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WATER TREATMENT PROCESSES FOR RURAL COMMUNITIES IN DEVELOPING COUNTRIES

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WATER TREATMENT PROCESSES FOR RURAL COMMUNITIES IN DEVELOPING COUNTRIES

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WATER TREATMENT PROCESSES FOR RURAL COMMUNITIES IN DEVELOPING COUNTRIES

INTRODUCTION

One of the major deterrents to advancement of community development in many parts of the world is lack of adequate supplies of potable* water. Many methods have evolved over the years and have been successfully applied to produce safe, palatable water from almost any raw water source. However, factors such as cost, complexity of operation and special materials requirements have precluded their broad application, especially in areas of limited economic development. An engineering study has been made of these water treatment problems as part of a broad GEL technical appraisal program, carried on for the Agency for International Development, U. S. Department of State. The main objective of this study has been to review and evaluate water treatment methods and currently available process equipments which are capable of providing potable water at costs commensurate with local economic conditions in relatively underdeveloped areas of the world. In this report, major aspects of field water treatment problems are delineated, including brief discussions of source water characteristics, standards of water quality and other pertinent factors. Methods of water treatment are evaluated for applicability to the conditions of interest and, finally, development opportunities of potential significance in these applications are described.

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*that is, water that can be used regularly for human consumption without adverse effect on health and that has taste, odor and color characteristics which are acceptable to humans.

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

A summary of the information developed in the course of this study is presented in matrix form in Table I. Process comparison information is summarized in Tables II and III.

Significant conclusions reached are as follows:

1. There is no single best method for producing potable water from untreated sources. Quality of available water, as well as other local conditions, varies substantially from place to place. To use universally a process which would always guarantee safe, palatable water, regardless of these local variations, would be unacceptably expensive. To meet the relatively difficult cost and operability requirements of rural communities in developing countries, each water supply situation must be carefully evaluated to determine the treatment process which is most suitable.

2. Economically and operationally feasible methods are available for handling the range of water quality control problems expected to be encountered in areas of limited development, with two possible exceptions.

(a) For source water that is too brackish or saline for human consumption (greater than approximately 1500 ppm total dissolved solids), there is no low cost method available for reducing the salinity to acceptable levels (on the order of ten cents per 1,000 gallons total cost).

(b) There is no completely satisfactory method for controlling the hardy enteric viruses* (particularly those causing hepatitis and poliomyelitis) if they are potentially present in the water supply. Although either high level chlorination or high temperature sterilization is effective against such organisms, these processes are not economically or operationally well

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*Viruses which are found, in quantity, in human feces and in sewage.

TABLE I

COMPARISON OF WATER TREATMENT METHODS

Qualitative scale, with higher numbers indicating more favorable characteristics, ranging as follows:

0;	No significant effect on water quality; impractical even for special applications.
up to 5;	Maximum improvement of practical value for human consumption; cost and operability well within developing country capabilities.
and down to -2;	Significant deterioration of quality.

	SAFETY		PALATABILITY		PRACTICABILITY		
	Turbidity	Pathogen* Content	Dissolved Solids	Color, Taste, & Odor	Capital Cost	Operation & Service	General Applicability
Source Protection*	1	3	1	2	5	5	yes
Sedimentation	3	2	0	0 to 2	5	5	yes
Filtration	4	3	0	1	4	4	yes
Coagulation - Filtration	5	4	0	2	3	2	maybe
Chlorination	0	5	0	-2 to 2**	2 to 5**	2 to 5**	yes
Radiation	0	5	0	3	3	3	maybe
Pasteurization	0	5	0	2	2	2	no
Distillation	5	5	5	3	1	1	no
Other	-	-	-	-	unfavorable	unfavorable	no
Required Performance	4	5	1	2	3	3	

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* Terms defined in body of report; pp 13-15

** Depending on chlorination level required to control pathogen content.

TABLE II

COMPARISON OF MECHANICAL TREATMENT METHODS

	Sedimentation	Filtration	Coagulation	Adsorption
1. **Effectiveness**				
a. Turbidity	Very effective when size range of suspended matter is such that sedimentation proceeds well.	Very effective, with proper design.	Most effective, in combination with filtration.	Effective for organic material and for slowing putrification of polluted sludge.
b. Bactericide	Quite effective (as above), but must be supplemented if raw water pollution level is significant.	Very effective, but requires supplementary treatment (e.g. chlorination) to assure safety.	Very effective, but still requires supplementation if raw water pollution is (or may be) high.	Quite low.
c. Vericide	Fairly effective if sedimentation conditions are good; must be supplemented.	Quite effective for most feed water conditions but must be supplemented.	Very effective but supplementation required, as above.	Quite low.
d. Color, taste and odor	Color may be improved; less effect on odor and taste.	Very little effect.	Little improvement.	Activated charcoal adsorption is best single method available.
e. Side effects	Palatability deteriorates if algae growth is excessive.	None	None	None
2. **Control**	Weed growth and basin "turn-over" are major problems. Since it is a passive process, effluent must be tested frequently to be sure of effectiveness.	Effectiveness varies with operation: e.g. low until "mat" is established, with capacity declining as solids accumulate. Must then be back washed, or otherwise reconstituted.	Considerable flexibility for meeting specific needs. Monitoring and control program required for effective application.	Effectiveness declines as total adsorptive capacity is reached so monitoring for periodic replacement is needed.
3. **Special Requirements**	Relatively large area required; excavation must be fairly impervious to water percolation.	None	Specific process design program required to determine needs and to establish optimum process conditions.	Useful only as a supplement to other methods.
4. **Costs**				
a. Capital Investment	Labor need high but can be unskilled. No special materials required.	Labor need fairly high but can be unskilled. Materials requirements more specific than for sedimentation but still low.	Must be followed by filtration but additional cost relative to that process is not very great.	Generally low.
b. Operation and maintenance	Except for routine surveillance, operating labor and materials requirements are very low.	Periodic maintenance needed with some operator training required. Unlikely that imported materials would be required.	Very specific operating material needs; may be expensive unless local supply is available. Constant attention by trained operators required.	Not excessive if adsorptive material (e.g. activated charcoal) can be manufactured locally.

TABLE III

COMPARISON OF DISINFECTANTS FOR WATER

	Chlorination	Ultraviolet Radiation	Ozonation	Pasteurization	Distillation
1. Effectiveness					
a. Turbidity	Effectiveness reduced by presence of turbidity due to potential "imbedded" organisms.	Effectiveness reduced as with chloronation.	Effectiveness reduced as with chloronation.	Process does not improve turbidity but latter does not impair effectiveness.	Effectively eliminates turbidity.
b. Bactericide	Very effective when dosage is sufficient to provide about 1 ppm of residual chlorine.	Very effective if well designed and properly operated.	Very effective if properly designed and operated.	Very effective; time and temperature requirements well established.	Very effective if thermal conditions are properly chosen.
c. Viricide	Generally effective although for certain viruses dosages up to 10 ppm and contact times[*] of 2 hours or more are required.	Very effective when properly used although difficult to assure protection against enteric viruses.	Generally very effective but the hardier enteric viruses may be a problem as with chlorination process.	Normal process conditions not adequate for hardy viruses. Higher temperatures and longer times will control.	Would not normally have process time and temperatures necessary although adequate designs can be devised.
d. Color, taste and odor	Little effect on color; may reduce odor by algae control and by masking but high dosage requirements may make treated water unpalatable.	Improves palatability; leaves no residual traces.	Very effective in improving palatability.	Some improvement in palatability.	Eliminates color, taste and odor factors but results in "flat" taste.
e. Residual protection	Proper dosage can provide enough residual chlorine content to prevent recontamination for up to 70 hours.	No residual protection provided.	No significant residual protection provided.	None.	None.
f. Side effects	Toxic to fish and shellfish in concentrations as low as 0.01 ppm.	None.	None.	None.	Extremely pure water is relatively corrosive.
2. Control	To assure disinfection and yet not waste chlorine and render water unpalatable, simple chemical test for residual chlorine content is required at least daily. Dosage rate should be adjusted accordingly.	No severe control requirements. Dosage rate depends on geometry, clarity of water, and extent to which lamps are kept clean.	As with ultraviolet, control requirements are not severe since overdosage introduces no bad effects.	To assure disinfection, time and temperature must be controlled fairly closely.	Normally not severe, but process control is required to assure protection against hardier organisms.
3. Special Requirements	Chlorine must be in convenient form, e.g. liquid chlorine or hypochlorite. Turbidity must be low.	Water to be treated must have turbidity less than 5 ppm.	Water should have low turbidity. Intake air may have to be dried.	None.	None.
4. Costs					
a. Capital investment	For liquid chlorine, sophisticated equipment is required and costs are high. For using hypochlorite tablets, extremely simple and inexpensive equipment can be devised.	May be very low. For example, 4 cents for each gallon per day of capacity.	High cost (~\$1/gpd) for currently available designs although simplification may be possible for the applications of interest here.	For simple heating, equipment cost can be very low, but energy requirements are then too high. For energy economy, capital cost goes way up.	Fairly high, even for simplest designs in the low capacity range (~ \$1/gpd).
b. Operation and maintenance	Very little labor required but frequent attention by skilled operator needed to achieve good control of the process. Chemicals required; liquid chlorine in tanks costs roughly 0.5 cents per 1000 gallons and hypochlorite about 2 cents per 1000 gallons in U.S. Field costs depend on location.	Daily attention required but no great skill needed. Operation takes from 0.1 and 1 kw-hr of energy per 1000 gallons treated. Lamp replacement costs should be less than one cent per 1000 gallons.	As with ultraviolet, daily attention required to assure operability and cleanliness but no great skill needed. Energy consumption is from 0.1 to 0.2 kw-hr per 1000 gallons treated.	Necessary controls can be rugged enough that operation by unskilled people is feasible. However, energy requirements (on the order of 40 kw-hr.per 1000 gallons at best) are unacceptably high.	Energy requirements of even the most efficient designs are too high to permit general application -of interest only for ultra-pure water production or for using saline sources.

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[*] Not complete agreement on the reliance that can be placed on residual chlorine as an indication of adequate protection against enteric viruses.

suited for field application. The most feasible approach appears to be protection of the water supply to prevent contamination by human or other animal wastes.

3. Source water protection (pollution control) is one of the lowest cost methods of water quality improvement and control applicable to underdeveloped areas. Generally, local labor and materials can be used, with competent guidance, for projects such as water shed clean-up, protected impoundment of surface water, sewage disposal and control, etc., by which the probability of the most serious forms of water supply contamination, i.e. by enteric bacteria and viruses, can be minimized. There are no specific development requirements entailed; field demonstration projects could be undertaken at any time.

4. A combination of sedimentation and filtration provides an effective impurity removal method for use in underdeveloped areas. Adequate information on the application of these processes has already been developed. Also, suitable materials and labor are available in almost any location. If properly applied, these methods will meet all but the most difficult water clean-up problems.

5. To obtain protection against reinfection of the water supply after treatment, there appears to be no substitute for chlorination. Extremely simple devices have been developed for controlled dissolution of pellets containing chlorine in a suitable form, and subsequent mixing of the chlorine solution with the water supply. These devices are cheap and effective where levels of biological contamination are not too high. Where contamination levels are higher, or where viricidal action is required, the principal problem is control of the amount of chlorine added, to assure disinfection

of the water and yet not waste chlorine or render the water unpalatable. Equipment is available to perform this function but present designs appear to be fairly expensive and, in addition, may be too difficult to operate and maintain for successful application in underdeveloped areas. Development of more suitable equipment designs appears worthy of additional attention. For example, for application where electric power is available, it may be possible to develop an electrolytic chlorinator which can use common salt as the raw material and which accomplishes controlled chlorination of water very effectively or, by incorporating chlorination with some combination of alternative processes, it should be possible to keep chlorine requirements down to where extremely simple equipment can be used and where residual chlorine levels will not result in objectionable odor and taste.

6. Where electricity is available, ultraviolet irradiation is a supplementary water treatment method which should be considered for developmental attention since it appears to have potential for simple, low cost application.

7. Installation of pressure water systems for distribution from protected storage to points of use to reduce the likelihood of pollution after treatment is another approach giving a high degree of effectivensss per unit of money spent where such systems do not already exist. Although local materials may have to be supplemented, significant improvement can be obtained without expensive mechanical systems or controls. For example, wind or manual pumping power and elevated storage can be used if electric power is not available or is in short supply. Development requirements are limited to specific system designs to suit particular local requirements. Effective demonstration installations could be made with materials and components which are readily available.

8. Higher order methods of water purification such as ion exchange, electrodialysis, pasteurization, distillation and freezing do not appear applicable to the needs considered here due to capital cost and energy (or operating material) requirements. The exception is for special purpose water supplies such as distilled water for a community health center, or where the purification process can be integrated into other systems being introduced, e.g. combination electric power production and water purification using waste heat from the power plant as the energy source. Distillation is also of interest where sea water must be considered as a source. Development effort on minimum cost designs using solar energy or waste heat from other sources is of potential interest if a significant need for this type of equipment is foreseen.

Recommendations

1. For early demonstration efforts, a "model" system of water source utilization should be set up. This should include applicable features from the following list:

(a) Optimum use of ground water resources; wells, pumping systems, storage facilities, etc. as appropriate for local conditions.

(b) Watershed delineation, clean-up and pollution control for surface water utilization.

(c) "Engineered" surface water impoundment facilities.

(d) Local sewage disposal control program.

(e) Pressurized distribution system.

2. Demonstration water treatment system designs should be prepared to provide detailed information on simplified sedimentation-filtration facilities, chlorination equipment and water quality monitoring methods.

3. Consideration should be given to engineering development effort on:

(a) Field adaptable chlorination equipment, particularly those providing simple, positive control of residual chlorine level and/or the ability to utilize readily available raw materials.

(b) Ultraviolet water disinfection devices suitable for field use.

(c) Utilization of locally available raw materials for water treatment purposes such as local manufacture of activated charcoal, production of compounds suitable for chlorinating water, development of local supplies of coagulants, etc.

(d) Possible utilization of low cost energy sources (e.g. solar energy, waste heat from powder production facilities, or wind power) at least for special purpose applications.

REQUIREMENTS

Source Water Characteristics

The types of water sources available for community or family use can be conveniently classified as follows:

1. Rain water
2. Surface water: streams, ponds, lakes, impounded reservoirs
3. Ground water: springs, shallow wells, deep wells
4. Sea water

Water drawn from these different sources has certain general characteristic variations in quality. In addition, there are substantial differences within each source group. These variations have a profound effect on the treatment required to produce potable water; that is, water that is safe to drink from a health standpoint and which has taste, odor and color characteristics to which humans can adjust.

Rain Water - Water precipitated from the atmosphere is practically pure. However, as the water descends through the air, it takes into solution a small amount of the gases normally present in air and also, as it approaches the earth's surface, varying amounts of dust, smoke, bacteria, spores, etc. which may exist in the belt of atmospheric pollution overlying populated areas. The amount of these impurities is fortunately small, particularly in the sparsely industrialized areas of the world about which we are concerned. Therefore, rain water is a potential source of potable water of very high purity. When caught and stored for consumption, its quality will largely depend upon the cleanliness of the catchment facilities and the particular materials with which it comes in contact during subsequent storage and distribution. The main drawback is that very few areas have sufficient rainfall, suitably distributed through the year, for this to be an adequately reliable source of water for family or community use, directly from man-made catchment facilities.

Surface Water - A substantial portion of the natural rainfall is immediately re-evaporated from the earth's surface. The rest either goes into the ground to build up the ground water supply or passes over the ground to surface streams, ponds or lakes. It is in this passage that impurities in the water arise. Geological factors as well as human activity, both domestic and industrial, along the water course between the point of precipitation and the point of potential use determine the quality of surface water sources. Thus, surface water, whether from streams, lakes or reservoirs, is potentially contaminated and thus is generally unsuitable for human consumption unless specific steps are taken to control the contaminating factors in the watershed or unless the water is properly treated at the point of use.

Types of potential surface water contamination vary greatly with location and season. For example, during periods of flood, streams may carry a great deal of surface wash, while at low water their main sources may be ground water seepage. Surface wash may include insoluble clay which makes the water turbid, or the watershed may be underlain with limestone and other rock formations containing soluble minerals so that the stream flow may be highly mineralized and hard. Communities or individual families may discharge sewage into a water course that is used as a domestic water supply. Also, soil washings may carry mud, leaves, decayed vegetation and animal refuse into the water. This material serves as food for the growth of living organisms in the water, as well as a means of transmitting such organisms from humans and other animals to the water supply, thus permitting the sort of life cycle conditions which can result in epidemics of certain serious diseases.

In regard to living organisms in water, bacteria are by far the most widely distributed. Next in abundance are the micro-organisms such as diatoms and algae. Organisms such as pathogenic* protozoa and the larvae of flukes, hook worms, tape worms, are less widely distributed, but are of concern since they are harmful to man. In general, bacteria, viruses, and certain protozoa render water unsafe, while micro-organisms often impart disagreeable tastes and odors to it.

Bacteria in water may be considered in three classes: (1) natural water bacteria, (2) soil bacteria and (3) bacteria of intestinal origin (enteric). Natural water bacteria are those which are usually found in all surface waters and are harmless to man. Soil bacteria are more numerous in surface waters after heavy rains or when turbidity is high. However, they do not persist long outside their natural environment and, in general, do not constitute a significant water potability problem. Of greatest concern are the organisms of intestinal or sewage origin which include those which cause typhoid fever, cholera, bacillary dysentery, anthrax and amoebic dysentery. A related category are the enteric viruses, the most notable of which are those causing hepatitis and poliomyelitis. The most critical problem, then, in surface water treatment is the control of enteric bacteria and viruses.

Ground Water - As mentioned above, some of the rainfall percolates into the ground and becomes ground water from which it is available to man through springs and wells. During its passage through the ground, the water comes in contact with a variety of minerals, some of which are relatively soluble in water. Iron, manganese and hydrogen sulphide are typical of the troublesome

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*causing disease in man

materials that are particularly apt to be picked up by percolating ground waters. In most cases, suspended matter, bacteria, etc. present as the result of surface drainage will be filtered out of the water as it passes through the ground. The advantages of ground water, relative to surface water, as a source for human consumption, are: clarity, freedom from bacteria, uniform mineral content, and relatively constant temperatures. Disadvantages are: scarcity in many areas, high mineral content in certain localities, and greater cost of utilization (drilling and pumping) than for surface water.

Sea Water - In a very few areas, fresh water sources of any type are so limited that sea water or other extremely saline sources are the only available alternatives if the level of community development is to be advanced.

The types of potential water impurities mentioned in the preceding sections can be described more fully as follows:

1. Turbidity (undissolved solids)

Virtually all surface water supplied are turbid; that is, they contain finely divided matter which is too light to settle unless long periods of time are allowed. The suspended solids usually consist of both organic and inorganic materials. The former include trash of vegetable and animal origin, as well as various living organisms, some of which are harmful to man. The inorganic solids such as clay or fine sand are not critical to human consumption except as they may contain "encased" organisms which the inorganic material may actually protect from the desired effects of water treatment processes. Thus, to be sure water is safe for human consumption, it is important that its turbibity be kept low.

2. Pathogen Content

The amount of bacteria, virus and other organisms in water which cause disease in man and domestic animals is termed the pathogen content. Many other microscopic organisms, both plant and animal, exist in water but are harmless to humans. For most of the pathogenic organisms, their presence in water is indicative of contamination by human excrement. This is commonly determined by observing the concentration of coliform bacteria* in cultures which are prepared and incubated under specified conditions; the absence of this group is taken as indication that the water is free of contamination by human wastes and is pathogenically safe. Although generally adequate, this is not a conclusive test of freedom from enteric viruses, positive detection of which is more difficult. It is of interest to note that there is not complete agreement among water treatment authorities on the question of enteric virus control. Basically, the question is how much more difficult is it to destroy the enteric viruses, particularly those causing hepatitis and poliomyelitis, than the more common pathogenic bacteria? From a review of the available literature, it is concluded here that enteric viruses are considerably more difficult to destroy and that conventional methods which are adequate for control of other pathogens are not capable of eliminating the danger of virus contamination.

3. Dissolved Materials

Virtually all water supplies contain appreciable amounts of dissolved solids and gases. Fortunately, human health is not particularly sensitive to the most common of these materials. Although suggested domestic standards are on the order of 500 parts per million total dissolved solids, levels up to 1500 parts per million may be tolerable, depending on the

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* any of a number of bacteria normally present in the intestinal tract of man.

materials involved. Almost all of the materials which are particularly critical for human consumption are chemical compounds or elements which are not normally found in dangerous concentrations except in the vicinity of industrial activity involving material processing. Control of this type of water impurity is not considered in detail here since, (a) it occurs fairly infrequently, at least in economically underdeveloped areas, and (b) there are no economically feasible methods available for reducing dissolved solids content by any appreciable amount.

Hardness of water is a characteristic which is related to the total dissolved solids content. This refers to the presence in the water of certain minerals which tend to form insoluble deposits in the course of domestic or industrial use. Hardness can be reduced more readily than can total dissolved solids, by simple processes which substitute more tractable materials for the troublesome minerals. However, this would be largely for convenience and the potential cost of even this simple process does not appear in keeping with the main interests of this study.

4. Color, Odor and Taste

Even when levels of both mineral and organic constituents in water are low enough to be considered safe, they may still be evident to the human senses and may exceed limits of acceptability for regular consumption. Salts and hydrogen sulphide, for example, are often found in source waters in sufficient quantities to be objectionable. Various relatively harmless organisms such as algae and protozoa can impart unpleasant flavors and odors which must be controlled if the water supply is to meet human needs adequately.

A summary of water source characteristics is given in Table IV.

Standards of Water Quality

In considering the objective of supplying potable water from available raw water sources, one must define standards of safety and palatability. Although men have recorded their opinions as to what constituted "good" water since ancient times, actual standards of water quality are a recent historical development. Bacteria were first observed in the 17th century, but the relationship between the presence of bacteria in water and the spread of infectious disease was not fully appreciated until the latter half of the 19th century. There were no real water quality standards in this country until 1914 and even now, the only national standards of an enforceable nature are those which govern the quality of water in interstate commerce. The major problem in developing standards has been that many of the most troublesome contaminants were difficult to detect and devious in their effect. Thus, a great deal of time has been taken both to establish meaningful purity criteria and to develop methods of effectively monitoring water supplies for compliance. This latter factor is very likely to be important in relatively underdeveloped locations today. Analyses which will give complete assurance that a given water supply is safe for human consumption require testing facilities and trained operators which are not readily available in the field. An attractive alternative goal is to specify water treatment and control processes which can be relied upon to produce the desired quality, regardless of variations in input conditions. However, this is not easily done at reasonable cost.

The drinking water standards published by the U. S. Public Health Service are too lengthy to include in this report but can be found in reference 14. In summary, they cover (1) source utilization, (2) bacteriological quality, and (3) physical and chemical characteristics. In considering water treatment problems for underdeveloped countries from an engineering point of view, the tendency is to seek some less stringent and more readily monitored set of standards, possibly stressing safety criteria and giving less emphasis to taste, odor, color, etc. However, consumer acceptance would seem to be as important in these applications as it is in more highly developed areas so, for this review, processes were judged on their ability at least to approach the U. S. Public Health Service standards on these physical characteristics, as well as on bacteriological quality as summarized in Table V. Standards of dissolved mineral content were not given detailed consideration in this study since there are no low cost water treatment methods available for controlling this characteristic.

Other Pertinent Factors

Several other criteria must be considered in defining the water treatment problem. The most important of these is the capital investment required to provide adequate facilities. As mentioned above, the quality of water sources is extremely variable from one place to another and, of course, the most dangerous supplies are the most expensive to purify. In appraising various treatment methods, the possibility of utilizing local materials and labor with minimum dependence on imports must be a prime consideration.

A closely related criterion is the availability and cost of energy in various forms. Those treatment methods and systems which require little or no electrical or heat energy are considered to be most useful for underdeveloped areas.

Operating and maintenance requirements are a third important consideration. The factors here include the amount of attention and the level of skill required to keep a system operating, and the material demands of the system such as chemicals, replacement parts, etc. An important concern is the kind of testing required to determine whether a system is performing its function properly - i.e., to ascertain that the water is neither under- nor over-treated.

Finally, the question of estimating costs of equipment, operation, etc. for purposes of comparison warrants brief discussion. In order to be of practical interest, the capital investment and the operating expense to provide water treatment in underdeveloped economies probably should not exceed ten cents per gallon per day of installed capacity and five cents per thousand gallons of water treated, respectively.* Thus, a 10,000 gallon per day installation should not require actual cash outlay greater than about $1,000, and should be capable of operation at capacity for about 50 cents per day. In the following discussion of water treatment methods, only crude cost data can be cited since costs of labor, transportation, electricity, etc. in different areas of the world cannot be estimated precisely. However, some methods can be readily shown to be practical or impractical by means of available data. Estimates of the costs of pumping or piping have not been included in the following discussions. These costs will vary with each location but will not vary significantly within a given location. For roughly comparing water treatment processes then, these costs can be ignored.

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*These are our own estimates, based on available reports of field conditions. No definitive conclusions in this area were found in any of the available literature.

WATER TREATMENT PROCESSES

Sedimentation

The simplest method for improving the purity of relatively large volumes of water is sedimentation, the process in which suspended matter is settled out by slowing the flow of water so that it is relatively quiescent.

When the motion of the water is sufficiently slow, solid matter in the water settles toward the bottom by gravitational attraction. The rate of settling in water due to the earth s gravitational field is dependent primarily on the sizes of the suspended particles and on their densities. Table VI, taken from reference (1), shows the settling rates for a range of particle sizes. It has been found that very fine particles which by themselves have quite long settling times, tend to be carried down by larger ones; thus, turbid water which contains enough silt particles clarifies rapidly on standing even if significant amounts of bacteria or clay particles are present. If necessary, particles of a suitable size may be artificially added to hasten settling. For a given water demand then, the main requirement is to provide adequate capacity to permit the settling times required.

TABLE VI

Settling Rates of Particles,
Specific Gravity = 2.65 in still water at 10°C

Particle Diameter mm	Typical Examples	Time to Settle One Foot
10.	Gravel	0.3 second
1.0	Coarse sand	3.0 seconds
0.10	Fine sand	38.0 seconds
0.010	Silt	33.0 minutes
0.001	Bacteria	35.0 hours
0.0001	Clay	230.0 days

TABLE V

DRINKING WATER STANDARDS

	US Public Health Service Standards (Ref 14)	Suggested Standards for Rural Communities
Turbidity	Maximum of 10 ppm, silica scale (a relative turbidity determination by which the sample is compared to a standard silica solution in a suitable instrument)	Jackson candle turbidity standard equivalent to 10 ppm. (Depth of column of the sample thru which the image of a standard candle flame can just be seen. This is a simple, low cost, time-honored, although inexact, method.)
Color	Maximum of 20 ppm, platinum-cobalt scale (comparison of sample with standard color solutions in a sensitive spectro photometer)	No quantitative standard; base acceptance on reaction of local consumers.
Taste and Odor	. . "water shall have no objectionable taste or odor."	As with color, standard should be based on local acceptance.
Pathogen Content		
a. Bacteria	1. Determined by bacteriological examination of samples collected at representative points throughout the distribution system. 2. Minimum sampling frequency based on population served, e.g., one standard sample per month for supplies serving 2000 people or less. 3. Either five-10 milliliter portions or five 100 milliliter portions can be used as standard sample size. 4. Presence of coliform bacteria considered confirmed if there is <u>any</u> gas formation during 48 hours incubation at 37°C of standard media such as brilliant green bile lactose broth, 2 per cent, prepared with sample water. 5. Not more than 10% of all 10 ml portions or 60% of all 100 ml portions examined per month shall show the presence of coliform organisms. Corrective action must be taken when results are unsatisfactory and daily samples must be collected until results again meet standards.	1. Suggest sampling at principal points of use <u>and</u> at the point where raw water enters the treatment facilities. 2. Regularly scheduled bacteriological sampling; for example, one sample each week, alternating between raw and treated water sampling points. 3. Not critical; larger size probably more appropriate. 4. Simplified methods for rough determination of coliform level in raw water and for detection of active coliform organisms in treated water are required. Standards should be equivalent to USPHS. 5. When active coliform organisms are detected in treated water or when levels in raw water exceed a specified level (e.g., 50 per 100 ml standard portion) predetermined procedures for intensifying the disinfection process and for correcting the cause of the rise in level should be instituted.
b. Virus	No standard specified. Absence of coliform bacteria is assumed to indicate freedom from pathogenic (enteric) viruses.	If possible, a simple method of detecting enteric viruses should be developed. In any case, the "emergency" measures mentioned above should be based on the assumption that such viruses are present.
Dissolved Solids	Total content should not exceed 500 ppm. However, if such water is not available, a total dissolved solids content of 1000 ppm may be permitted. Analysis need be made only semiannually.	1500 ppm, measured by a simple but not necessarily precise method is suggested (e.g., evaporation of a standard sample and weighing of residue).
a. Ions having required limits	Flouride - 1.5 ppm, Lead - 0.1 ppm, and Hexavalent Chromium -0.05 ppm by methods defined in "Standard Methods for the Examination of Water & Sewage," current edition. Arsenic-0.05 ppm and Selenium-0.05 ppm, as in "Official & Tentative Methods of Analysis," Assn. of Official Agricultural Chemists.	No change. However, adaptation of analytical methods to suit the facilities, personnel & materials apt to be available in remote and relatively underdeveloped areas would be desirable. Frequent analysis is not required since these constituents are only apt to result from industrial or agricultural activity.
b. Ions & substances with suggested limits	Copper-3.0 ppm, Iron & Manganese together,-0.3 ppm, Zinc-15 ppm, Chloride-250 ppm, Sulphate-250 ppm, & Phenolic compounds-0.001 ppm, in terms of phenol, by methods defined in "Standard Methods for the Examination of Water & Sewage," current edition.	Suggest that standard be based on palatability, rather than specified levels to be determined by chemical analysis.

In many areas, construction of suitable basins is quite easy, particularly if natural features of the terrain can be used advantageously. In the municipal water system of St. Paul, Minnesota, for example, considerable sedimentation occurs as the water from the Mississippi River traverses an eight mile course through a chain of four lakes enroute to the water plant. Satisfactory basins can be constructed, maintained, and operated by local labor with little or no outside assistance or materials.

When sedimentation takes place under the proper conditions, very substantial removal of biological impurities in the water is effected. Two agencies operate to provide purification. Firstly, bacteria and other very fine particulate matter are carried down by the sedimentation of larger particles, the smaller ones adhering to the larger through chemical, electrical, or physical affinity. Secondly, water is an unfavorable medium for bacterial growth; not only are the required nutrients and environment lacking, but natural predators, especially protozoa, also destroy tremendous numbers of bacteria. It is reported that practical sterility from bacilli can be reached by storage of contaminated water at $64^{o}F$ for two weeks, or at $50^{o}F$ for three weeks, or at $32^{o}F$ for five weeks. Tests of Thames River water before and after reservoir storage for two weeks showed reduction of bacterial content of 80 to 95% depending on the type of bacteria.

A report on removal of virus from water states that "storage of slightly to moderately polluted surface water at temperatures prevailing in warm months can inactivate 99% or more of Coxsackie A2 virus in about a week." Infectious hepatitis virus, however, survived 10 weeks' storage at summer temperatures (7). Thus, the retention period is an important consideration in designing a sedimentation basin; that is, the length of time the water takes to travel the length of the facility.

To supply water at the rate of 10,000 gallons per day with a two-week retention period, a basin volume of 18,800 cubic feet is required, neglecting losses due to seepage and evaporation. This is the volume, for example, of an excavation 5 feet deep by 20 feet wide by 200 feet long. The velocity of the water in this basin would average 13 feet per hour which is slow enough to permit adequate sedimentation. The design and planning of such a project is the province of civil engineers. Because field conditions vary so greatly, no meaningful costs can be stated for this method. Obviously, capital investment can be very low under favorable conditions.

Sedimentation is not, however, a completely satisfactory way to purify water. Although the process is the ultimate in simplicity, its very simplicity also obviates human control. The effect of seasonal temperatures on the "turnover" of water in ponds and lakes is a well-known phenomenon; as the density of the surface water changes with temperature, the bottom water is displaced, and settled matter is frequently redispersed throughout the stored water. Bottom sediments are often disturbed by wind and wave action and by rain storms. Furthermore, some protozoa, though effective bacteriophages, impart offensive odors and tests to the water. Finally, in shallow basins, weed control is likely to be a problem unless preventive steps are taken. Both protozoa and weeds are reduced substantially by the exclusion of light. Thus, sedimentation will be of principal interest in localities where raw water quality, geography, and climate are favorable and where such facilities could be considered as a first step in the development of a more elaborate water supply system.

Filtration

A second simple method for purifying water is filtration. During passage through a layer of a suitable medium containing small interstices, particulate matter is strained out of the water stream. During the 18th and 19th centuries, "filter basins" were constructed along streams and lakes by excavating long conduits parallel to the shore line of the water body. Water which seeped into the basin, both from the adjacent body of water and from underground water flowing toward the lake or river, was filtered during its passage through the ground. Properly designed installations served satisfactorily for many years.

The same principle is utilized in a more elaborate device called the sand filter. In this device, water passes through a two to three foot layer of moderately fine sand or other medium, such as crushed anthracite, magnetite, coke cinders, and charcoal; mixtures or alternate layers of different materials are sometimes used in special situations. With use, the pores in the filter become clogged with solids; initially, this improves the quality of the effluent water, but eventually the through-put becomes too low, and the filter must be renewed by removal of the top inch of medium. Such filters with capacities of roughly two gallons per hour per square foot were common in England and the United States during the latter half of the 19th century but, more recently, increased demands for water have necessitated the use of so-called fast sand filters. The principles of the two are the same but the fast filter requires more frequent regeneration using air and water under high pressures; fast filters are, therefore, less practical for water treatment in primitive areas.

Slow sand filters are known to be effective in purifying water which is not too high in turbidity, bacterial and algal content, or in color and taste. Their effect depends largely on the presence of living organisms in the top layers of the filter medium. These organisms consume organic matter in the water and thereby purify it and oxygenate it. The efficiency of this biological action, however, depends on the water temperature and, therefore, fluctuates. Each time the filter surface is renewed, a fresh mat of organisms must develop before the filter is again highly effective. The fact that about 100 slow sand filter plants are still in operation in the Eastern United States is evidence of their practicality.

Both filter basins and slow sand filters can be utilized advantageously in many areas to improve the quality of water supplies. Filters require occasional maintenance but no operating supplies are needed. For a given water demand, filters require less plant area than sedimentation basins do; furthermore, much better control of water quality is possible with filters and many of the problems of pond storage are avoided. Where conditions permit, filtering the effluent of a sedimentation basin would provide substantial purification of the raw water. However, it must be recognized that sedimentation and filtration are inadequate treatment for waters containing any appreciable coliform loading.

The construction of filter basins is very simple, since only an excavation is needed. Sand filters are more complicated since some means for collecting the filtered water and transporting it to storage is required; again, in many places judicious use of local topography would minimize the need of imported construction materials. Both kinds of device can be designed by qualified civil engineers and constructed, operated, and maintained with local labor and materials. Demonstration projects could be readily established as desired.

Coagulation

Practically all modern water supply systems use the "flocculation" or "coagulation" process to treat the raw water. This process consists of adding to the water substances which form flocculent, gelatinous precipitates; after a suitable aging treatment, during which the precipitate particles capture solid matter suspended in the water, the precipitate is removed, usually by filtration. Commonly used additives are compounds of aluminum or iron, usually the sulfates. This process is very effective in reducing the solid content including disease-producing organisms; tests have shown the removal of 95 to 99% of enteric virus in a single flocculation treatment (7). In some areas of the world suitable substances for the flocculation treatment can be obtained quite readily. The addition of these to raw water, followed by sedimentation or filtration, is an effective way to provide substantial improvement in water quality. The cost of coagulation cannot be stated with any certainty; in a few localities where suitable materials are available, the cost would be very small, while in many, the cost would be excessive.

Charcoal

Carbon in the form of charcoal has been used to some extent to purify water for many centuries and, because its production is easy, its use might seem attractive. It is the best single method for odor, taste, and color removal, but its efficiency in removing disease-producing organisms is rather low. Ordinary charcoal is much less effective than activated charcoal, which is only slightly more difficult to produce. It can be added to water as powder and then removed by sedimentation or filtration; or the water can be passed through filters containing charcoal. Organic matter is removed by adsorption on the surfaces of the charcoal, so that periodic replacement of the charcoal is required. When applied at about 20 pounds per million gallons, charcoal is effective in dechlorinating water. To purify badly polluted water then, treatment first with large concentrations of chlorine followed by dechlorination with charcoal is often used. Finally, charcoal is reported to counteract putrefaction of sedimented sludge in storage basins; its use for this purpose might be desirable in some circumstances, especially in areas where it is manufactured or could be manufactured. The cost would depend entirely on local conditions and how it was applied.

Disinfection

The most critical treatment of water supplies is to remove disease-producing organisms. Although water is more palatable when it is limid and free of taste and odor, freedom from toxic materials is obviously more important. Several different methods of water sterilization have been used with varying degrees of success. Chemical treatments for which extensive experience has been accumulated include chlorination and ozonation, as well as other methods used for relatively small volumes of water. Disinfection by ultraviolet radiation has limited application. Finally, adsorption of organisms on suitable materials such as flocculants and charcoal is one of the important methods for reducing the number of undesirable organisms.

1. Chlorination

Chemical disinfection is commonly practiced in water treatment plants, especially in the United States, with chlorine being used most extensively, either as the gas or in chemical combination. It is thought that chlorine acts as a bactericide in the form of hypochlorous acid (HOCl) which forms when chlorine dissolves in water. Some bacteria are more resistant than others to the lethal effects of chlorine, while virus organisms are quite difficult to kill. As one would expect, this resistance can be counteracted to a large extent by increasing either the chlorine concentration or the time the organisms are exposed to chlorine, or a combination of the two. Unfortunately the dose necessary for good viricidal effect is so great that the water must be dechlorinated later in order to make it palatable. It frequently is impossible to predict accurately how much chlorine must be added to accomplish satisfactory disinfection as some waters will absorb much more chlorine than others. For example, chlorine does not discriminate between the pathogenic organisms and the other organic matter in the water which may be considered harmless. Also, the presence of sulphides and of unoxidized iron and manganese will increase the absorption of chlorine. Other variables which will affect requirements are temperature and pH of the water. The general method used to determine the adequacy of dosage is to test for the presence of "free" chlorine at a suitable time (e.g. five minutes) after chlorine application. This slight amount of chlorine in excess of the demand is called residual chlorine. It represents a factor of safety as well as an indicator that all (at least all readily reacted) organisms have been destroyed. Residual chlorine usually is measured colorimetrically with the use of certain standard detectors. Although these are not difficult tests to perform, they require some training, supplies, and initiative. This may be a problem in some areas of potential application.

Available data (reference 12) indicate that "clean" waters containing monthly average coliform densities somewhat in excess of 50 per standard 100 milliliter sample can be treated by simple chlorination to produce bacteriologically acceptable water. The term "clean" here means that the water is free from particulate matter in which pathogens are so inbedded as to survive disinfection. Bacteriological acceptability has no universal definition but, for example, may be stated was water for which regular sampling shows not more than 2 per cent of the samples examined during any one month positive for the presence of coliform bacteria. Filtration or other means for removing suspended solids should be provided in addition to the chlorination if the source water has an appreciable coliform content, e.g. significantly greater than 50 per standard 100 milliliter sample.

In summary, disinfection by chlorination is a very effective method but should include regular surveillance of input water quality and of residual chlorine content in the treated water output. This information should be used to adjust the rate of chlorine addition in order to assure an adequate yet not excessive dosage despite daily, seasonal and unusual variations in source water characteristics.

Chlorine is applied to water most extensively in the form of gas, or as hypochlorite. In highly industrialized areas, chlorine is readily available as a compressed liquid and is cheap; hence, its use for water purification is widespread and the technology of its injection into water has been well developed. Many commercial equipments in a large range of sizes are available for this purpose. A small device to generate chlorine by electrolysis of sodium chloride solution and to inject it into a water supply shows considerable promise (reference 24) . In areas where industry is poorly developed (but not nonexistent) it is often practical to use chlorine combined as chlorinated lime ("bleaching powder") or as sodium or calcium hypochlorite, all of which are watersoluble solids. Chlorinated lime can be made in rudimentary apparatus by the interaction of gaseous chlorine and hydrated lime, a chemical available in most areas of the world. The product is unstable and gradually decomposes with loss of the chlorine content. The manufacture of sodium or calcium hypochlorite is more complicated, but the product is much better for field use since it is stable and has twice the chlorine content of bleaching powder. These sources of chlorine can be injected into water supplies by primitive metering devices such as float-controlled flow from head tanks. Such a device is described in reference 10. These devices could be made locally. To treat 10,000 gallons of water per day with 5 ppm chlorine, the yearly consumption of calcium hypochlorite would be 210 lbs.; the domestic price ranges between 26 and 42 cents per pound depending on the form, the quantity, and packaging. This amounts to two or three cents per 1,000 gals. of water and is, therefore, attractive where transportation facilities are such that hypochlorite can be supplied at reasonable cost.

2. Ultraviolet Radiation

Ultraviolet radiation can be very effective in destroying both bacteria and viruses and is used to purify air in many public buildings as well as to purify water for special purposes such as food and beverage processing, pharmaceutical and chemical manufacturing, and private water supplies.

The radiation is commonly generated in mercury-vapor filled lamps operated at high voltage. Quartz bulbs must be used, because glass is essentially opaque to the desired radiation. For effective destruction of pathogens, the thickness of water being irradiated must be carefully controlled and sufficient contact time must be provided, although the time required is extremely short. Commercial water purification devices consist of a box of suitable inside dimensions, (see Figure 5), containing the lamp and fitted with connections for water; the transformer may be in the box or may be externally mounted. Most incorporate a convenient means of wiping off the quartz lamp housing since accumulations of solid matter seriously attenuate the ultraviolet flux in the water layer, thereby reducing germicidal action. For the same reason, the entering water must be clear with turbidity not exceeding about 5 ppm. For most raw water supplies to meet this requirement necessitates pretreatment such as sedimentation or filtration. Furthermore, ultraviolet output of the lamps diminishes as they are operated, and they must be replaced after several thousand hours of operation. Finally, ultraviolet treatment provides no residual germicidal action so that recontamination during storage may occur.

On the other hand, properly designed and maintained units can provide practically sterile water without the use of chemicals. Daily maintenance consists of periodic operation of the lamp housing wipers. Overexposure for this process has no particular bad effects since the excess energy is merely wasted as heat in the water.

Two typical commercial units have maximum capacities of 500 and 1800 gallons per hour respectively. The capital investment is about $400 for the 500 gph unit and $1200 for the 1800 gph unit. Energy requirements amount to less than 1.0 kilowatt-hours per 10,000 gallons of treated water for these designs. One lamp engineer (8) has stated that currently available ultraviolet lamps are not optimum for water purification and that significant improvements in lamp design could be achieved if sufficient demand developed.

TABLE VII

Comparison of Three Commercial Ultraviolet Equipments For Water Treatment

	Rated Capacity gal/hr	Initial Cost $	Watts	kw-hr per 1,000 gal.	Lamp Cost per 1,000 gals.
Hanovia Lamp Div.	1800	1200	1760	0.98	0.013
" (2 units in series)	5000	2500	3500	0.70	
Ultra Dyn. Corp.	500	400	90	0.2	0.08
Atlantic Ultraviolet Co., Inc.	5000	1300	400	0.1	0.04

Total operating cost depends on cost of electric power. GEL studies of rural electrification costs indicate that 4 to 8 cents per kw-hr might be expected. Therefore, this process offers the possibility of getting down to less than five cents per 1,000 gallons which should be of potential interest.

3. Ozonation

Ozonation is an effective way of disinfecting water and offers the advantage of requiring no chemicals. Water is ozonated by injecting into it a stream of air which has been passed through a silent electric discharge between two metal plates at a high voltage. Ozone, like chlorine, is a very strong oxidizing agent and seems to be very effective in destroying bacteria, viruses and other organic matter, and in improving taste, odor and color. The ozone process enjoyed considerable popularity during the first three decades of the present century in certain areas of the words. Ozonating plants with capacities of 20 million gallons of water per day were built in Paris, while smaller plants were located in Philadelphia, Nice, and many other cities.

Electric power consumption for ozonation varies somewhat: An experimental plant in New York City in 1906 required about 200 kilowatt-hour per million gallons of water, while an Indiana installation of 1932 required only 80 kw-hr per million gallons. With the advent of liquid chlorine, these plants became uneconomical to operate.

One manufacturer estimates that a packaged ozonating plant with a capacity of 10,000 gallons per day could be provided for $10,000. Larger installations would be more economical since the capital investment per unit volume of water decreases substantially as the capacity increases. Power consumption to treat 10,000 gallons is estimated at 10 kw-hr.

4. Thermal Disinfection

The practical success that has been achieved in killing pathogens in milk supplies by pasteurization and in higher temperature sterilization of equipment and materials suggests the use of heat as an approach for a small, simple-to-operate water treatment device. Certainly the application of heat as a disinfection process has been known for a long time and is thoroughly understood. In potential effectiveness it ranks high since, in addition to bacterial pathogens, heat readily inactivates other water organisms such as amebic cysts, worms, viruses, etc. Also its effectiveness is insensitive to variations in other water characteristics such as dissolved solids content, turbidity, etc. Its major drawbacks are that the process requires substantial amounts of energy and that it provides no residual protection so that reinfection downstream from the point of treatment is a hazard.

For simple pasteurization which will control all pathogenic pollution problems except for the most hardy (enteric) viruses, there are well established time temperature relationships, ranging from 161°F for 15 seconds to 145°F for thirty minutes. Most practical applications will lie between these two sets of conditions. Simply to heat water from ambient to the required pasteurization temperature requires an unreasonable amount of energy, even though heating and control equipment can be relatively crude and inexpensive. Generally then, for the process to be economical, it is necessary to re-use the energy; that is, to transfer heat from the output stream of treated water to the input stream of water to be treated. It is also necessary to minimize heat losses by means of appropriate design features. Such provisions can reduce the amount of energy required per gallon of water treated but, of course, they contribute to increased capital cost. Data have been developed (reference 11) for a simple, minimum cost pasteurizer design, suitable for field assembly and use, which would reduce energy requirements to about 40 kw-hr/1,000 gal*. Although field costs for thermal energy in the required temperature range may in some cases be quite low, this still represents a potentially high operating cost.

Capital cost is also a problem, principally because of the design features required to get the energy consumption per unit output down, e g. counter-flow heat exchanger, insulation, treated water storage, and associated pumps. One of the cheapest forms of counter-flow heat exchanger (proposed in the reference design) consists of a substantial length (for example, 100 feet for a 20 gallon per hour capacity) of 1/4 inch copper tubing inserted in a similar length of 1/2 inch copper tubing. With the necessary fittings and insulation, the cost of the materials for such an exchanger is over fifty dollars in the United States, with little chance of significantly lower cost any place else

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*Detailed description of this unit and the supporting development effort are not given here since complete information is readily available from the Water Supply and Research Branch of the Robert A. Taft Sanitation Engineering Center, 4676 Columbia Parkway, Cincinnati 26, Ohio.

in the world nor do there appear to be alternative designs more readily adapted to local manufacture. Total material cost for the pasteurizer, as developed in reference 11, is on the order of five hundred dollars. Reduction by a factor of two is likely to be the limit in cost improvement possible by further simplification of controls, selection of alternate materials, and so forth. This is considerably in excess of the target cash outlay on which applicability in areas of low economic development appears to depend.

Distillation devices are also of potential interest since they are capable of disinfecting water by heat and also of removing dissolved solids. However, the trade-off problem between energy utilization and capital cost is even more didficult than for pasteurization equipment. For example, a diffusion still concept has been developed in the General Engineering Laboratory (Reference 13) in which distillation takes place in the presence of air at atmospheric pressure. This represents an extremely simple process, free from most of the expensive and complex auxiliaries normally associated with vacuum distillation devices. It is also capable of very good energy utilization, if properly designed. However, the practical limit in energy requirements is still on the order of 200 kw-hr. per 1,000 gallons of water treated and, for such thermal performance, capital cost probably cannot be brought below one dollar for each gallon per day of capacity. These costs, again, are well in excess of the target values which obtain for the applications of interest in this study. A possible exception is for medical or pharmaceutical requirements for pryogen-free, injection quality water. In this case, the diffusion still concept is a very interesting possibility, being considerably simpler and less expensive to operate and maintain than other types of water sterilization equipment now available.

Since the practicability of the thermal processes is so dependent on the field cost of thermal energy, there has been a great deal of interest in the utilization of solar energy to drive these processes. This aspect is of particular interest in those low latitude areas where arid conditions and high solar energy availability exist but with saline water sources near at hand. Typical development efforts are reported for Australia (16) eastern Mediterranean (17), India (18), Spain (19) and the Virgin Islands (20). Work has also been carried on in the United States, including a broad program under sponsorship of the Office of Saline Water, U. S. Department of the Interior (21).

The most common concept for solar distillation consists of a "greenhouse" type installation where solar radiation enters through a transparent cover over an evaporating basin. The water vapor produced from the evaporating basin condenses on the under surface of the transparent roof and runs down to collection channels. There are a large number of design variations employed with the object of improving performance. These include multiple effect designs, air circulation to carry the water vapor to a separate water cooled condenser, recovery of heat from the brine stream to preheat the feed water, automatic regulation of feed water flow to match variations in solar energy input rate, etc. However, for all such designs there appears to be the inescapable conclusion that the average rate of solar energy receipt on the earth's surface is so low that very large collector area per unit of capacity will always be required. Although much ingenuity can be exercised in minimizing the cost of such facilities, considerable quantities of special materials of one sort of another (e.g. transparent "roof" material) are required which results in minimum capital investment costs on the order of 87¢ for each gallon per day of capacity, according to a recent GEL study. The example used for this estimate called for minimal use of procured materials and a seacoast site where solar energy was plentiful. The design was based on ponds constructed of locally manufactured blocks, a black polyethylene liner and a covering of clear W-1 Mylar film over a supporting wooden framework. Distillation rates, estimated from published data for test installations of this type, were 0.10 gpd for each square foot of pond area. Thus a 10,000 gpd unit suitable for a rural community would require 100,000 square feet of pond area. Total installation area, including allowance for individual pond walls, service paths, collection troughs, etc. would be 162,000 square feet or almost four acres. Assuming the land, labor and local materials to be free, the cost of Mylar, polyethylene, pumps, motors and piping would total some $8,700, based on available prices in this country, and with no allowance made for transportation costs, etc. This cash outlay requirement would appear to be fairly difficult to meet for an area of limited economic development. Simple pasteurization with solar energy might be possible at a somewhat lower capital cost, but the general conclusion is that for the applications of interest to this study, thermal processes using solar energy do not adequately meet over-all requirements.

Other Processes

A number of other water purification processes either already available or currently being given development attention were considered for this application. These included ion-exchange, electrodialysis and freezing processes. Very preliminary evaluation indicated that installation costs, as well as materials supply and process control characteristics were so far beyond the criteria set for this study that they could not be considered as likely candidates for application in underdeveloped areas.

SYSTEMS CONCEPTS

Most water purification installations combine one or more of the methods discussed in the preceding sections. Typical municipal treatment plants, for example, incorporate coagulation, filtration and chlorination treatments. Practices vary with the quality of the water source but instances in which a single treatment method is used are quite rare. The reason, of course, is simply that no one method is adequate for satisfactorily handling the several deficiencies of most water supplies. Because this will no doubt be the case for water sources in most areasof the world, some combinations of treatment methods are discussed below.

A system combining sedimentation and filtration would appear to be the best initial step . Although such a system will not be universally applicable, it offers several advantages in areas where it can be used. As discussed previously, construction can be accomplished entirely by indigenous labor under the guidance of competent engineers largely, or perhaps entirely, of locally available materials. Also, the completed system could be operated by native labor, independent of imported supplies and with relatively simple equipment maintenance. This system is primitive compared to modern practice, yet it served effectively in many localities; for example, the city of London during the 19th century. One expert (1) concluded from a consideration of bacteriological studies of raw and treated water that "the performance of the London filters in 1885 was not greatly inferior to present day practice - - - - - - -. These results were achieved without the use of coagulants or chlorine; plain sedimentation and slow sand filtration only were the processes by means of which these early results were attained."

The second system to be considered here would improve on the first one by adding to it a disinfection step. A likely candidate, where electric power is available, would be ultraviolet radiation because the devices to produce the desired effects are relatively inexpensive, yet cheap to operate, and easily maintained. Complete destruction of pathogens of all kinds can be assured by proper design. Chlorination could be substituted, probably at lower capital cost, but process control problems would be more difficult, particularly if protection against certain of the hardier pathogenic organisms is required.

A modification of the previous system would provide complete protection, still at modest cost. For this approach, the water would be treated by sedimentation and filtration, as above, following which it would be disinfected with ultraviolet radiation and then chlorinated to about 0.5 ppm. This final step would provide for residual germicidal protection, thus reducing substantially the likelihood of recontamination during storage. In regions where salt (sodium chloride) is readily available (at the rate of 100 lbs. per year for a 10,000 gpd plant) electrolytic generation of chlorine would be reasonable; elsewhere, hypochlorination (21 lbs. of calcium hypochlorite per year for a 10,000 gpd plant) might be preferable. Assuming that labor costs for construction of sedimentation basins, filters, and hypochlorinators and for operation and maintenance were negligible, for a 10,000 gpd plant, the capital investment for ultraviolet equipment would amount to less than four cents per gpd of installed capacity; electrolysis equipment cost two cents per gpd of capacity. Operating supplies would cost less than four cents per thousand gallons for ultraviolet lamps and about two cents per thousand gallons for calcium hypochlorite. Electrolytic generation of chlorine would require 0.4 kw-hr per thousand gallons while the lamps would consume less than 0.2 kw-hr per thousand gallons. These data are based on commercially available ultraviolet water treating units which are not necessarily the optimum design for a 10,000 gpd plant.

Small capacity water treatment systems of the coagulation-filtration-chlorination type have been developed in packaged form for military and Civil Defense use. An example is the so-called ERDLator developed by the U.S. Army's Engineering Research and Development Laboratory at Fort Belvoir, Virginia (22). These systems have been built in quantity and have proved capable of handling a wide range of troublesome water treatment problems, including high pathogenic content. In current form (see Figure 3) the equipment is fairly complex and requires close adherence to specified operating procedures and thus, does not meet the cost and operational requirements of this study. However, from the knowledge and experience gained in this work it might be possible to develop simplified designs of a more appropriate nature, trading off capacity or versatility for lower cost and easier operation.

Still another systems concept that has been considered is one which combines water treatment with electric power generation, utilizing waste heat from the latter as a source of thermal energy for distillation or pasteurization processes. As an example, a 50 kw generating station, driven by a diesel engine, might be considered for a community power plant. Waste energy from such a plant would be most readily obtained from the cooling water (water to water heat exchange equipment is cheaper than gas to water, and exhaust back pressure effects are avoided). About one-third of the fuel energy used in the diesel would be removed in the cooling water. This would amount to about 248,000 BTU/hr (72 kw) for a 50 kwe plant. Maximum coolant temperature would be approximately 185°F. This is quite adequate for driving a distillation device. Equipment is now on the market, in a range of small capacities, which will produce a gallon of water for approximately 8500 BTU from such a heat source. Thus, the output of such a still, integrated with a 50 kwe diesel power plant, would be almost 30 gallons per hour while the power plant is running. Assuming a daily operating schedule of ten hours, this system would yield about 300 gallons per day. A specific example of such a device, as described in reference 23.

Stills having higher energy utilization are, of course, available. One of the simplest of these would be the diffusion still, described in reference 13. For this type of heat source, such a still would be capable of about 140 gallons per hour. Although incremental operating costs would be very low for this system, the capital cost would still be high, relative to the goal set for this study.

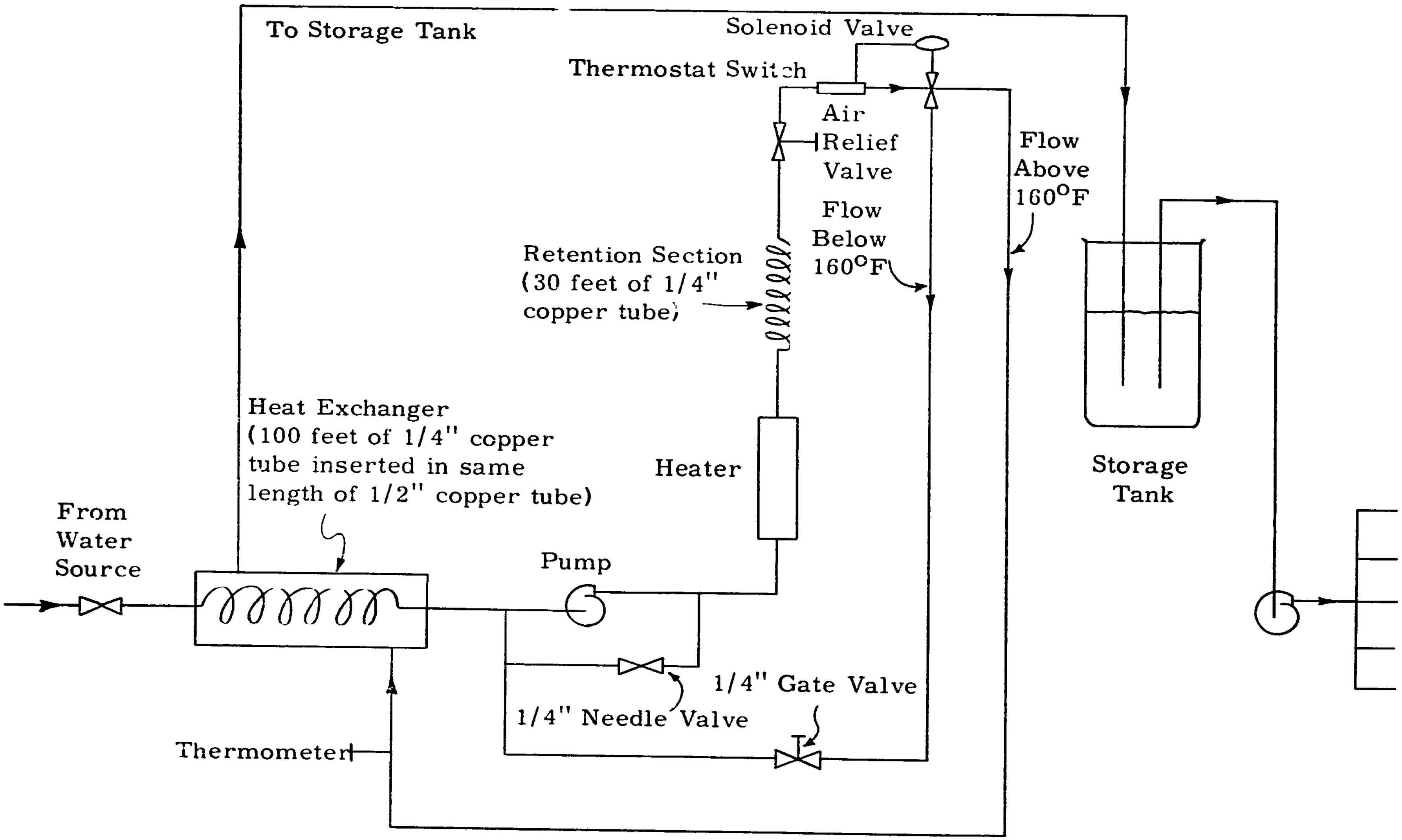

Fig. 1. Continuous Flow Pasteurizer. Approximately 250 Gallons per 12-Hour Day. (As Described in Reference 12.)

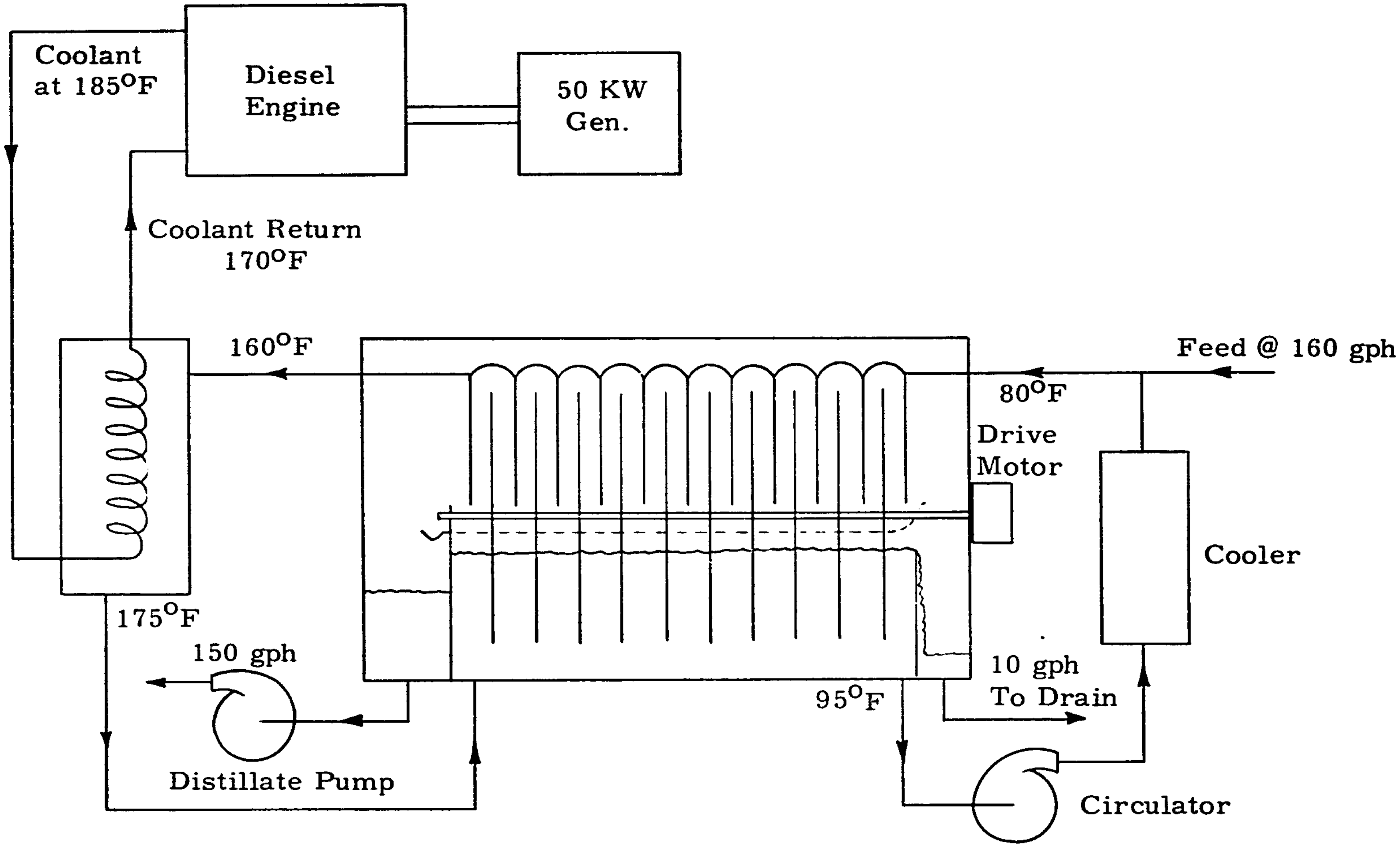

Fig. 2. Combined Power Plant - Distillery.

Note: For Key to Numbering System Refer to Page 36D.

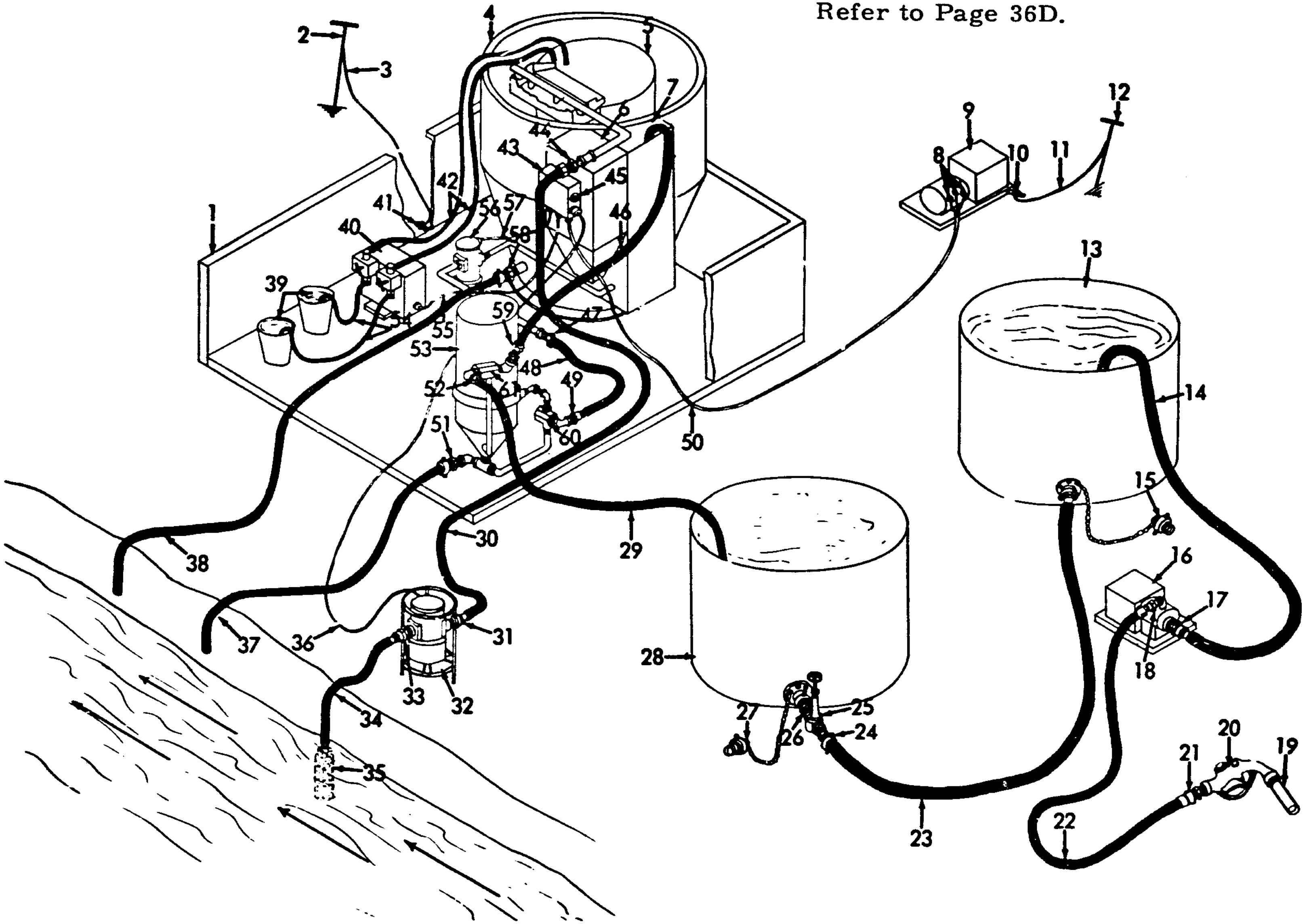

Figure 3. Typical Installation of Packaged Water Purification Unit

Key To Numbering System On Figure 3

1 Cargo body
2 Cargo body ground rod
3 Ground cable
4 Erdlator tank
5 Downcomer
6 Sludge concentrator tank
7 Wet well
8 Generator terminal lugs
9 Generator set
10 Generator ground lug
11 Generator ground cable
12 Generator ground rod
13 Second filtered water storage tank
14 Distribution pump suction hose, rubber, 1-1/2 in. x 10 ft.
15 Filtered water tank chain and cap, 1-1/2 in. male hose
16 Distribution pump (gasoline driven)
17 Adapter, male pipe to female hose, 1-1/2 in.
18 Adapter, male pipe, 1-1/2 in.
19 Distribution nozzle extension pipe, 1-1/2 in.
20 Distribution nozzle, 1-1/2 in. pipe thds
21 Adapter, male, pipe to female hose, 1-1/2 in. x 25 ft.
22 Distribution hose, fabric, 1-1/2 in x 25 ft
23 Hose, rubber, 1-1/2 in. x 10 ft
24 Adapter, male pipe to hose, 1-1/2 in.
25 Valve, gate, 1-1/2 in. female pipe
26 Adapter, male, pipe to hose, 1-1/2 in.
27 Cap and chain male pipe, 1-1/2 in.
28 First filtered water storage tank
29 Filtered water hose, 1 in. x 25 ft
30 Raw water pump discharge hose, fabric, 1 in. x 25 ft
31 Adapter, male pipe to female hose, 1 in.
32 Raw water pump
33 Adater, male pipe to female hose, 1 in.
34 Raw water pump suction hose, rubber, 1 in. x 10 ft
35 Strainer, raw water pump suction, 1 in. female
36 Raw water pump electric cable
37 Filter waste water hose, rubber, 1-1/4 in. x 10 ft
38 Erdlator tank waste water hose, rubber, 1-1/4 in. x 10 ft
39 Rubber pails
40 Chemical solution feeder
41 Cargo body ground lug
42 Chemical solution feeder discharge plastic tubing, 3/4 in. od x 68 in. (2 ea)
43 Electrical control box
44 Adapter, male, pipe to male hose, 1 in.
45 120 volt outlet receptacle
46 Recirculating hose, rubber, 1 in. x 10 ft
47 Adapter, male pipe to hose, 1 in.
48 Hose, rubber 1 in. x 10 ft
49 Adapter, male pipe to female hose, 1 in.
50 Main power cable
51 Adapter, male pipe to hose, 1-1/4 in.
52 Adapter, male pipe to male hose, 1 in.
53 Diatomite filter
54 Chemical solution feeder suction tubing, 3/4 in. od x 48 in.
55 Chemical solution feeder power cable
56 Filter pump
57 Filter pump power cable
58 Adapter, male pipe to male hose, 1-1/4 in.
59 Adater, male pipe to male hose, 1 in.
60 Influent plug valve, 1 in.
61 Effluent plug valve, 1 in.

DEVELOPMENT OPPORTUNITIES

There appear to be a number of engineering development programs which, if directed at specific requirements, would make a significant contribution to the feasibility of providing safe, palatable water for family or community use in the relatively underdeveloped areas of the world.

1. There is a great deal of information that has been developed over the years on the utilization and management of water supplies; how to appraise the relative merits of alternative sources; how to minimize the degree of contamination and the risk of epidemic conditions, etc.

Agencies publishing data in this field include the United Nations Water Resources Development Centre, the American Water Works Association, the U. S. Senate Select Committee on National Water Resources, the U. S. Department of Health, Education and Welfare, U. S. Department of Agriculture, and the U. S. Department of the Interior. However, very few of the available publications have the practical problems of potable water supply facilities for developing areas of the world as a major focus. Therefore, the presently rather diffuse information should be organized and presented in such a form that it could be readily used in the field by people without specific civil or sanitary engineering training to direct the development or improvement of small capacity water supply systems. Compilation of information on minimum cost pumping, storage and distribution equipment would also be of value. From such effort, specific opportunities might come to light; for example, to extend the application of wind or solar power to a wider range of water system components.

2. Since the very simple water treatment methods such as sedimentation and filtration can in many cases go a long way toward providing potable water, steps should be taken to provide technical information and direction, in

appropriate form, for applying such methods. As with the water resource utilization problem mentioned above, extensive information has been developed but it is presently available only in diffuse form. The available data should be compiled, assessed, and organized for direct applicability to the conditions of interest in this study: Specifically, criteria should be developed for simplifying the identification of suitable water treatment sites; for example, the kind of water problems for which alternative methods are best suited, the quantities of water that can be handled effectively by the various processes, and the natural features such as topography, soil types, etc. that can be utilized as well as those which should be avoided. Basic engineering information for the design and construction of the treatment facilities should be assembled, including such subjects as kinds of construction best suited to a range of typical local conditions, utilization of locally available materials, excavation and construction methods feasible with unskilled labor, etc. Published in handbook form, such information could be very valuable to field personnel who might have to select methods and designate sites for water treatment facilities as well as to those who would actually direct design and construction. There should be enough successful field experience available, coupled with sound engineering principles, to provide substantial, realistic assistance in this area.

3. In many instances, the water treatment equipment which is available commercially is designed for use in relatively well developed environments in regard to availability of materials, parts, skilled repair service, trained operators, etc. It appears very likely that more simple and rugged designs could be devised which would still be functionally adequate for remote locations. For example, rudimentary chlorinators have been developed which are inexpensive and simple to operate (ref. 10), using hypochlorite tablets.

Additional designs should be developed which can use other forms of chlorine, such as "bleaching powder," for locations where supply of the prepared tablets is a problem. Methods of determining residual chlorine in treated water so that the rate of addition can be controlled to achieve safe, economical operation are deserving of attention. Presently available approaches appear to require a level of skill and operator discipline which may not be feasible in many field locations where chlorine requirements are sufficiently high for such control to be of critical importance. A development opportunity of this type is represented by the device mentioned earlier which is capable of generating chlorine by electrolysis of sodium chlorine solution and injecting it into a water supply in a readily controlled manner, with very little operator attention required.

Other specific equipment design development opportunities include devices which use ultraviolet energy for disinfecting water. In certain circumstances, this could provide a supplementary method which would be very well suited for integration into an over-all water treatment system. Available equipments, in general, have not been designed for simplicity, ruggedness and reliability. The potential for development effort in these directions should be investigated in more detail.

4. Another area of engineering study which could be of considerable importance to field water treatment is the utilization of indigenous materials and manufacturing capability. Possibilities in the materials area include filter material, compounds suitable as sources of chlorine, potential coagulants, activated charcoal, etc. Collection of pertinent data and thorough exploration of the potential opportunities would be a formidable engineering task but the results could be extremely significant since they might also point the way to potential opportunities for economic development

not now recognized. In the area of field manufacture, effort should be integrated with the development of simplified equipment designs, mentioned in (3) above.

5. Parallel efforts on community development possibilities other than water treatment such as communications, electric power, sanitation and health, etc. are being carried forward on a relatively extensive scale. In many cases, the potable water supply problem is considered separately from such efforts. Attention should be given to the integration of water treatment systems with these other activities. Effort should be made to assess the status and potential accomplishments of the various programs to determine their possible influence on the relative feasibility of alternative water treatment methods. Specific proposals for electric power generation systems, cold storage facilities, community health centers, etc. should be examined for potential integration opportunities with water treatment requirements. Both capital costs and operating needs for certain approaches to the problems of potable water supply may be strongly influenced by such developments.

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REPRESENTATIVE SOURCES OF WATER TREATMENT EQUIPMENT

Chlorinators

Everson Mfg. Corp.
Wallace and Tiernan,Inc.

Filters, small

Wilson Chemical Feeders, Inc.
Ogden Filter Co.

Indus. & Municipal Equip., general

Hungerford and Terry, Inc.
Culligan, Inc.
Refinite Water Conditioning Co.
Belco Industrial Equip. Div.

Hypochlorinators

Wilson Chemical Feeders, Inc.
Everpure, Inc.
Precision Chemical Pump Corp.

Ozone Disinfection Devices

General Ozone Corp.
Groak Engineering Corp.
INVEX, Inc.

Purifiers (color, odor, taste)

Wilson Chemical Feeders, Inc.
Everpure, Inc.

Ultraviolet Disinfection Devices

Atlantic Ultraviolet Co.
Hanovia Lamp Div.
Ultra-Dynamics Corp.

Unitized Treatment Systems

Culligan, Inc.
Hungerford and Terry, Inc.
R. P. Adams Co.
Met-Pro, Inc.

R. P. Adams Co. Inc.
Buffalo 17, N. Y.

Atlantic Ultraviolet Co.Inc.
2410 40th Ave.
Long Island City 1, N. Y.

Belco Ind. Equip. Div.
100 Pennsylvania Ave.
Paterson 3, N. J.

Culligan, Inc.
Northbrook, Ill.

Everpure, Inc.
2627 West 19th St.
Chicago 8, Ill.

Everson Mfg. Corp.
217 Huron Street
Chicago 10, Ill.

General Ozone Corp.
1111 West Fulton Market
Chicago 7, Ill.

Groak Engineering Corp.
3601 South Iron St.
Chicago 9, Ill.

Hanovin Lamp Div.
100 Chestnut St.
Newark 5, N. J.

Hungerford & Terry, Inc.
Clayton, N. J.

INVEX, Inc.
1100 N.E. 125th St.
North Miami, Fla.

Met-Pro, Inc.
Lansdale, Pa.

Ogden Filter Co. Inc.
4214 Santa Monica Blvd.
Los Angeles, Calif.

Precision Chemical
Pump Corp.
1396 Main St.
Waltham 54, Mass.

Refinite Water Cond. Co.
728 Meadows Bldg.
Dallas, Texas

Ultra-Dynamics Corp.
Thornwood, N. Y.

Wallace & Tiernan,Inc.
25 Main Street
Belleville 9, N. J.

Wilson Chemical
Feeders, Inc.
Buffalo 5, N. Y.