. When the evaporation is completed, the cycle can be repeated. While the refrigerant is evaporating, it is extracting heat from its surroundings, and thus produces the refrigerating effect.

This system as applied to the problem of interest would be inherently simple, since it would operate from solar energy and would require only two basic parts, each of which would serve a dual purpose, plus an accessory. One part would act as the generator and the absorber, and the other as the condenser and evaporator. In addition, a solar-energy collector would be needed to provide a concentrated heat source for the generator.

A partial analysis of the intermittent-absorption system showed that the evaporation time required to collect 4 pounds of water would be inversely proportional to the evaporator area and would be a function of the air velocity over the evaporator surface. Even with the assumption of an air velocity of 20 feet/second, which would require a blower and a source of energy for the blower, an evaporator operating time of 4 hours would require an evaporator area of 25 square feet. Additional time would be required for the other phases of the cycle, and some difficulty might be caused by the necessity for removing the heat of condensation and the heat of absorption. In view of the limitations apparent in the evaporator portion of the system, no further analysis of this system was undertaken.

A simple method of obtaining water by condensation would be to use a large collector which would radiate to the sky at night. On a clear night, the sky has a low effective temperature. Assuming an effective sky temperature of about -80 F* at night, a perfect radiator with an area of about 100 square feet could collect about 4 pounds of water during the night. With a thin plastic film as the radiator, two other parallel films to shield the collector from ground radiation, and a lightweight, aluminum, tubular supporting structure, the entire assembly would probably weigh 20 to 25 pounds.

The successful operation of this type of collector would depend on having a clear, calm night. Cloud cover would make it inoperable; and wind would tend to raise the temperature of the device above the dew point, unless suitable shielding could be provided, and thus would result in ineffective operation. It is anticipated that a relatively small amount of developmental effort would be necessary in order to exploit this method.

Absorption or Adsorption by Desiccants

Many desiccants, both solid and liquid, are available that will absorb or adsorb moisture from desert air; in fact, there are solid adsorbents which will remove nearly all of the moisture. To be useful for the application of obtaining potable water, however, some means must be devised to ultimately extract the moisture from the desiccant as liquid. Desiccants are normally regenerated by heating to a high temperature, usually in the range of

*On a clear night, a radiating body located on the surface of the earth loses heat at a rate which would prevail if the body were radiating to an infinite sink at a temperature of about -80 F.

300 to 1000 F, depending on the desiccant. In the application of interest, the moisture would thereby be driven off as vapor and would have to be condensed. Also, while it would be possible to obtain the usual regeneration temperatures by concentrating solar energy, to attempt to provide for this function in a small portable unit does not appear practical.

However, there have been developed in Germany several thermodynamic cyclic processes utilizing desiccants which have removed water from the desert air, on the basis of a smaller temperature difference. In fact, units have been operated successfully on the basis of the temperature difference existing between a plane solar receiver and an adjacent shaded zone. In these systems, water plus water vapor was the working fluid, with dry air as the inert carrier gas. The Dannies' systems are outlined in the following; a detailed description is available in a series of three articles by J. H. Dannies that appear in the January, 1959, issue of "Solar Energy".

In the course of the Work Order No. 10 activity, calculations were made on these types of systems, to determine the weight of desiccant required to obtain 2 quarts of water per 24-hour day. While this value would not represent the total weight of the unit required, the other components could probably be made quite light in weight, particularly if a solid desiccant were used; the desiccant weight would therefore be a large part of the total weight and could be used as a basis for comparison.

Both solid and liquid absorbents were considered as desiccants in the calculations; a survey of solid-desiccant properties were made. Silica gel appeared to be by far the best for the present application and was the only solid for which calculations were made. This was the desiccant used by Dannies in his operating units, although he stated that other solids, as well as liquids, would function under the temperature conditions associated with the use of incident solar radiation. Liquid absorbents with the most desirable properties appeared to be lithium chloride and calcium chloride solutions, and both were used in the calculations.

Both the simultaneous and successive systems of Dannies were investigated analytically. However, the Dannies' simultaneous system was modified slightly to suit the requirements of the application of interest. For Dannies' application, self-operation and immobility were quite desirable; in his simultaneous system, which operated only during the daytime, two beds of desiccant were used, one facing east and one facing west. In the morning, the east desiccant was regenerated while the west desiccant was adsorbing moisture; in the afternoon, the functions were reversed. This procedure is rather inefficient for two reasons. First, the maximum solar radiation, which occurs near noon time, is not used, since the system is reversing at that time. Second, for most desiccants, 6 or more hours are not required for the equilibrium moisture content to be achieved. Therefore, on the assumption that a limited amount of manual operation would be possible in the application of interest, a shorter cycle was devised during which the beds would be alternately directed toward the sun. In order to determine the optimum time for the cycle, an analysis was made of the dynamic data on silica gel. While considerable extrapolation of the data was necessary to fit the conditions of interest, it was found that a 2-hour half-cycle would permit the regeneration of approximately 80 per cent of the adsorbed moisture. Beyond 80 per cent, the rate of regeneration would decrease rather rapidly, so a longer half-cycle appeared uneconomical on a weight basis.

The successive system explored by calculation was essentially that outlined by Dannies. This system involved adsorption in the cooler night air, followed by regeneration by solar energy and condensation in a closed system during the daytime.

Table 2 shows the results of the calculations. Most of the headings have already been explained or are self-explanatory. The temperatures for the simultaneous system were taken directly from actual data given by Dannies. For the successive system, the limiting adsorption temperatures simply represent the nighttime conditions; the typical spring and summer nighttime desert conditions are also actual data from Dannies for the Sahara Desert. The limiting regeneration dry-bulb temperature is the maximum air temperature in the closed system as obtained by solar heating during daytime operation, and the limiting regeneration dew point represents the shade-cooled condenser temperature. As the table indicates, the efficiency of the system is largely dependent on these regeneration temperatures. Most of the data presented in the table are only approximations. Ultimately, the actual values would have to be determined by testing a complete unit. However, they could be approximated more closely than is the case in Table 2, by a detailed heat balance using known heat-transfer correlations, once the actual physical arrangement of a unit was determined.

The systems based on using liquid desiccants appear quite attractive when only the weight of desiccant is considered. However, a word of caution

TABLE 2. CALCULATED DATA ON EXTRACTION OF WATER FROM DESERT AIR USING DESICCANTS (DANNIES' SYSTEMS), TO YIELD 2 QUARTS PER DAY

Type of System	Limiting Regeneration Conditions		Limiting Adsorption Conditions		Regeneration Efficiency, per cent	Desiccant Used	Cycle Efficiency, Water Yield / Water Adsorbed, per cent	Cycle Time, hr	Weight of Desiccant + Adsorbed Water, lb		Weight of Dry Desiccant, lb
	$t_{Dry\ Bulb}$, F	$t_{Dew\ P}$, F	$t_{Dry\ Bulb}$, F	$t_{Dew\ P}$, F					Max	Min	
Simultaneous - solid desiccant	117	47	94	94	80(1)	Silica gel	12	4(3/day)	59.5		47.6
Successive - solid desiccant	150	90	60 (Typical of spring nighttime in desert)	40	100	Silica gel	55	24	32.1	27.9	24.5
Successive - solid desiccant	150	90	74 (Typical of summer nighttime in desert)	51	100	Silica gel	35	24	67.8	63.6	55.6
Simultaneous - liquid desiccant	117	47	94	85	80(1)	LiCl	12	4(3/day)	10.8		3.6
Simultaneous - liquid desiccant	117	47	94	85	80(1)	$CaCl_2$	12	4(3/day)	14		5.2
Successive - liquid desiccant	150	90	60	40	100	LiCl	44	24	12.9	8.7	3.5
Successive - liquid desiccant	150	90	84	51	100	LiCl	29	24	21.7	17.5	7.0
Successive - liquid desiccant	180	95	84	51	100	LiCl	78	24	8.0	3.8	2.6

(1) Depends on cycle time; this is an assumed value with some experimental basis.

must be injected in this regard, because the actual physical arrangement of either type of system when using a liquid desiccant has not been worked out completely. The calculations assume that such arrangements can be made to operate. The prospects of a practical, functioning unit based on either type of system appear promising, but considerable development work would be necessary.

On the other hand, physical arrangements of both types of systems when using solid desiccants have been designed and operated successfully. These units would probably be simpler than those required for liquid desiccants, but the weight of the required amount of solid desiccant would be much greater.

Compression-Expansion Systems

Systems in which a gas is compressed, cooled, and then expanded with work extraction are used for cooling gases in commercial liquefaction processes. The direct application of this technique to the desert-water-supply problem is not attractive, primarily because of the difficulty of cooling the working gas after compression. However, a system has been suggested that might be practical. This involves a compressor-expander with a rotating cylinder block, and regenerative cooling of the compressed air before it enters the expander. The key to this possibly applicable system is that the water would condense during the expansion process and be thrown clear by the centrifugal force created by the rotation of the cylinder block, before the air was reheated by passing through the regenerator. Such a machine would require a prime mover to supply the operating power; the prime mover might be a solar-energy-operated engine or possibly a man. The energy needed to produce the required quantity of water has been estimated to be about 2 horsepower hours; this would probably be too much energy to be provided by an average man.

It is estimated that the weight of an appropriate compressor-expander unit would be about 8 pounds, exclusive of the energy source. An air-cycle engine, operating from solar energy, might weigh about 3 or 4 pounds.

This system appears attractive in concept. However, both the compressor-expander and the prime mover would require appreciable development effort.

Chemical Reactions

Water can be produced as a product of a number of chemical reactions. Common examples of such reactions are those underlying combustion processes. In theory at least, one could burn materials which yield large quantities of water and collect the water from the combustion gases. Many hydrides yield appreciable quantities of water. For example, the combustion of 27.6 pounds of boron hydride (B_2H_6) will yield 54 pounds of water, or 1.96 pounds of water per pound of boron hydride. Similarly, the combustion of methane (CH_4) will yield 2.25 pounds of water per pound of methane. An even more direct approach would be to burn pure hydrogen, which will yield 9 pounds of water per pound of hydrogen burned.

Some additional weight would be required in connection with all of these processes, in order to provide equipment for combustion and for recovery of the water vapor from the products of combustion. Moreover, storage of gaseous fuels would be difficult. Storing under high pressure would reduce the volume, but would of course require heavy containers. A suggestion has been made that the hydrogen be stored at low pressure in balloons. This arrangement offers the unique advantage that it would impose no carrying load on the man.

However, it has some obvious problems in terms of volume, ease of handling, and susceptibility to observation in hostile territory. For these various reasons, none of the systems involving combustion appears promising.

Miscellaneous Methods

In addition to atmospheric air, rocks or soils represent a source of water which might possibly be tapped. Many kinds of rocks contain trapped water in amounts ranging from a trace to more than 10 per cent by weight. In concept, a solar still or a simple solar furnace could be used to drive off and collect the moisture from crushed rocks. This approach has been suggested by North American Aviation as a possible means of obtaining water from the rocks on the moon. Probably the equipment could be made reasonably light in weight so as to be portable. However, the applicability of this technique is dependent upon the availability of suitable rocks.

Soils extract moisture from the air and hold it in quantities which depend on the humidity of the atmosphere, and the particle size and absorption characteristics of the soil. The upper limit of the particle size of soils which will absorb or adsorb water vapor from the air is about 0.001 millimeter, corresponding to the particle size of a clay soil. Sand particles are much larger than this, and would hold practically no moisture*. The value of this source of water would depend on the availability of fine-particle soils. Again, extraction could probably be accomplished by a solar still. However, considerable effort would be needed to develop the required equipment and techniques.

*Puri, A. G., "Soils: Their Physics and Chemistry", Reinhold Publishing Co., 1949.

FUTURE WORK

No further effort in connection with the provision of potable water to a desert traveler is contemplated at this time. The three above-outlined methods which are considered to be quite promising have been discussed with the Sponsor. It is recommended that the Sponsor give further consideration to these. If the original specification of particularly the weight and also the size desired for the unit of interest could be relaxed slightly, we believe that a developmental effort to exploit any one of these methods would be likely to provide a satisfactory unit for this application.