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NUCLEAR DESALINATION PROGRAM

ANNUAL PROGRESS REPORT on Activities Sponsored by The Atomic Energy Commission

Period Ending October 31, 1971

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NUCLEAR DESALINATION PROGRAM ANNUAL PROGRESS REPORT ON ACTIVITIES SPONSORED BY THE ATOMIC ENERGY COMMISSION FOR PERIOD ENDING OCTOBER 31, 1971

R. P. Hammond, Director

Report Compiled by
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NOVEMBER 1972

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Contents

1. Introduction

The Atomic Energy Commission's program on the application of nuclear energy to desalting and other energy-intensive processes has the following objectives: (1) to define and explore potential applications of nuclear energy to processes and services which may have significant potential for economic, social, or environmental improvements and (2) to cooperate with industry and other government agencies in developing the technology needed to implement the above applications of nuclear energy. Most of the AEC program is carried out at ORNL, where closely related work is supported by the Office of Saline Water (OSW) and by the Department of Housing and Urban Development (HUD); these related projects are done under an interagency agreement with the AEC. The OSW supports research and development related to desalting process technology; HUD has sponsored studies of the use of reject heat from nuclear power plants to alleviate urban problems.

Elements of the AEC program on nuclear desalting and other process applications are shown in Fig. 1.

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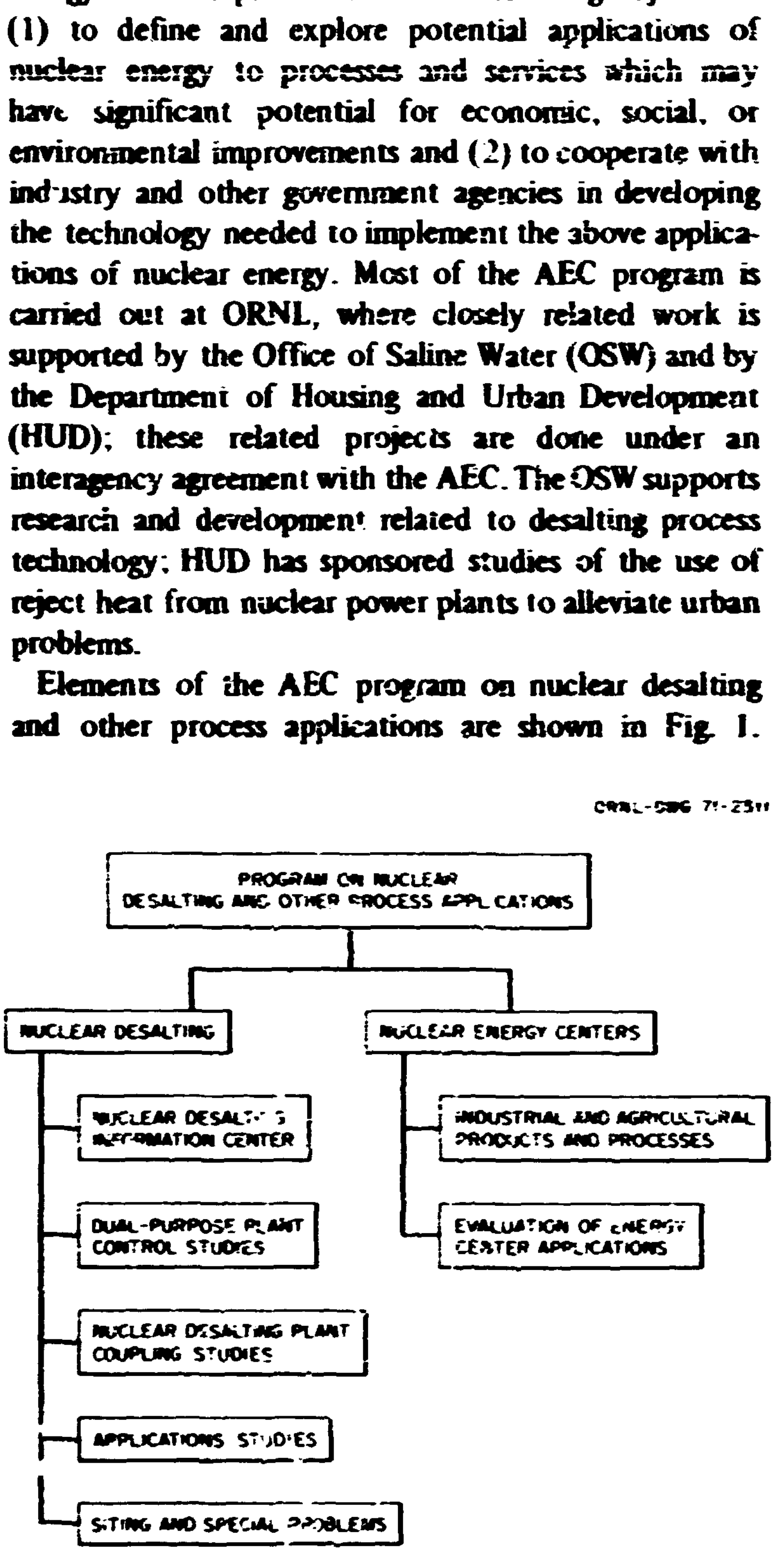

Fig. 1. Elements of program.

There are two major divisions of the program: nuclear desalting and nuclear energy centers.

In the field of nuclear desalting, one important function of the program is to make available to industry, government agencies, and potential desalting plant owners the results of studies as well as generally useful data and techniques that will allow independent evaluations of desalting plant designs and applications. This is accomplished through (1) the development and documentation of general-purpose computer programs for investigating the design, operation, and economics of nuclear power-desalting plants; (2) parametric studies to permit systematic comparisons of methods of producing power and water using alternative heat sources, evaporators, and coupling systems; (3) conceptual studies of new concepts that may be attractive in satisfying future water and energy requirements; and (4) studies and experimental investigations of the practical control and coupling problems related to the design and operation of dual-purpose plants using light-water reactors.

The operation of the Nuclear Desalination Information Center (NDIC) aids the work on all aspects of desalting. Rapid growth of the body of published information on desalting makes the services of the Center especially valuable to engineers and others who are hard pressed for time to keep abreast of current developments in the field.

The same advantages that make nuclear energy attractive for desalting extend to other processes and operations which benefit from low-cost heat and electricity. In particular, the nuclear energy complex, a concept developed at ORNL, has been found to be potentially useful in many parts of the world. Studies at ORNL on the nuclear-powered agro-industrial complex began in 1967 with an intensive multidisciplinary "summer" study. The principal question posed for this study was: How and to what extent could the low-cost energy anticipated from nuclear reactors be used effectively to increase both industrial and agricultural production, with particular attention being given to applications in developing countries? This study provided detailed data and the basic methodology for

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evaluating the costs and benefits of agro-industrial complexes under differing assumptions for location, level of technology, and economic parameters. Work since the initial study has included evaluations of many energy-consuming industrial processes that are suitable for nuclear energy complexes, studies of crops and farming techniques applicable to complexes, and evaluations of specific applications of agro-industrial complexes in both developed and developing countries.

This report summarizes ORNL's work in the above areas for the period from November 1, 1970, through October 31, 1971. More complete information can be found in the technical publications listed at the end of this report.

2. Highlights of Progress

2.1 NUCLEAR DESALTING

Evaluations were made of a number of potential questions concerning coupling of nuclear power plants with evaporators. Cost-benefit studies indicated that certain auxiliary systems would be worthwhile additions to large dual-purpose plants. These included a bypass steam system and an auxiliary condensing system which appear to significantly improve plant availability and flexibility. An investigation was made of health and safety questions related to nuclear desalting plants. The emphasis of this study was on the possibility and consequences of radioactive materials entering the evaporator from the nuclear power plant. It was concluded that the public health and safety can be adequately protected by proper design of the interface between the steam supply and the evaporator.

Studies of the dynamic characteristics of dual-purpose plants indicate that the major control questions and uncertainties lie in the evaporator portion of the plant. Digital simulator studies were made to identify the factors affecting multistage flash (MSF) evaporator stability. It was found that evaporator stability is dependent on the method of coupling to the energy source as well as evaporator plant design features. When brine heater steam temperature is controlled, as it is in single-purpose desalting plants, the evaporator tends to be more stable than when steam flow rate is controlled; the latter approximates a method of control applicable to dual-purpose plants. In effect, the use of MSF evaporators in conjunction with power plants places greater emphasis on designing the evaporator for inherent stability.

Studies related to the application of nuclear desalting plants to long-term water supply problems included a review of the water resources and alternatives for the California region and participation in a study of supplemental water sources for the New York metropolitan region; the New York study was a joint effort by the AEC, the Office of Saline Water, the city of New York, the state of New York, and the Consolidated Edison Company.

2.2 NUCLEAR ENERGY COMPLEXES

Most of the nuclear energy complexes examined by ORNL and other national and international groups have included agriculture as one major element. The key to the successful use of relatively expensive desalted water in agriculture appears to be improved water use efficiency. Economic studies indicated that the development of a low-cost subsurface irrigation system may offer the best means of achieving a large increase in water use efficiency. A survey on the state of the art of subsurface irrigation was made, and this showed that a prime need is to develop an improved emitter device. Flow tests were made on polyethylene tubing with short axial slits controlled by spring clips. The slit-clip concept appears promising, but additional development is required to achieve better reproducibility of flow results.

3. Summaries of Work Completed and in Progress

3.1 NUCLEAR DESALTING PLANT COUPLING STUDIES

Introduction

The Office of Science and Technology, in their recent report on the Federal Desalting Program, concluded that the achievement of low-cost desalted water will depend on the close integration of desalting plants with large-scale energy sources. The ORNL program on nuclear dual-purpose plant coupling is directed toward providing basic information and demonstrating techniques which will lead to the successful integration of nuclear energy sources with large-scale evaporators.

Status Summary

Figure 2 is a schematic illustration of a large-scale dual-purpose plant. This schematic is not based on any particular plant design but is intended to indicate the general scale of major components for a large dual-purpose plant of the future. Only one 50-Mgd train of the evaporator is shown; six such trains would be required to produce 300 Mgd for the total plant. The nuclear steam supply unit is one of the largest commercially available at this time and would produce a total of 705 MW(e) in the dual-purpose plant as opposed to 1171 MW(e) in a power-only plant.

The back-pressure turbines illustrated would exhaust steam at 35 psia to the evaporator. The turbine cycle as shown is very similar to a power-only plant cycle except for the high exhaust pressure. Although this cycle is quite practical and workable, ORNL studies have shown that there are some changes which would probably contribute to making the plant more economical. First, the six-flow back-pressure turbine could be combined

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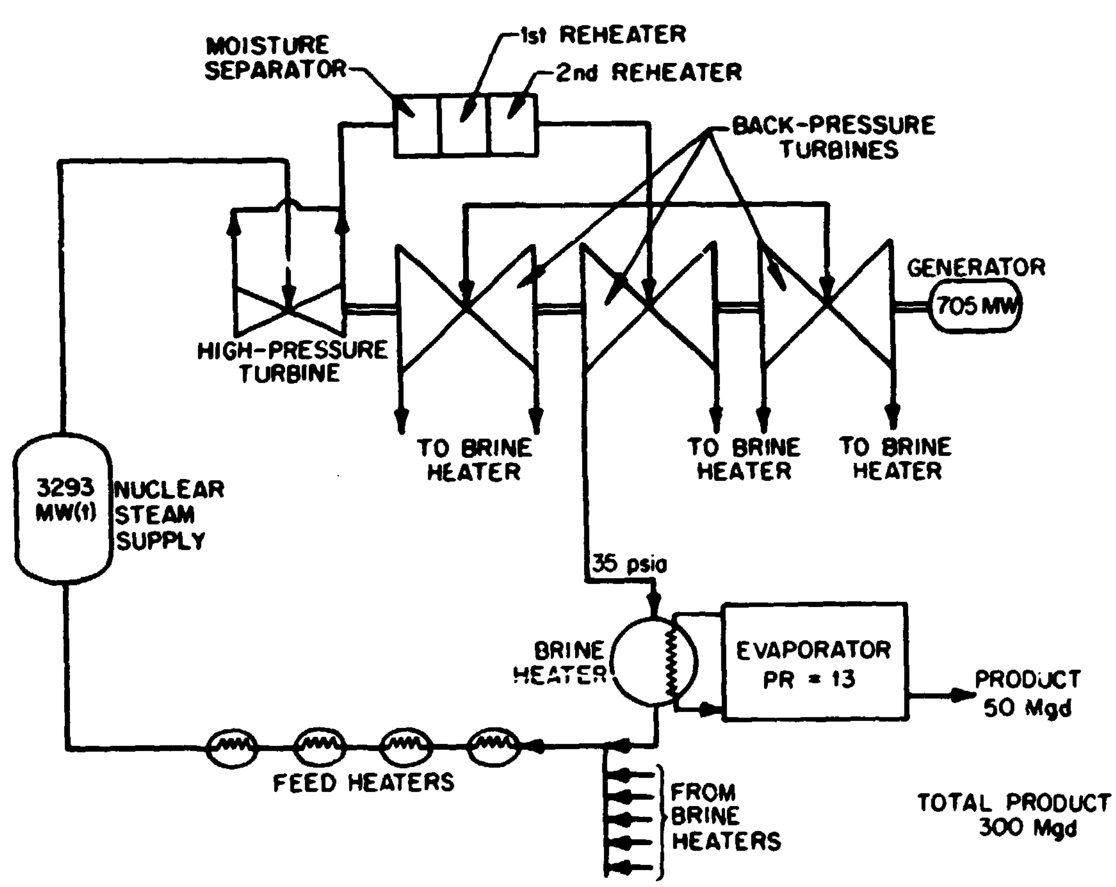

Fig. 2. Schematic of full-scale dual-purpose plant.

into a single-flow unit or, at most, a two-flow unit since the large low-pressure stages of the turbine are omitted. Second, the reheaters could be eliminated economically for the dual-purpose plant cycle. The major benefit of reheaters is to reduce moisture content in the large low-pressure stages of the power-only turbine.

The cost of a full-scale dual-purpose plant such as is shown in Fig. 2 would approach a half billion dollars. Before such an investment in dual-purpose plants is made, it will be necessary to resolve several technical questions and to demonstrate the technology in smaller-scale demonstration or prototype plants. What is the status of dual-purpose plant technology, what technical questions remain to be answered, and what must be demonstrated before large dual-purpose plants can be seriously considered as an alternate source of new regional water supplies? The following discussion of these questions emphasizes coupling components.

Large evaporator train. Evaporator technology is not well developed at this time. Only the MSF process, for example, is considered sufficiently developed for the state of California 40-Mgd prototype plant at Diablo Canyon, currently in the conceptual design phase. Other processes which might be considered are in the module testing phase. The largest evaporator train currently in operation is in the order of 5 Mgd. Various conceptual designs have shown that the train size for large-scale plants should be in the range of 40 to 62.5 Mgd. For whatever process is developed, prototype plants with a single train in this size range need to be demonstrated.

Back-pressure turbine. Small back-pressure turbines are used in pump drives and many other process systems, but these units are in the size range of 5 MW(e) or smaller. Many problems are involved in designing and building large back-pressure turbines; basically, however, they are the same sort of problems which had to be solved for the current large nuclear plant turbines. From the standpoint of technology only, it seems clear that these large back-pressure turbines can and will be designed and built when there is sufficient demand or a foreseeable market. From our studies and contacts with industry we have determined that the unit cost [$/kW(e)] of large back-pressure turbines would likely be equal to or slightly less than that of conventional condensing turbines of equal capacity.

The problem is that no work is in progress to design or develop these back-pressure turbine units. It seems very likely that the influence and support of the federal government will be required to encourage development of large back-pressure turbines for desalting.

Plant availability and flexibility. To be economical the large dual-purpose plants must demonstrate a very high plant availability. The power plant and the evaporator are interdependent; that is, the power plant is the heat source for the evaporator, and the evaporator provides the heat sink for the power plant.

Another related problem is plant flexibility. Our studies have shown that without special variable orifices and other control features the flexibility of the MSF plant to operate at part-load or off-design conditions is quite limited. On the other hand, power plants typically have a much wider range of flexibility for load-following purposes.

In coupling these units, ways must be considered to increase plant availability and to allow for power plant flexibility to follow load without losing the economic benefits of the dual-purpose concept. The cost and benefit of providing an alternate heat source for the evaporator and an auxiliary heat sink for the power plant have been investigated.

An alternate heat source could be provided by a bypass desuperheater system from the nuclear plant prime steam directly to the evaporator, thus bypassing the turbine. Such a system would allow the evaporator to operate during periods of turbine plant outage and would also allow for power plant flexibility to follow load while maintaining evaporator operation at full load.

In the conventional power-only plant a bypass line is provided from the prime steam source to the condensers to protect the reactor from overpressure in the event of turbine trip and to provide a heat sink for the reactor during startup. A similar bypass system would be required for the dual-purpose plant, and with minor modifications it could also be adapted to serve as an alternate heat source for the evaporator. An evaluation of the incremental cost of producing water from bypass heat (as opposed to no production) during turbine outage is very favorable. The incremental costs of operation in the "water-only" mode are incurred from the exposure-dependent portion of the fuel cycle cost and from the cost of power and chemicals to operate the reactor and evaporator. All other costs would continue whether or not the plant was run in the "water-only" mode. The incremental cost derived is only about half the average cost of product. The conclusion is that it is economically beneficial to operate the evaporator at full load by bypass heat during periods of turbine outage or turbine operation at part load.

An auxiliary heat sink for the power plant during periods of evaporator plant outage was also evaluated. Our contacts with the power industry have verified their judgment that a reliable heat sink must be assured. We examined the costs and benefits of providing an auxiliary heat sink.

In all large dual-purpose plants the evaporator is composed of four or more independent trains. For a well-developed evaporator concept, which we believe is a prerequisite for the large dual-purpose plants, no more than one of these independent trains would be expected to be shut down at any one time. An evaluation of the economic effect of including an auxiliary condenser sized to take 25% of the exhaust heat (equivalent to one of four trains shut down) resulted in a benefit-to-cost ratio of 5, assuming an evaporator availability of 0.95. An auxiliary heat sink provides a substantial benefit in increased power plant availability and is a good economic investment.

Control systems. Suitable control systems and techniques must be demonstrated to assure that a large dual-purpose plant can be controlled adequately in all phases of operation. The control studies program is discussed under a separate heading in this report.

Environmental impact. The question of environmental effects of large power plants has become a critical issue in the last few years, and it is certain to be so for dual-purpose plants as well. Achieving and demonstrating favorable environmental effects for dual-purpose plants must be an important goal for prototype or demonstration projects. Specifically, coupling these dual-purpose plants to achieve the maximum utilization of available energy will not only provide an economic benefit but will also reduce the environmental impact of waste heat disposal.

Public safety considerations. The steps which must be taken to avoid radioactive contamination of the brine and product water and to avoid brine contamination of the steam condensate were examined. The study of this problem is presented in more detail under a separate heading. Following is a brief summary of the results:

1. The hazard of radioactive contamination of the brine and product water is slight. Considering a severe set of operating conditions without special isolation techniques, the levels of contamination do not exceed the limits set by 10 CFR 20 regulations.[1]

2. It seems reasonable and practicable to further safeguard the public by isolating the evaporator from radioactive contamination by means of brine overpressurization in the brine heater. Combined with a special welded brine heater, this isolation technique would cost about 0.1¢ per thousand gallons of product and would provide adequate protection for the public and the power plant operator.

3. A pressurized-water intermediate isolation loop was considered. This system would cost 2.5 to 3¢ per thousand gallons of product and is not justified technically or economically.

Condensate demineralization. Some method of removing contaminants from the condensate in the turbine cycle is required in all power plants and would also be required in the dual-purpose plant. Some pressurized-water reactor power plants have a pool-boiling-type steam generator. In this type of system the contaminants tend to concentrate in the steam generator so that a blowdown from this point provides a satisfactory method of purification. Other PWR's, which have once-through steam generators, and boiling water reactors require a demineralizer in the system. The demineralizers normally operate at the condenser exhaust temperature (about 100°F) in the power-only plants. For the dual-purpose plant the brine heater condensate temperature is about 260°F, which creates a problem because the anion resins in the conventional demineralizer are not satisfactory in this temperature range.

Development of a high-temperature demineralizer would apparently be required if the reactor systems which require a demineralizer are used in a dual-purpose plant. The pool-boiling-type PWR would seem to have an advantage for application in dual-purpose plants.

Demonstration Plant Studies

As a prerequisite to the construction of large economical dual-purpose plants, one or more demonstration projects will be required. Studies were made to determine the demonstration plant coupling arrangements which would provide the most information relative to the problem outlined above. A hypothetical demonstration flowsheet was developed based on a 50-Mgd evaporator coupled to an 1100-MW(e) power plant. The best coupling arrangement for this plant consists of a small back-pressure turbine which utilizes steam from the crossover of the main power plant turbine and exhausts the steam to the brine heater of the evaporator.

1. *U.S. Code of Federal Regulations*, Title 10, "Atomic Energy," Part 20, "Standards for Protection against Radiation" (1971).

Turbine Cycle Calculations and Code Development

Work is in progress to make a modified version of ORCENT (a code for steam turbine cycle analysis).[2] The modified version contains the following improvements: (1) it permits the first stage of a two-stage reheater to receive its steam supply from any turbine stage and drain to any heater as specified, (2) a heat balance with valves wide open is possible, (3) a balance may be obtained with steam generator flow as input, (4) feed pump efficiency may be input rather than default, and (5) the user has the option of obtaining steam properties based on the 1967 ASME Steam Tables rather than Kennan and Keyes.

Turbine cycle studies were made in support of the work on dynamic simulation of dual-purpose plants described elsewhere in this report. To aid in these studies a code (TURBINE4) was written to analyze combinations of back-pressure turbines, brine heaters, and feed pumps under various load and back-pressure conditions. TURBINE4 uses ORCENT subroutines to determine noncondensing turbine exhaust loss, moisture removal stage effectiveness, and steam properties.

In addition to its use in developing dynamic simulations, TURBINE4 can be used to explore changes in certain parameters such as turbine-generator characteristics (last-stage blade length and pitch diameter), feedwater heater drain cooler approach and terminal temperature difference, reheater terminal temperature difference, throttle temperature, pressure, moisture, condenser pressure, and efficiency of various turbines. TURBINE4 has been used to obtain heat balances at 50, 75, and 100% of rating conditions and at conditions with valves wide open.

Evaporator Isolation Studies

As a part of the coupling study, the possibility of radioactive contamination of desalting plants by nuclear steam was investigated.[3] The following questions were considered:

1. What is the possible extent of radioactive contamination of product water and plant effluent?
2. What preventive measures are available to protect the water plant from such contamination?
3. What is the probable cost of the various preventive measures?

The basis for evaluation of the degree of contamination of the product water and plant effluent is 10 CFR 20. This regulation sets forth limits on the radioactivity of water to be released from control.

Several assumptions concerning leak rates must be made to arrive at the concentration of radioactive materials in the water plant. Leak rates were assumed to be larger than values which could be tolerated as operating conditions, and it was assumed that 1% of the secondary steam delivered to the brine heater would leak into the water plant. Leakage rates from primary to secondary systems specified as limiting conditions were assumed to be the normal conditions in this analysis. Data concerning the radioactive content of the reactor coolants were obtained from reactor safety analysis reports[4,5] and from earlier studies of water plant contamination.[6,7] The maximum values reached by the contamination under these assumptions were found to be acceptable for all cases, even under the conservative assumptions used.

Three preventive measures are available to reduce the probability of leakage of steam into the desalting plant: (1) provision of increased reliability in the brine heater in the form of welded tube sheets and tubes of improved integrity, (2) operation of the brine heater with the brine at a higher pressure than the steam so that any leaks will be from the brine into the steam, and (3) provision of a closed loop for transfer of heat from the nuclear steam to the brine.

Evaluation of these possibilities has shown that a combination of items 1 and 2 can provide the necessary protection for the quality of product water and plant effluent. The cost of these modifications would be about 0.1¢ per thousand gallons of product water. With these modifications, contamination of the water plant by nuclear steam would be caused only by brine heater leaks and a simultaneous breakdown in the control of the process. Contamination could exist, therefore, only as a temporary or transient condition.

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2. H. I. Bowers, *ORCENT: A Digital Computer Program for Saturated and Low Superheat Steam Turbine Cycle Analysis*, ORNL-TM-2395 (January 1969).

3. F. G. Welfare, *Public Health and Safety Aspects of a Nuclear Dual-Purpose Plant*, ORNL-TM-3423 (to be published).

4. *Preliminary Safety Analysis Report, Nuclear Unit 2, Diablo Canyon Site*, Pacific Gas and Electric Company, San Francisco, California (July 1968).

5. *Final Facility Description and Safety Analysis Report, Indian Point Nuclear Generating Unit Number 3*, Consolidated Edison Company of New York, Inc. (1969).

6. F. E. Crever, *A Study of Water Plant Isolation from Contamination*, OSW R&D Progress Report No. 526 (October 1969).

7. W. H. Kelley, *Studies on Control of Brine Heater Leakage in Large Dual-Purpose Nuclear Desalting Plants*, ORNL-TM-2049 (May 1968).

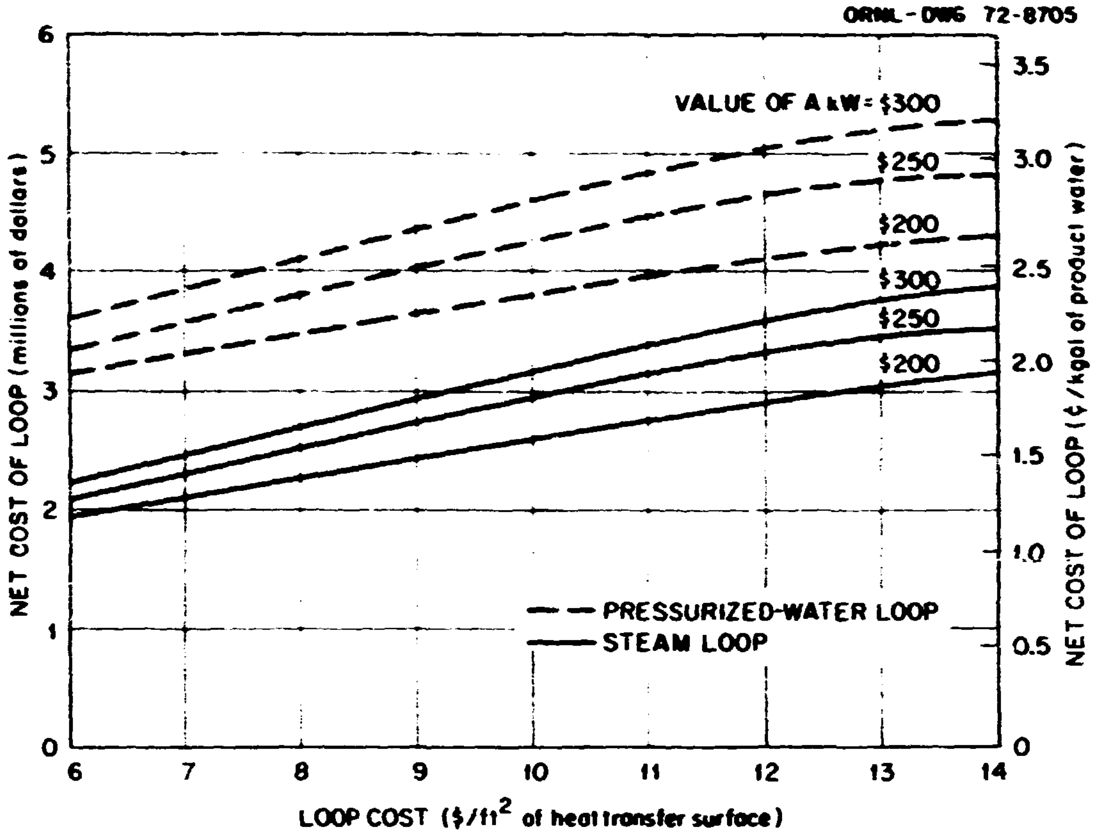

Fig. 3. Cost of closed loops for isolating the evaporators.

Preventive measure 3 represents the maximum degree of separation which can be achieved by practicable means. For this reason, its cost was investigated, even though a special combination of circumstances would be required to justify the inclusion of such a device. Provision of an isolating loop requires operation of the back-pressure turbine at a higher exhaust pressure and temperature. As the exhaust pressure and temperature are increased, there is a simultaneous loss of electrical capacity and a decrease in the capital cost of the loop. Figure 3 shows the *minimum* cost of loops (using steam or water as heat transfer medium) as a function of economic parameters. The cost of providing this degree of separation ranges up to 3.3¢ per thousand gallons of product water.

3.2 DUAL-PURPOSE PLANT CONTROL STUDIES

Introduction

Studies of dual-purpose plant dynamics have continued to indicate that the major control problems and uncertainties lie in the evaporator portion of the plant. Resolution of these uncertainties is essential to a sound engineering design of adequate control systems for dual-purpose desalting plants. Thus a significant part of our effort has continued to consist of working toward a better understanding of MSF evaporator dynamics and stability characteristics.

Overall MSF plant stability is related to the problem of brine levels in one section of the plant seeking equilibrium values that are functions of levels at the other end. Depending on the time lags involved, the extent of the brine level interdependence, and other thermodynamic considerations, our studies show that unstable, and therefore unsatisfactory, behavior is a distinct possibility. Recent digital simulations have also indicated that evaporator stability is critically dependent on the means of coupling to the energy source as well as evaporator plant design features. In fact, the closer the coupling scheme approaches the economically ideal, full dual-purpose plant design (i.e., using back-pressure turbines exclusively), the greater the tendency for instabilities to occur.

The immediate application of MSF dynamics studies would be to prototype plants such as that proposed for Diablo Canyon in California. A longer-range application, however, would be to combined VTE/MSF plant designs. In this case, while the MSF feed heater output may represent only about 20% of the total, its steady operation very near design conditions is a prerequisite to successful operation of the VTE portion. Initial investigations of VTE and combined VTE/MSF plant dynamics were made.

State of Technology

A program of analytical and experimental investigation has been developed to resolve the control problems. The goal of the experimental program is the development of accurate correlations for use in the plant simulations which will permit us to relate specific stage designs to predicted overall plant performance. The correlations in MSF evaporators which are most crucial (i.e., to which the dynamics are most sensitive) are orifice flow, nonequilibrium loss (Δ'), and stage tray brine dynamics (in that order). We have developed test methods, data acquisition, and analysis techniques which have been demonstrated to be capable of acquiring these correlations. However, a comprehensive test program on "promising" stage designs has yet to be implemented. Ideally these stage designs should correspond to those to be used in a prototype plant such as the proposed Diablo Canyon MSF plant. However, since such designs are not yet known or available, tests run on state-of-the-art designs could be used to develop performance criteria which in turn could be used in specifications for the prototype stage designs.

General-purpose and special-purpose dynamics simulators have been developed for studying a variety of plant configurations and designs. The MSF digital simulator[8] permits (1) the direct use of output cards from a steady-state design and optimization code, (2) choice of a wide variety of input perturbations and output displays, including off-line automatic plotting, and (3) provisions for modifying critical models and parameters.

A special-purpose version of the MSF digital simulator was developed for the nine-stage OSW MSF module at San Diego. Another special-purpose simulator was developed for predicting the dynamics of the OSW VTE-X, also at San Diego, and development has begun on a simulator for the VTE-MSF module to be built at Fountain Valley, California.

The general-purpose MSF simulator was coupled to a turbine-generator plant simulator consisting of both high- and low-pressure turbines, a back-pressure turbine, and feed heaters corresponding to a plant about the size of the proposed Diablo Canyon plant.

Experimental Studies of MSF Evaporator Dynamics

While no additional experiments were run during 1971, further analyses were made of frequency response test data taken in August 1970 at the OSW three-stage evaporator at Wrightsville Beach, North Carolina. (Results of the Δ', interstage orifice flow, and blow-through tests were reported in last year's annual report.[9]) The basic approach was to use the difference between the Fourier transforms of the test data and a calculated model response as the error to be minimized by varying several parameters in the model. The test stage model consisted of two parts, one defining the response of the test stage condenser and one defining the response of the test stage tray brine outlet temperature. A distributed parameter model was chosen to define the condenser response, and optimization was performed by varying the mean value of the inside heat transfer coefficient, the number of transfer units (NTU), and the mean value of driving-force temperature. The test data consisted of the measured response to various combinations of recirculating brine flow rate and brine heater steam flow perturbations utilizing pseudorandom binary sequences (PRBS). Figure 4 shows an example frequency response diagram resulting from the optimization, plotting the magnitude ratio and phase for the condenser coolant outlet temperature, TCO, as a function of vapor temperature, TV. The model response is shown as a solid line, and the transformed experimental data are indicated by the points. The comparison of measured and calculated results indicated reasonable accuracy up to the 69th harmonic of the basic PRBS frequency, or 0.414 radian/sec

The best fit for the tray brine temperature model is shown in Fig. 5, which plots the model response of the transfer function between brine outlet temperature, TBO, and inlet temperature, TBI, as a solid line, and transformed data are indicated by the points. The comparison of measured and calculated results indicates reasonable accuracy up to the 39th harmonic (0.38 radian/sec). The tray brine model consists of a certain fraction of the inlet flow "short-circuiting," or passing quickly along the bottom of the tray to the exit orifice, and the balance of the brine flow appearing as input to a well-stirred tank model. The optimized time constants for the TBO/TBI transfer function indicated a total effective tray brine holdup time of 2.3 sec, which compared quite favorably to the mean (mass-balance) holdup time of 2.9 sec. Results of several large-perturbation pulse-type input tests which were analyzed using the ORNL Hybrid Computer[9,10] indicated tray brine mixing models to be of the same form. Further

8. J. G. Delene and S. J. Ball, *A Digital Computer Code for Simulating Large Multistage Flash Evaporator Desalting Plant Dynamics*, ORNL-TM-2933 (September 1971).

9. *Nuclear Desalination Program Annual Progress Report on Activities Sponsored by the Atomic Energy Commission for Period Ending October 31, 1970*, ORNL-4668 (April 1971).

10. N. E. Clapp, Jr., *A Hybrid Computer Program for Flash Evaporator Model Parameter Optimization*, ORNL-TM-3419 (to be published).

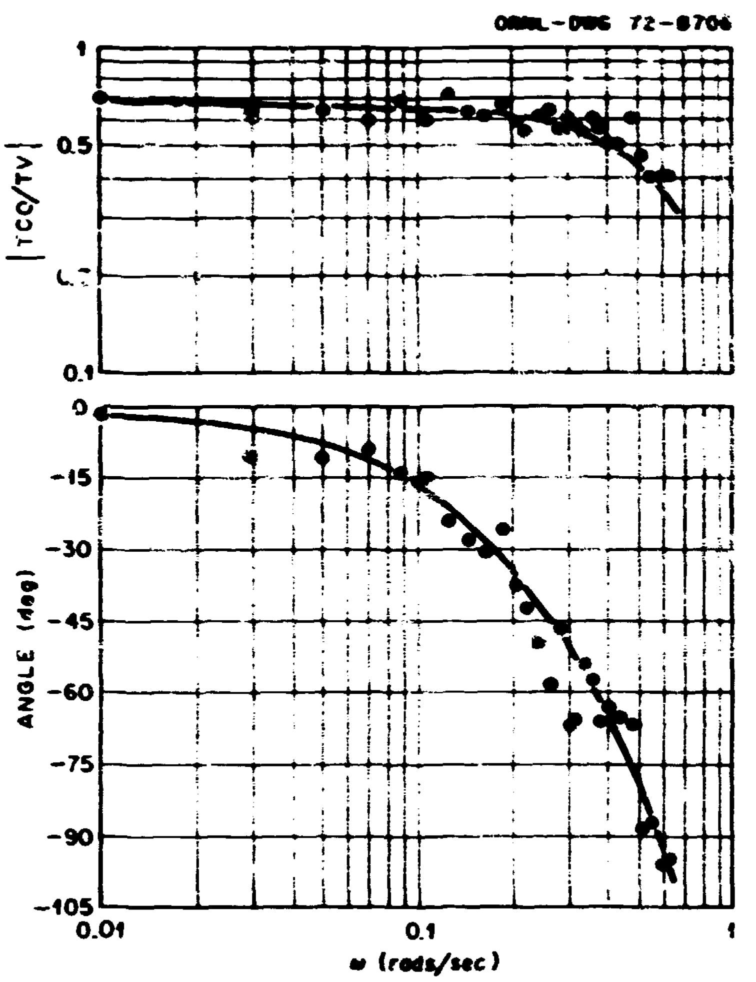

Fig. 4. Comparison of experimental and optimized model frequency response for test stage condenser. Coolant outlet temperature, TCO, as a function of vapor temperature, TV.

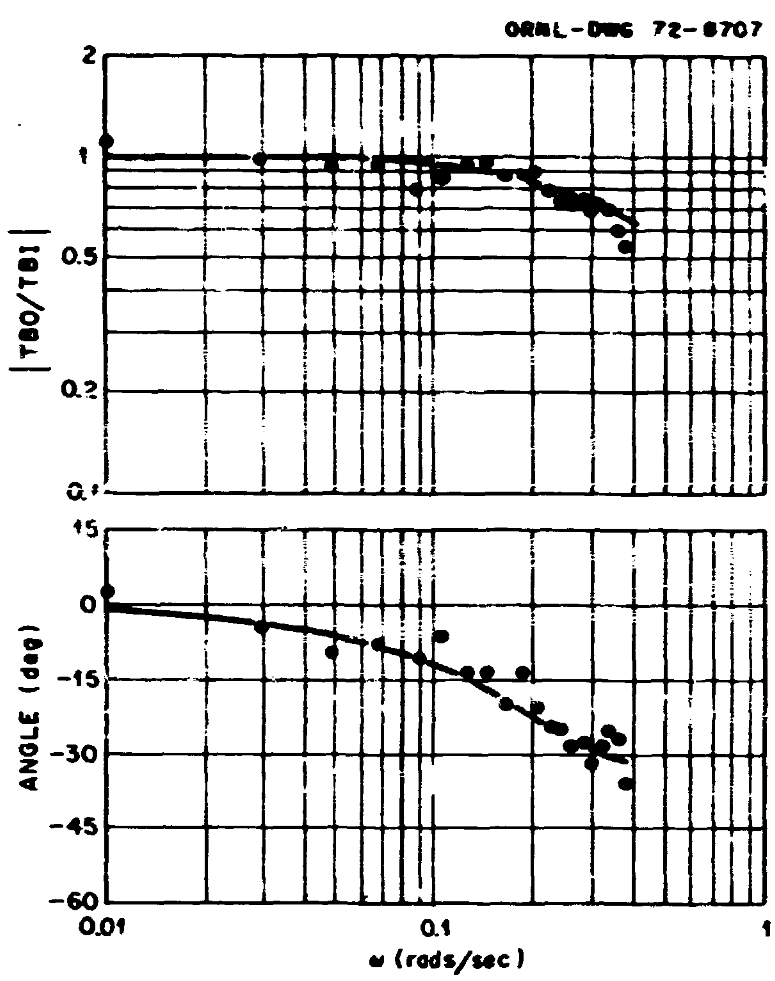

Fig. 5. Comparison of experimental and optimized model frequency response for test stage tray brine dynamics. Tray brine outlet temperature, TBO, as a function of tray brine inlet temperature, TBI.

tests of stage dynamics are being planned utilizing the new on-line computer which is scheduled for installation at the Wrightsville Beach facility in early 1972.

Theoretical Studies

In a complex machine or combination of machines, such as a dual-purpose nuclear plant, potential problems exist in tying together the various components in such a way that the plant will operate as a unit. Control systems required to perform this integration are not intuitively obvious. Since cut-and-try methods are not applicable to large, expensive plants, the only alternative route to control system development is through plant simulation. Results of some simulator runs are discussed below.

Dependence of evaporator stability on the means of coupling to the steam supply. As has been noted, the more closely the plant approaches the full dual-purpose plant design, the greater the tendency for instabilities to occur. This is demonstrated first in Fig. 6, showing the simulated response of tray brine levels in stages 10, 20, and 30 in a 50-stage MSF plant model which is stable when the brine heater steam temperature (T_s) is controlled (as in a single-purpose plant) and unstable when steam flow rate (W_s) is controlled. The latter case assumes that W_s is controlled according to turbine requirements and corresponds closely to the case where the steam comes from a back-pressure turbine (BPT) which comprises a small fraction of the total turbine plant output and where the total plant electrical output is controlled by throttling prime steam flow to the entire plant. For both simulated responses, the input perturbation (which is typical of all simulator results shown) is a sudden decrease of approximately 2% in heat rate to the brine heater for a period of 10 min, followed by a return to the original heat rate. The differences in stability characteristics for the two cases can be attributed to the fact that any perturbations in temperature of the inlet brine are attenuated in one case (T_s control) and not in the other. In the case of W_s control, for example, since the heating rate for a given flow rate W_s is very nearly constant, a perturbation of 1° of the brine at the inlet will show up as a 1° change in the brine outlet temperature. For T_s control, the brine temperature is closely coupled to the steam

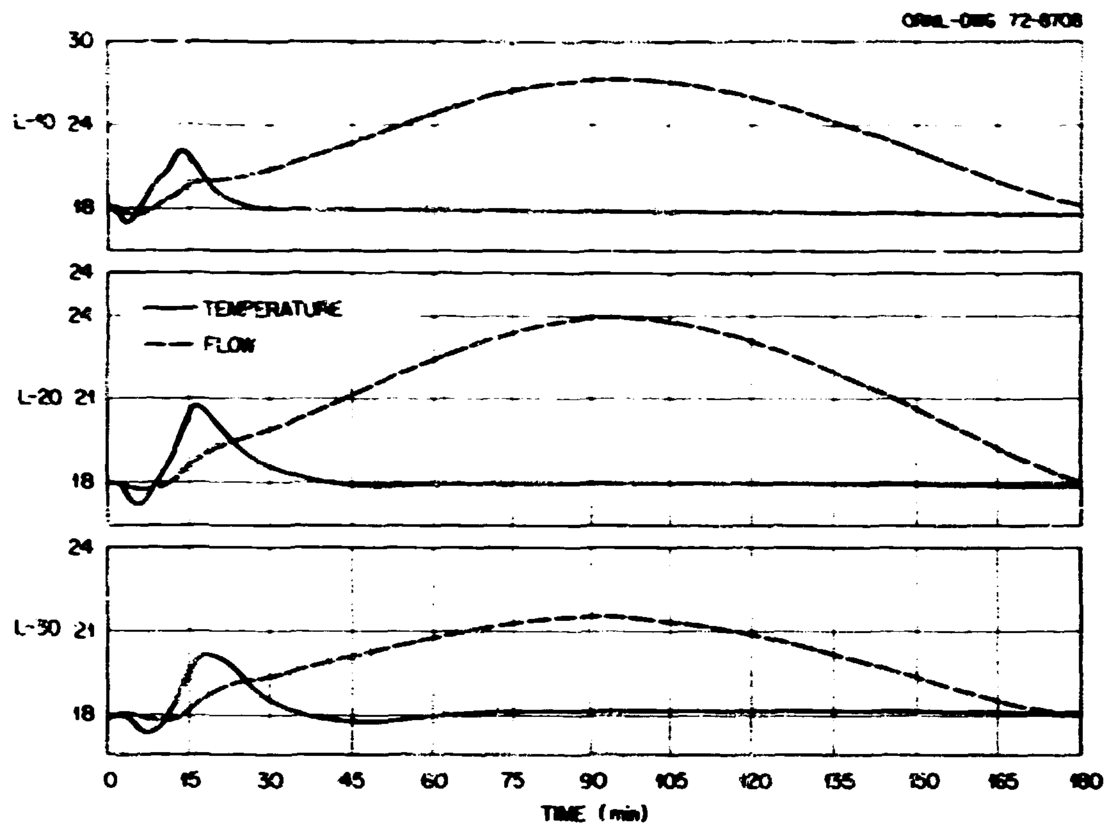

Fig. 6. Simulated response of stages 10, 20, and 30 tray brine levels in a 50-stage MSF plant. Comparison of stability characteristics for brine heater steam flow control vs steam temperature control.

temperature, and only a fraction (typically ~30%) of any inlet brine temperature perturbations passes through to the outlet. Brine heater inlet and outlet temperatures for these two cases are shown in Fig. 7.

A further destabilizing tendency is seen if the electrical output of the BPT supplying steam to the brine heater is controlled directly, as shown in Fig. 8. As before, the MSF plant models used in the two cases are identical, and a plant design which is stable under W_s control is unstable (eventually) with BPT(e) control. Here destabilization is due to the fact that changes in brine heater conditions cause controlled W_s changes which augment, rather than attenuate, the effect of the initiating disturbance.

Dependence of stability on MSF plant design features. While the previous section illustrated coupling factors affecting stability, this section will illustrate three points related to the dependence of stability on MSF plant design. It should be recognized, however, that the simulators are not capable of accurately predicting dynamics for a given (hardware) design. At this point they can only determine whether certain *changes* in design features will have stabilizing or destabilizing tendencies. (That is why more data are required.)

The first point is that higher baffles (downstream of the interstage orifice) lead to greater stability, as shown in Fig. 9. The unstable case uses interstage brine flow equations in which the coefficient defining the relative effect of brine level on inlet brine flow is increased slightly (~12%). The means of coupling to the steam supply are identical.

The second point is that the greater the number of stages in a plant, the more apt it is to be unstable; this is illustrated in Fig. 10. Here the model assumptions, stage designs, and coupling scheme are the same for the simulations of the 9-stage MSF module and a 50-stage plant. Brine levels are shown for stages 1, 10, and 30 of the 50-stage plant and for stages 1, 3, and 5 of the module, and the differences in stability are clear. Obviously, the conclusion cannot be drawn that because a 9-stage plant is stable, a 50-stage plant (of the same design) will also be stable.

The last point to be made is that intuitive "fixes" of the MSF plant design using baffles may not be successful. Comparisons of successful and unsuccessful attempts to stabilize a plant are shown in Fig. 11. In the unstable case, "tall baffles" were added in stages 6, 16, 26, 36, and 46, attempting to decouple the plant into six sections. In the stable case, tall baffles were used in each stage in the higher-temperature end of the plant, with successively smaller ones used in each stage toward the lower-temperature end. Again it should be noted that this does not solve the problem; that is, we still do not know what (if any) baffle hardware corresponds to the successful set of baffle equations.

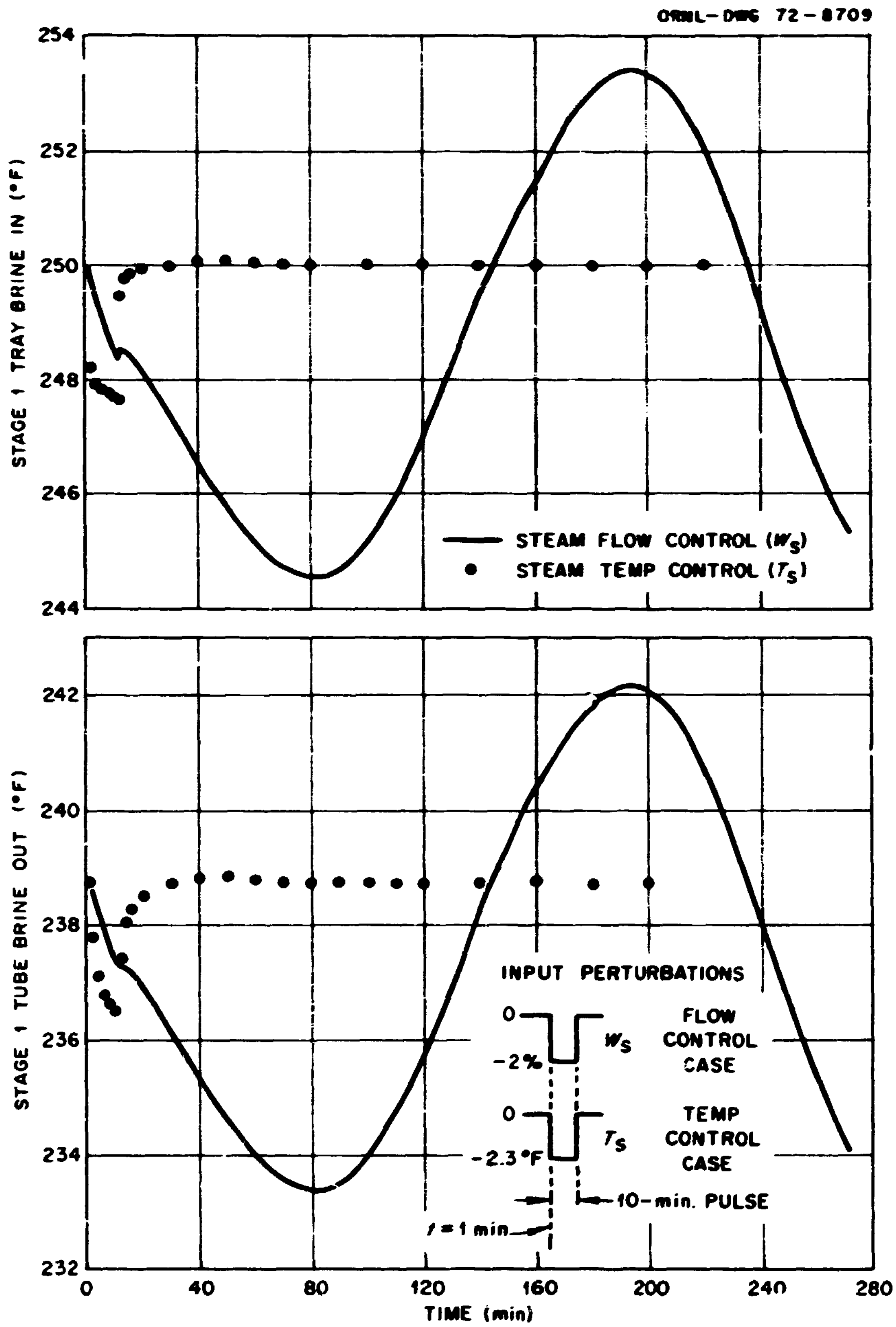

Fig. 7. Brine temperature vs time for brine heater steam temperature vs flow control.

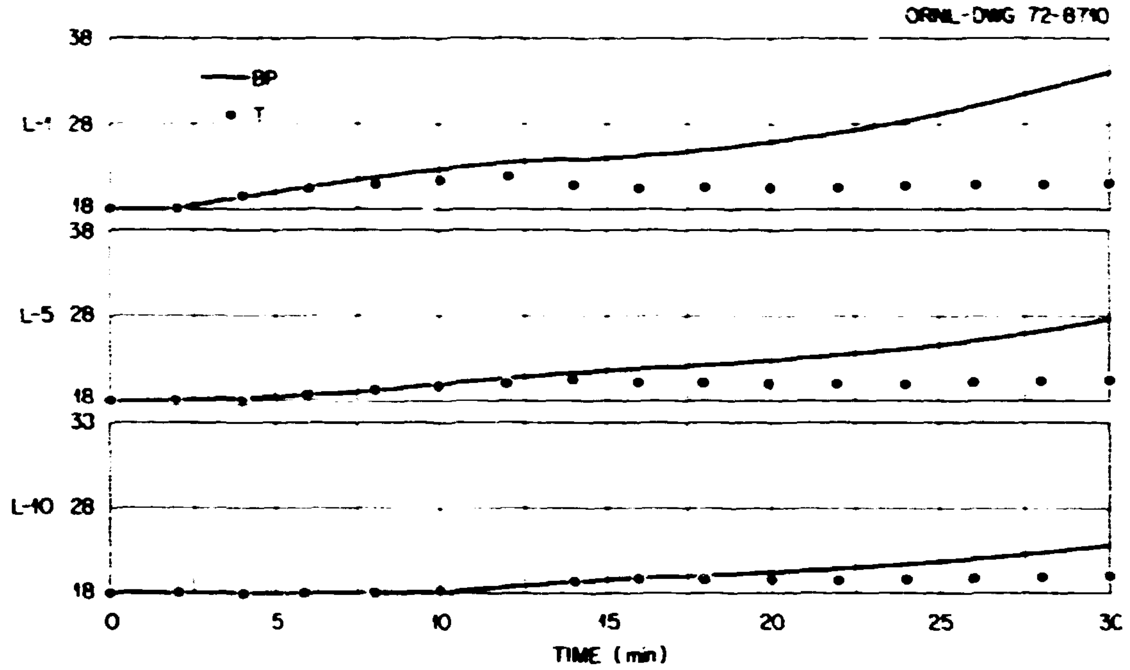

Fig. 8. Simulated response of stages 1, 5, and 10 brine levels in a 50-stage MSF plant. Comparison of stability characteristics for back-pressure turbine electrical output load control vs brine heater steam flow control.

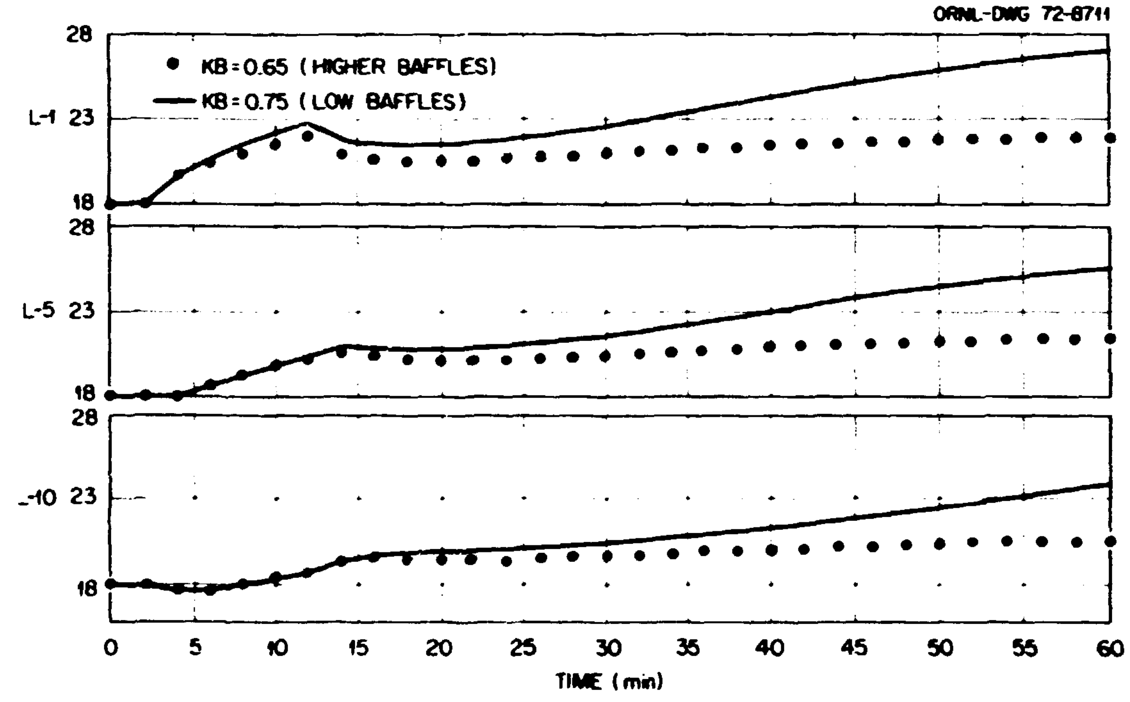

Fig. 9. Simulated response of stages 1, 5, and 10 tray brine levels in a 50-stage MSF plant. Comparison of stability characteristics for different interstage brine flow baffle heights.

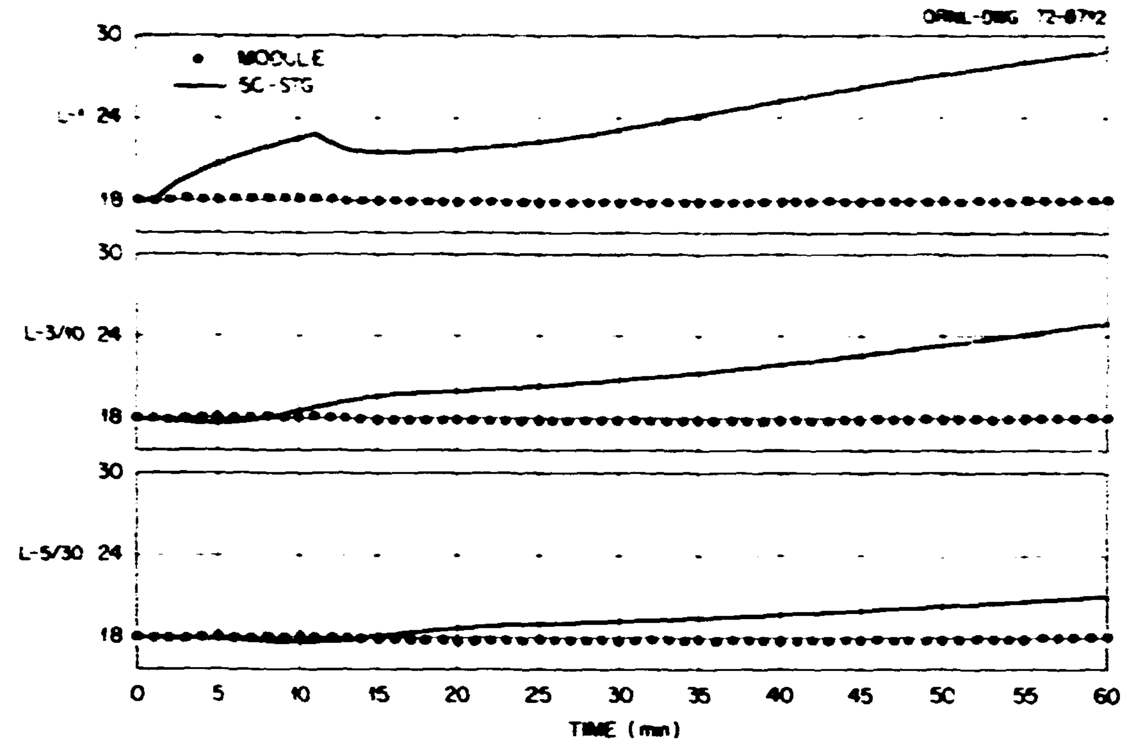

Fig. 10. Simulated response of tray brine levels in the MSF module (stages 1, 3, and 5) and a 50-stage MSF plant (stages 1, 10, and 30), where stage models and coupling schemes are the same.

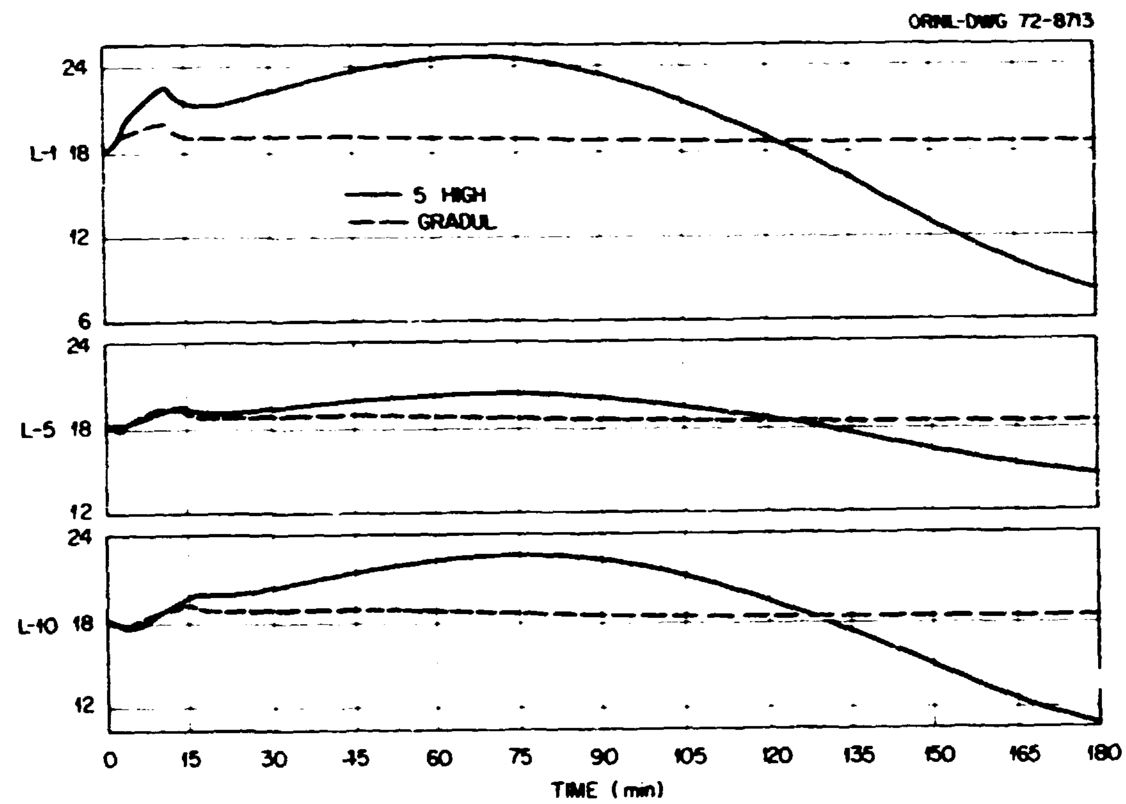

Fig. 11. Simulated response of stages 1, 5, and 10 tray brine levels in a 50-stage MSF plant. Comparison of stabilizing schemes using baffles.

Conclusions

While a broad array of simulators, experimental techniques, and analysis procedures have been developed, it is clear that accurate correlations are required in the simulators which will permit us to relate specific hardware designs to predicted overall plant performance. To accomplish this, a comprehensive test program on promising stage designs needs to be implemented. Ideally these stage designs should correspond to those to be used in a prototype plant such as the proposed Diablo Canyon MSF plant. However, since such designs are not yet known or available, tests run on state-of-the-art designs could be used to develop performance criteria which in turn could be used in specifications for the prototype stage designs.

3.3 NUCLEAR DESALTING APPLICATION STUDIES

Introduction

The United States water resources and future water requirements are being studied in depth by federal and state agencies. As information from these studies is published, possible applications of desalting in meeting projected water needs of the future are being evaluated for various regions of the country. The studies show that there are water needs for which desalting plants may be the most attractive source of supply even at the comparatively high desalted water costs being experienced by the plants now in operation. Applications of today's desalting technology in some areas are already highly successful and are expanding rapidly to meet the requirements of water-short regions, for example, in the Caribbean resort areas and the Middle East oil fields.

California Region

California's major reservoirs and aqueduct systems today supply about half the water used in the state. The remainder is supplied in nearly equal amounts from local streams and reservoirs and from pumping of groundwater. About 3 billion gallons of water per day (Bgd) is imported from the Colorado River through the 80-mile All-American Canal to the Imperial Valley. In addition, nearly 1 Bgd is transported through the 242-mile Colorado River Aqueduct to the Los Angeles–San Diego area. Aqueducts from reservoirs in the Sierra Nevada Range supply water to the coastal cities; the aqueduct capacities are rated as follows: 430 Mgd to Los Angeles, 300 Mgd to San Francisco, and 325 Mgd to the East Bay area of Oakland and surrounding communities. These are the state's oldest major aqueducts, built between 1913 and 1950.

The Bureau of Reclamation's Central Valley Project was the first large-scale regional water supply project. It was started in 1937, financed by the federal government with reimbursable costs to be recovered from water and hydroelectric power sales. The Central Valley Project reservoirs and aqueducts now supply an average of almost 5 Bgd and will ultimately supply about 10 Bgd, mainly for irrigation in the valleys of the Sacramento and San Joaquin rivers. Their irrigation water rates are in the range of 1 to 2¢ per thousand gallons. The water rates for municipal and industrial use are higher than irrigation rates, but still below 10¢ per thousand gallons in almost every area. These rates were calculated to repay all capital costs allocated to municipal and industrial water with interest and to repay the irrigation water capital costs without interest by the year 2030.[11-13]

The California State Water Project transports water from northern California to meet needs in water-short areas. The main conveyance facility is the California Aqueduct, which has the capacity to deliver an average of about 4 Bgd to service areas along its route from the Sacramento River Delta near San Francisco to southern California. This conveyance system will meet southern California's estimated water requirements through the year 2000 at costs of 14 to 25¢ per thousand gallons for untreated water.

The State Water Project, almost all of which has been constructed in the last ten years, is now estimated to cost $2.8 billion in state construction funds with an additional $0.6 billion in federal funds for the jointly supported projects. The main aqueduct is 440 miles long, extending from the Sacramento–San Joaquin River Delta east of San Francisco to the Perris Reservoir east of Los Angeles. The concrete-lined open canal follows a gravity flow path along the west side of the San Joaquin Valley. In this alluvial, almost rock-free soil, canal costs amounted to $1.2 million per mile including design, right-of-way, and construction.

At the southern end of the Central Valley, the aqueduct crosses the Tehachapi Mountains. The Wind Gap Pumping Plant provides a 518-ft lift, and the next unit, the A. D. Edmonston Pumping Plant, lifts almost 2.5 Bgd 2000 ft to cross the mountains. Hydroelectric plants recover some of the pumping energy as water comes down the southern slopes from the high mountain crossing. Revenue from hydroelectric power sales offsets some of the pumping power costs.

The California State Water Project uses a sophisticated method of computing equivalent unit charges for water at delivery points along the aqueduct. The system takes into account the capital and operating costs of facilities the water has passed through in reaching each delivery point. From these, plus other factors, a "wholesale" water charge is computed for each irrigation district or municipal water district receiving water, based on actual costs, with full capital cost recovery by the year 2035. The water rates cover interest on water

11. *Central Valley Project, Reclamation Project Data (1961) and Supplement (1966)*. Bureau of Reclamation, Denver, Colorado (1961 and 1966).

12. *Central Valley Project 1970 Annual Report*. U.S. Bureau of Reclamation, Sacramento, California (July 1971).

13. *Water Marketing Policies for Water Service Contracts in the Region 2 Central Valley Project, July 1970*. U.S. Bureau of Reclamation, Sacramento, California (July 1970).

project bonds which now averages 4.255% and is increasing as new bonds are sold at higher interest rates. If the interest rate were 7%, a value often used in studies of desalted water costs, the average water charge for southern California would increase from 18 to 33¢ per thousand gallons.

The irrigation districts, municipal water districts, and cities in California are the water retailers from whom individual customers buy. Their irrigation water rates usually are in the range of 1 to 5¢ per thousand gallons, with domestic rates for treated water sometimes as high as 25¢ per thousand gallons. But the irrigation and municipal water districts have a supplementary source of revenue in that the state permits them to impose ad valorem taxes on all land, and sometimes other property, in their district. Of 109 California irrigation districts reporting in 1966, 79 imposed property taxes, obtaining about half as much revenue from this source as from the sale of water.[14] The Metropolitan Water District of Southern California (MWD), which supplies the coastal regions from Los Angeles to San Diego, imposes an annual tax which yields revenue about equal to their water sales revenue. If MWD's tax revenue were considered as part of the cost of water, the average rates for softened and filtered city water would increase to about 35¢ per thousand gallons.[15]

Desalting vs long-distance imports as a source of future increases in water supply. The population increases forecast for the United States as well as for the state of California will have important effects on future water requirements in California. Food for growing populations will require greater production from irrigated farms. The 1971 projections of the state population show an increase of 10 million by 1990 and an additional increase of 16 million by 2020, compared with the 1970 census total of 19 million.

Consumption of agricultural products within the state will more than double by 2020, while consumption throughout the United States will also increase. As the leading state in agricultural production, California expects to encounter strong economic incentives to provide water which can bring previously unirrigated land into fruitful use. The state must also bring into production new agricultural lands to replace the 30,000 to 40,000 acres per year taken for urban growth.

14. Houston I. Flournoy, *Annual Report of Financial Transactions Concerning Irrigation Districts of California, Calendar Year 1966*, State of California, Office of the Controller, Sacramento (1967).

15. *Thirty-Second Annual Report, 1970*, The Metropolitan Water District of Southern California, Los Angeles (1970).

The increases in irrigated acreage are expected to occur mainly in the Central Valley, which has the best combination of good climate, good soil, and comparatively easy access to additional water supplies. The Sacramento River Basin is expected to have increased its irrigated acreage by 400,000 acres in the year 2020, with the San Joaquin River Basin and the Tulare Basin accounting for an additional increase of 920,000 acres. The corresponding increases in water demand for irrigation in all these areas are expected to require an additional 4.2 million acre-ft/year (3.65 Bgd, on the average) by 2020.[16]

Water storage and conveyance facilities already constructed or authorized for construction are expected to take care of all anticipated needs until some time after 1990. When additional water is needed, the Central Valley Basin has only two undeveloped major streams with significant potential for water storage. The full development of these streams, which flow from the coastal mountains into the Sacramento River, could add only about 0.75 million acre-ft/year, leaving 3.5 million acre-ft/year (3.1 Bgd, average) to be supplied by other sources.

Outside the Central Valley Basin are several large rivers which drain into the Pacific Ocean in northern California. These could be tapped by creating reservoirs at the highest possible mountain sites and drilling tunnels through the mountains to carry water into the Sacramento River Basin, where it could be added to the supplies of the State Water Project and the Central Valley Project. The estimates of firm supplies that could be developed from these rivers are 4,500,000 acre-ft/year (4 Bgd) from the Klamath River, 2,600,000 acre-ft/year (2.3 Bgd) from the Trinity River, 1,600,000 acre-ft (1.4 Bgd) from the Eel River, and 200,000 acre-ft (180 Mgd) from the Mad and Van Duzen rivers. Exploitation of these northern California coastal rivers would require almost a hundred miles of tunnels, according to the most recent development studies.

Development of the northern California rivers is very controversial in California, with strong objections being raised by conservationists and others who wish to retain these rivers in their natural state insofar as possible.[17] It may be that their full development for water supply will not be permitted, in which case alternate water supplies may have to be developed at some time after

16. *Water for California, The California Water Plan Outlook in 1970*, Bulletin No. 160-70, State of California, Department of Water Resources, Sacramento (1970).

17. Jackson Doyle, "New Senate Bill to Save Rivers," *The San Francisco Chronicle*, Jan. 15, 1971.

1990. From the standpoint of evaluating the potential need for desalting as a means of meeting the state's expected requirements, it seems safe to predict that if development of supplemental water supplies from the northern California rivers is not permitted, the need for desalting plants will come much sooner.

Reducing salinity problems in the Imperial Valley. In the Imperial Valley, a different situation exists in that there are no surface water sources which could be tapped to augment present supplies. The quantity of water available to California from the Colorado River is fixed by law and is adequate for the foreseeable future. However, there is a water quality problem in that the salinity of the Colorado River water, normally about 800 ppm, is at times too high for some sensitive crops[18] and is expected to increase in the future as a result of municipal and agricultural waste water returned to the river upstream.

Geothermal energy. Underlying large areas of the Imperial Valley and Mexico are geothermal brines ranging in temperature from 500 to 700°F and occupying a geothermal belt extending from the Salton Sea to the Gulf of California. This geothermal belt contains brine reserves which may support 1000 to 3000 geothermal wells, each with an average yield of 1,200,000 lb/hr of steam.[19] A preliminary investigation by the Oak Ridge National Laboratory[20] indicated that the steam from the geothermal wells might be obtained for 2¢ per million Btu, which is much lower than the cost of steam from a power plant. Such low-cost energy would be very attractive for desalting applications.

Desalting applications. Large quantities of desalted water could be used very advantageously to dilute the salinity of Colorado River water and to increase the total water supply, but only if the cost of the desalted water were low enough. For example, 1 Bgd of desalted water blended into the water carried by the All-American Canal to the Imperial Valley would reduce the salinity by about 30%. Even if the desalted water were priced as low as 3¢ per thousand gallons, the diluted water price would be about twice the present irrigation water rate, that is, about $5/acre-ft, which is below the lowest rates of the State Water Project but which is higher than most irrigation water rates in the Central Valley.

Desalting by one method or another seems likely to be more economical for the Imperial Valley than long-distance imports of additional water from northern California. Importing water from other states is so controversial in the Western states that the U.S. Congress in 1968 imposed a ten-year moratorium on even conducting studies of importation of water from outside the Colorado River Basin to supplement the flow of the river.[21]

Possible desalting applications for meeting municipal and industrial water needs. California's population is expected to increase from the present 19 million to 44.7 million in the year 2020. The forecast is that 80% of the population increase will occur along the coast from San Francisco southward, where essentially all local water supplies have been fully utilized and all major increases are being met by importing water from other regions.

San Francisco region.[16] In the San Francisco Bay area, imports of additional water can meet future requirements at reasonable cost because import distances and pumping requirements are not too great. However, pollution of San Francisco Bay is a chronic problem which will worsen unless widespread corrective measures are taken. As an illustration of the problem, the summer flow of the San Joaquin River is composed almost entirely of municipal and agricultural waste water which, by the time it reaches the delta, is not only high in salinity but also low in dissolved oxygen, high in nutrients, and contaminated with agricultural pesticides.[22] The Federal San Luis Drain is being constructed to carry the high-salinity agricultural drainage to discharge into San Francisco Bay.

Waste water reclamation is in effect on a small scale at the Golden Gate Park, where reclaimed water supplies 1 Mgd for the park's ornamental lakes and irrigation system. Additional reclamation could be readily accomplished if economically justified; but present reclamation costs are in the range of $5 to $20/acre-ft (1.5 to 6.0¢ per thousand gallons) for nothing more than secondary treatment, which is generally suitable only for groundwater replenishment or controlled irrigation uses.

18. Ralph Dighton, "Water Salvaged a Desert, Salt May Kill Its Bloom," *The Chattanooga Times*, Jan. 4, 1970.

19. R. W. Rex, *Investigations of Geothermal Resources in the Imperial Valley and Their Potential Value for Desalination of Water and Electricity Production*, University of California, Riverside (June 1970).

20. I. Spiewak, E. C. Hise, S. A. Reed, and S. A. Thompson, *Preliminary Investigation of Desalting of Geothermal Brines in the Imperial Valley of California*, ORNL-TM-3021 (March 1970).

21. *Need for Controlling Salinity of the Colorado River*, Colorado River Board of California, Los Angeles (August 1970).

22. *San Joaquin Valley Drainage Investigation*, Bulletin No. 127, and *Waste Water Quality, Treatment and Disposal*, Appendix D. State of California, Department of Water Resources, Sacramento (1969).

Central Coastal area.[16] The Central Coastal area covers the region between Santa Cruz on Monterey Bay and Santa Barbara, north of Los Angeles. Its present population of 750,000 is expected to triple by 2020. At present, groundwater is the main source of supply in this region, but overdrafts are causing seawater intrusion problems, especially in the lower Salinas Valley. Two water import projects are planned: the Coastal Branch of the California Aqueduct to deliver water to San Luis Obispo and Santa Barbara counties and the San Felipe Division of the Central Valley Project which will convey water from the San Luis Reservoir across the mountains to Santa Clara County and to Santa Cruz County near Monterey Bay. Because of the pumping requirements and the rough terrain, both the San Felipe Division of the Central Valley Project and the Coastal Branch of the State Water Project are expected to have the highest water costs in their entire systems. However, their projected costs are still comparatively low – 2¢ per thousand gallons for irrigation and 10¢ per thousand gallons for municipal use in the San Felipe Division and a flat rate of 25¢ per thousand gallons from the Coastal Branch. If urban populations grow as expected, the needs for additional water in urban areas, especially those around Santa Barbara, might be met by seawater desalting. Other urban needs in the Monterey Bay region may develop after the year 2000, at which time seawater desalting may be an attractive source of supply. Reclamation of municipal waste water could supply some of the needs for groundwater recharging in the lower Salinas Valley, especially after population growth increases the urban water usage in this region.

The feasibility of constructing a prototype seawater desalting plant in conjunction with the Diablo Canyon nuclear plants near San Luis Obispo is now being studied by the state of California and the Office of Saline Water in a joint project. The prototype desalting plant would be in the size range of 30 to 50 Mgd to supply water to San Luis Obispo and Santa Barbara counties. If the feasibility study indicates sufficient promise, the state and the OSW plan to request authorization and appropriation of funds in 1972 for construction of the desalting plant.

South Coastal area.[16] Water consumption from currently available supplies in the South Coastal area is about 2.5 million acre-ft/year (2.3 Bgd, average). When the California Aqueduct system reaches its full capability in 1973, the water available in the South Coastal area will be nearly twice the current usage. It is likely that the area will have a surplus water supply until after the year 2000.

At some future date, coastal desalting plants might allow some attractive tradeoffs to be made. For example, a 500-Mgd desalting plant could replace the Los Angeles water supply now brought in by aqueduct from the Owens River, releasing this water for use in the Owens Valley or in the desert regions. Similarly, large desalting plants could provide the water now imported through the Colorado River Aqueduct (1.2 million acre-ft/year, or 1.1 Bgd, at present but scheduled to be reduced to 0.5 million acre-ft when the Central Arizona Project needs the Colorado River water in the mid-1980's). The Colorado River Aqueduct could very conveniently supply its water to the Coachella Valley area north of the Salton Sea.

With the expected need for many additional nuclear power plants along the southern California coast, it seems likely that dual-purpose installations may be desirable at some locations. In the period after the year 2000, continued growth may be hampered unless additional water supplies are developed.

Colorado Desert region.[16] The Colorado River provides the only significant source of water for the Colorado Desert region, although groundwater pumping does provide water in some areas. There are no additional freshwater sources to tap within the desert region. For supplemental water the area must look to imports from sources other than the Colorado River, which is already utilized up to the legal limit, or must pursue desalting of the Salton Sea, the geothermal brines, or seawater from the nearby Gulf of California. From the standpoint of economic desalting plant operations, seawater would probably be the best source; but the nearest seawater source is the Gulf of California, across the Mexico-California border, 40 to 50 miles away at the closest point. The construction of large desalting plants to serve this general region of California, Arizona, and Mexico has been explored in detail by a joint study team with participants from the United States, Mexico, and the International Atomic Energy Agency. Their report[23] recommends construction of very large dual-purpose plants near the end of the Gulf of California, and their conclusion was that several 1-Bgd desalting plants could be justified for the needs of Mexico, California, and Arizona.

Conclusions. Supplying desalted water for California at competitive rates depends upon the costs of alternative supplies, the choice of methods of defraying the

23. U.S.-Mexico-IAEA Study Team, *Nuclear Power and Water Desalting Plants for Southwest United States and Northwest Mexico*, TID-24767, National Technical Information Service, Springfield, Va. (September 1968).

desalting plant costs, and advances in desalting technology. California's long experience in developing water rates and methods of obtaining supplemental revenues to cover water costs includes two relatively standard methods which can be applied to desalted water as well. One method is to use the revenue from electric power sales to offset part of the cost of water as well as the cost of electricity. The other method is to levy a special water district property tax in the area served, the tax being justified by the increase in property values as a result of having an adequate water supply.

The potential reduction in the sale price of desalted water as a result of revenue from a special property tax in the water district is difficult to estimate; but the Metropolitan Water District of California obtains more revenue from taxes than from water sales, the tax in 1969 being equivalent to 11¢ per thousand gallons for the regular tax, or 13.7¢ per thousand gallons including the special tax.

Another economic factor of importance is the cost of money. The irrigation and municipal-type water districts obtain funds from the sale of bonds with comparatively low interest rates, usually in the range of 4 to 6%. In a dual-purpose plant, a change of 1% in the interest rate amounts to several cents per thousand gallons in the water cost.

These potential reductions in water selling price are attainable in California if a dual-purpose plant is built and operated by a municipal water district or by an irrigation district which can utilize power revenues to offset some of the water costs, can obtain revenue from property taxes, and can sell bonds at low interest rates. Thus, if provision of water at the lowest possible price is taken as an objective, advantage can be taken of the additional revenues and special financing opportunities as well as the advances in desalting technology.

New York Metropolitan Region

ORNL participated in the work of a joint study team evaluating methods of obtaining supplemental water supplies for the New York metropolitan region. The joint study team included members from the AEC, the Office of Saline Water, the city of New York, the state of New York, and Consolidated Edison Company. For the study team report, ORNL prepared chapters covering desalting technology, nuclear plant siting, and the design of a desalting plant for operation in conjunction with natural water supplies. Chapters contributed by other participants were compiled and edited by ORNL, distributed for review, and revised in the light of comments and suggestions received. At the end of the reporting period, a second draft had been distributed to team members for review.

The joint study team concluded that by 1980 the New York metropolitan area would be using 1500 Mgd in the municipal water system and would have firm yields of only 1325 Mgd from the natural water supply systems. Future increases in water requirements are forecast to exceed the present water supply system firm yield by about a billion gallons per day in 2020. The natural water supply system has yielded an average of 2250 Mgd over many years and has exceeded 1850 Mgd in 75% of the years and 1470 Mgd in 90% of the years. But in the prolonged drought of 1961–1967, winter and spring rains were inadequate to fill reservoirs, and the system yields dropped to 1500 Mgd in 1961–1964 and 1300 Mgd in 1964–1967. Thus the New York water supply system experienced severe water shortages during the 1961–1967 drought, which was the worst on record, but during normal years (more than half the time) was capable of yielding enough water to take care of the needs forecast for the next 50 years. Taking the yield during the worst drought years as the minimum firm yield of the system, the joint study team concluded that desalting plants, operated only as needed to maintain reservoir levels in the natural water supply system, could increase the minimum firm yield to meet forecast needs of the future.

The specific program recommended by the joint study team requires construction of six desalting plants of 125-Mgd capacity installed at approximately five-year intervals until a total desalting capacity of 750 Mgd is reached. These desalting plants, operating in conjunction with the existing surface water supply systems, would keep pace with anticipated growth in water demand and would provide protection against water shortages in unusually dry years. Optimum results would be obtained by operating the desalting plants only when natural water supplies cannot maintain minimum reservoir levels in the municipal water supply system. The general plan would be to start desalting plant operations when reservoir levels fall below the established minimum and to operate the desalting plant, using off-peak power as much as possible, until the desired reservoir levels are reached. Preliminary studies indicate that this type of operation in conjunction with the existing water supply system provides "drought-proofing" and additional capacity for future growth in demand at costs which are sufficiently low to warrant serious consideration and further study.

3.4 AGRO-INDUSTRIAL COMPLEX STUDIES

Introduction

Since it appears that widespread use of large-scale nuclear-powered desalting plants depends strongly on the ability to economically use desalted water in agriculture, some effort has been devoted to this problem during the past year. The problem is basically one of improving water use efficiency, that is, using less water per unit of production so that the cost of water becomes a relatively small cost factor. The development of a low-cost subsurface irrigation system (illustrated in Fig. 12), wherein soil surface evaporation losses are minimized and water distribution efficiency is improved, appears to offer the best means of achieving a large increase in water use efficiency. To illustrate the potential improvement in the farm economics, the following computational example was developed.

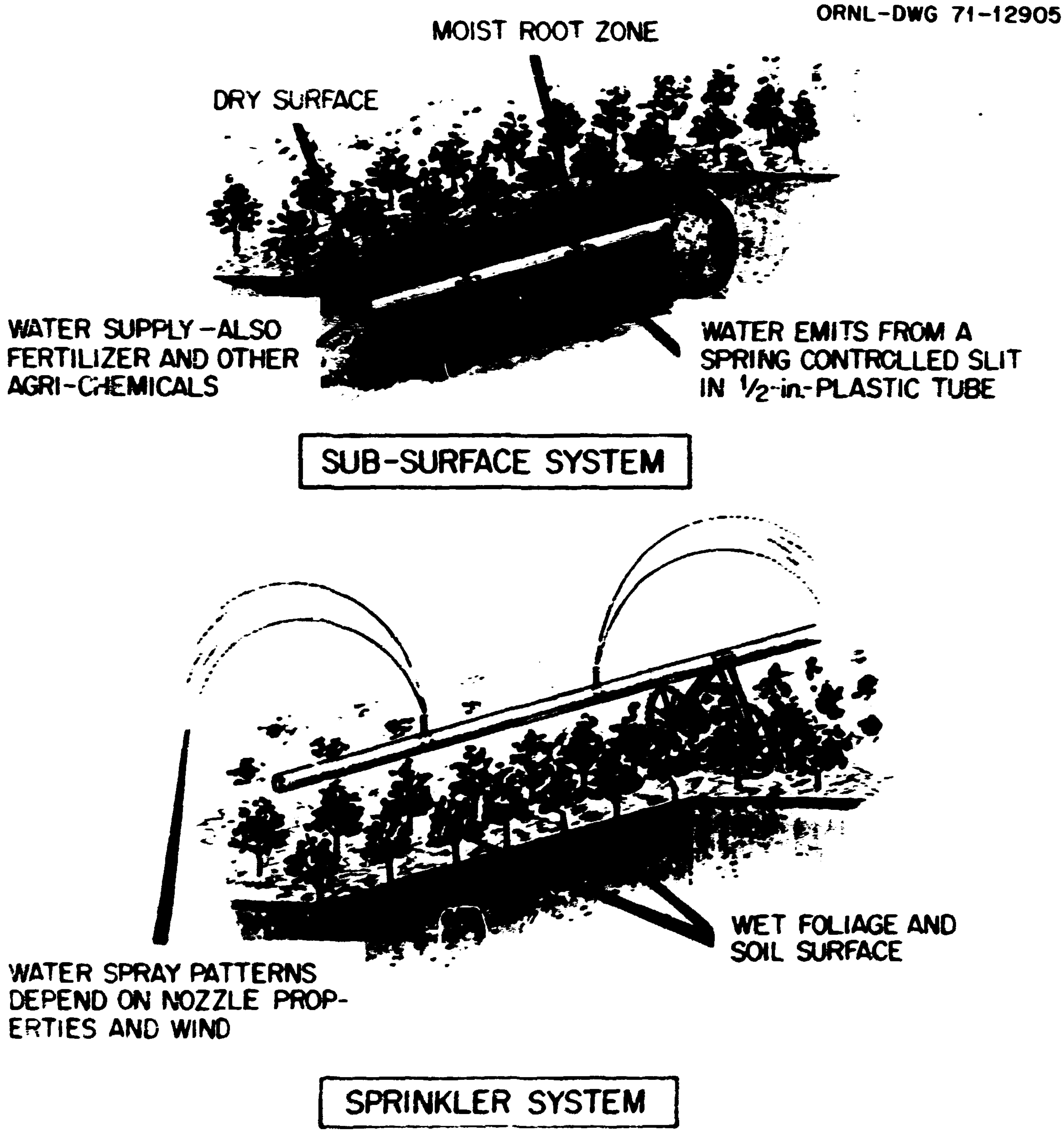

Fig. 12. Subsurface and sprinkler irrigation systems.

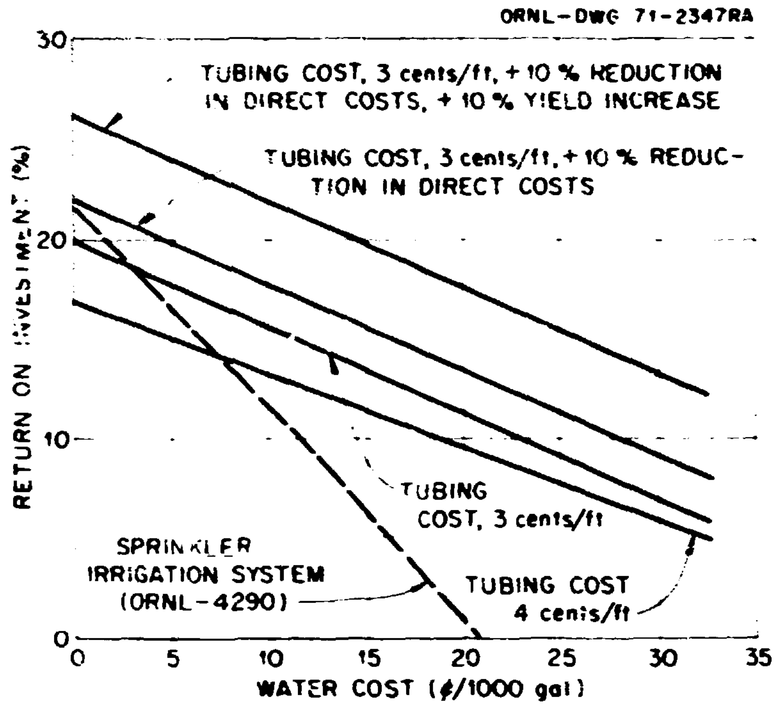

Fig. 13. Subsurface irrigation return on investment vs cost of water.

The overall effect on the economics of a large farm in changing from the sprinkler irrigation system assumed in the previous studies[24] to a subsurface system is illustrated in Fig. 13. Underlying assumptions in this computation are:

1. The subsurface system uses one-half the water per acre, thus permitting doubling of the farm size without changing the size of the desalting plant.

2. Use of the subsurface system allows the elimination of the drainage system and the moving laterals used in the farm example in ORNL-4290 (system 2, high profit, export price level), thus achieving a capital cost saving of $123/acre.

3. A subsurface plastic row spacing of 4½ ft is used with two basic tubing costs of 3¢ and 5¢/ft. (A 4½-ft row spacing at a tubing cost of 5¢/ft is equivalent to a 3-ft row spacing at 3.4¢/ft.) These costs result in total costs of $300 and $500/acre, respectively. Figure 14 illustrates this basic relationship.

As shown in Fig. 13, use of the more expensive but more efficient system results in less dependence on the cost of water. With low-cost water, the return on investment (ROI) would be lower with the subsurface system than that with a sprinkler system. However, it appears that an acceptable ROI could be obtained with a subsurface system using water at 30 to 35¢ per thousand gallons.

24. *Nuclear Energy Centers: Industrial and Agro-Industrial Complexes*. ORNL-4290 (November 1968).

25. T. E. Cole, *Subsurface and Trickle Irrigation–A Survey of Potentials and Problems*. ORNL-NDIC-9 (November 1971).

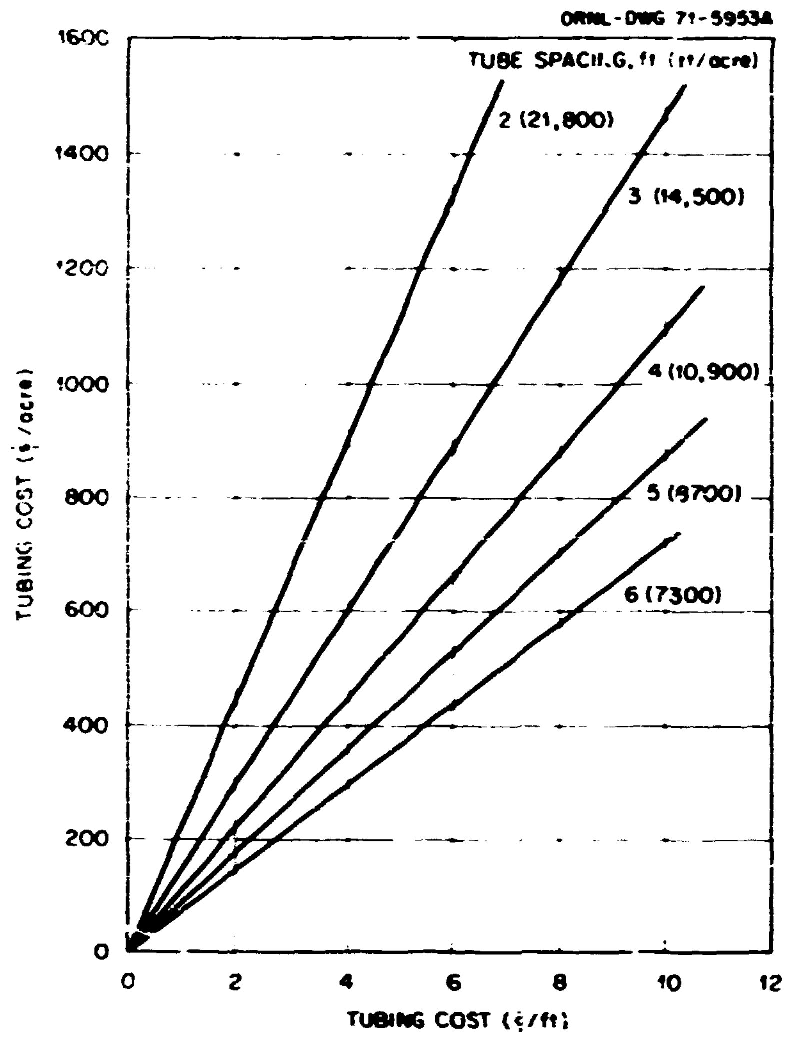

Fig. 14. Effect of irrigation tube spacing and basic tube cost on the overall cost per acre irrigated.

A literature review (58 reference documents cited)[25] of information on subsurface irrigation indicates that both reductions in system operating costs and increases in yield are probable in comparison with conventional irrigation systems. Lower operating costs result from decreased labor, less power, lower fertilizer application costs as well as lower fertilizer requirements, and lower weed and insect control costs. Increases in yield result from better control of the soil moisture to near optimum conditions. No large-scale applications of subsurface irrigation have been made, although several pilot projects have been in operation for some years.

Special additional advantages appear to be possible when using desalted water in such an irrigation system, that is, this water would be especially clean and free of disease, extraneous seeds, spores, and insects. Being essentially free of dissolved solids, soil flushing is minimized, as is "runoff pollution." The possibility of some water temperature control is good, so approaching the optimum plant (root) growth environment therefore becomes possible.

Subsurface Emitter Evaluation

The survey[25] of the state of the art of subsurface irrigation indicated that a prime need is to develop an improved emitter device which should meet the following criteria:

1. Low installed cost, that is, less than 5¢/ft.
2. Long lifetime, that is, ideally it should remain buried and functioning properly for 10 to 20 years.
3. A consistent, reproducible water flow flux; emitter should be capable of being cleaned in situ.
4. Relatively high-pressure operation ($\gtrsim$ 10 psig) so that long tubing runs may be used with a minimum header requirement or, more generally, give a uniform water flow distribution over long lengths, that is, more than 1000 ft.
5. Usability for distribution of plant nutrients (perhaps including CO_2) and other required plant chemicals.

While no commercial emitter which meets these criteria is currently available, one type now being widely tested is a porous ABS plastic tube. Samples of this material were obtained and flow tested (in air), both with and without a 20-μ filter in the water line upstream of the porous tubing. Considerable unexplained variability in the flow-ΔP (pressure drop across the wall) characteristics were observed, with time of operation, both with and without the filter, and between samples. These problems, plus the relatively high cost of this tubing, led to the consideration of the use of ½-in.-OD polyethylene tubing which can be purchased for 2 to 3¢/ft. A modification of a previously unsuccessful system using short axial slits in a tube is now being evaluated. Wire or flat spring clips are placed around the tube at the slit to give more control in the flow of water through the slit. This arrangement, shown in the top half of Fig. 15, appears to provide sufficient design choices to give any desired flow-ΔP relationship and at the same time to be amenable to self-cleaning. The bottom half of Fig. 15 illustrates a possible modification suitable for a surface system where the tube is combined with a plastic film to prevent surface evaporative losses.

Testing of the slit-clip concept has been done primarily on short lengths of tubing containing one or two emitters, although two tests of a 200-ft length were made by an MIT Practice School team. None of these tests have given satisfactory reproducibility, which is probably due to problems inherent in hand production of the spring clips. The self-cleaning feature does appear to be functional, particularly during a pressure pulsing mode of operation. In this mode, water flows through the slits during a pressure pulse; for example, 0.5 sec at 18 psig followed by a 10-sec interval of pressure decay to the zero-flow pressure of 13 psig.

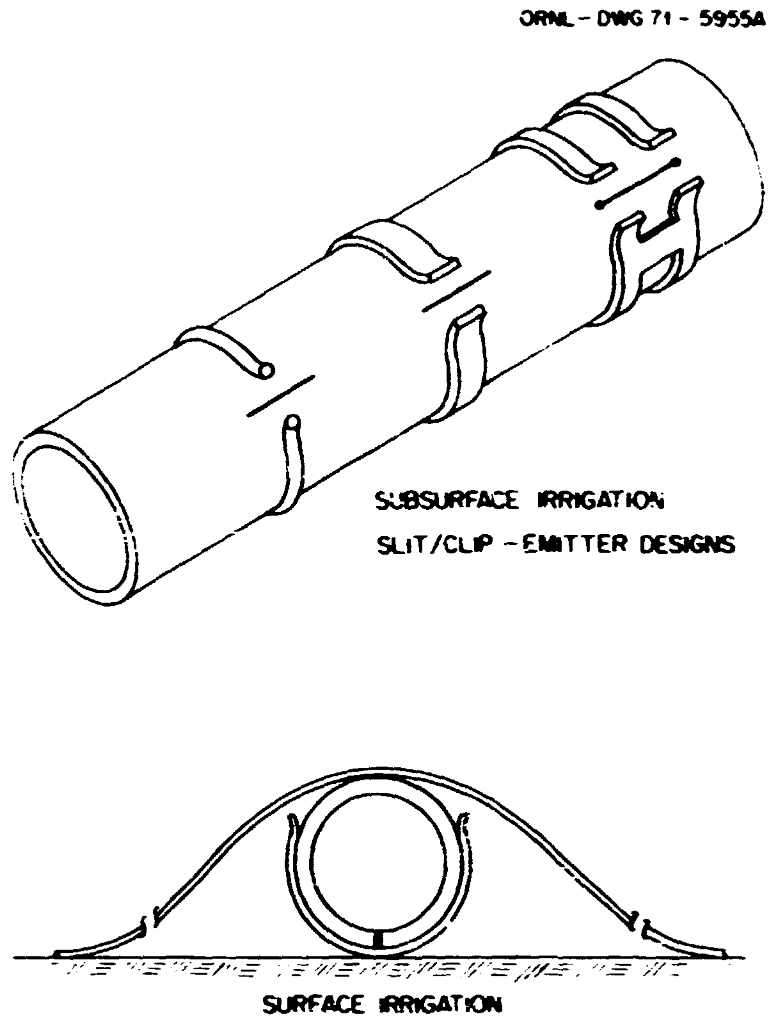

Fig. 15. Slit-clip emitter designs for surface and subsurface irrigation.

Greenhouse Demonstration Experiment

In order to gain a general insight into the problems related to growing plants using desalted water in a subsurface irrigation system and to provide a means for performing preliminary tests on new systems, a small greenhouse experiment was performed. The soil box shown in Fig. 16 (2½ × 2 × 2½ ft) fitted with a section of porous ABS tubing and filled with sterilized soil (provided by the Horticulture Department of the University of Tennessee) was instrumented and installed (see Fig. 17) in a greenhouse. Ryegrass was planted in January, and the experiment was discontinued in June.

The main conclusions drawn from this preliminary experiment were:

1. Subsurface irrigation permits prolific plant growth with a bone-dry soil surface, thus indicating a great potential for decreasing overall plant water requirements by essentially eliminating surface evaporation.

Fig. 16. Soil box for use in greenhouse demonstration experiment.

Fig. 17. Greenhouse demonstration experiment.

2. Plugging of the particular subsurface irrigation tube used in the experiment was a problem and emphasized the need for the development of an improved water emitter.

3. Addition of plant nutrients with the subsurface irrigation water was easily accomplished, but special precautions must be observed to prevent growth of algae in the water supply system. Tube plugging due to algae can, however, be largely eliminated by water flushing of the tube and system.

4. A simple yet satisfactory automatic soil moisture control system was developed and is available for performing additional plant growth tests.

5. Near the water source the roots were concentrated in the top 6-in. layer of soil, while away from the water source the roots extended to a greater depth.

Following the ryegrass experiment, rice was planted, that is, in half of the box rice seed was sown in rows, while in the other half rice plants about one month old were transplanted. The seeds germinated in about two weeks and within two months had reached a height of about 3 ft (slightly higher than the plants which were transplanted). The purpose of this experiment was to demonstrate seed germination without surface watering, to observe rice growth with a dry soil surface, and to provide confirmation of a reported claim of a rice ratoon process, that is, a second crop of grain without reseeding.

University of Tennessee Irrigation Experiment

Assistance in the form of engineering design and loan of equipment has been given to the University of Tennessee for carrying out an experiment to compare several irrigation systems used to grow tomatoes. The systems being evaluated in this replicated experiment

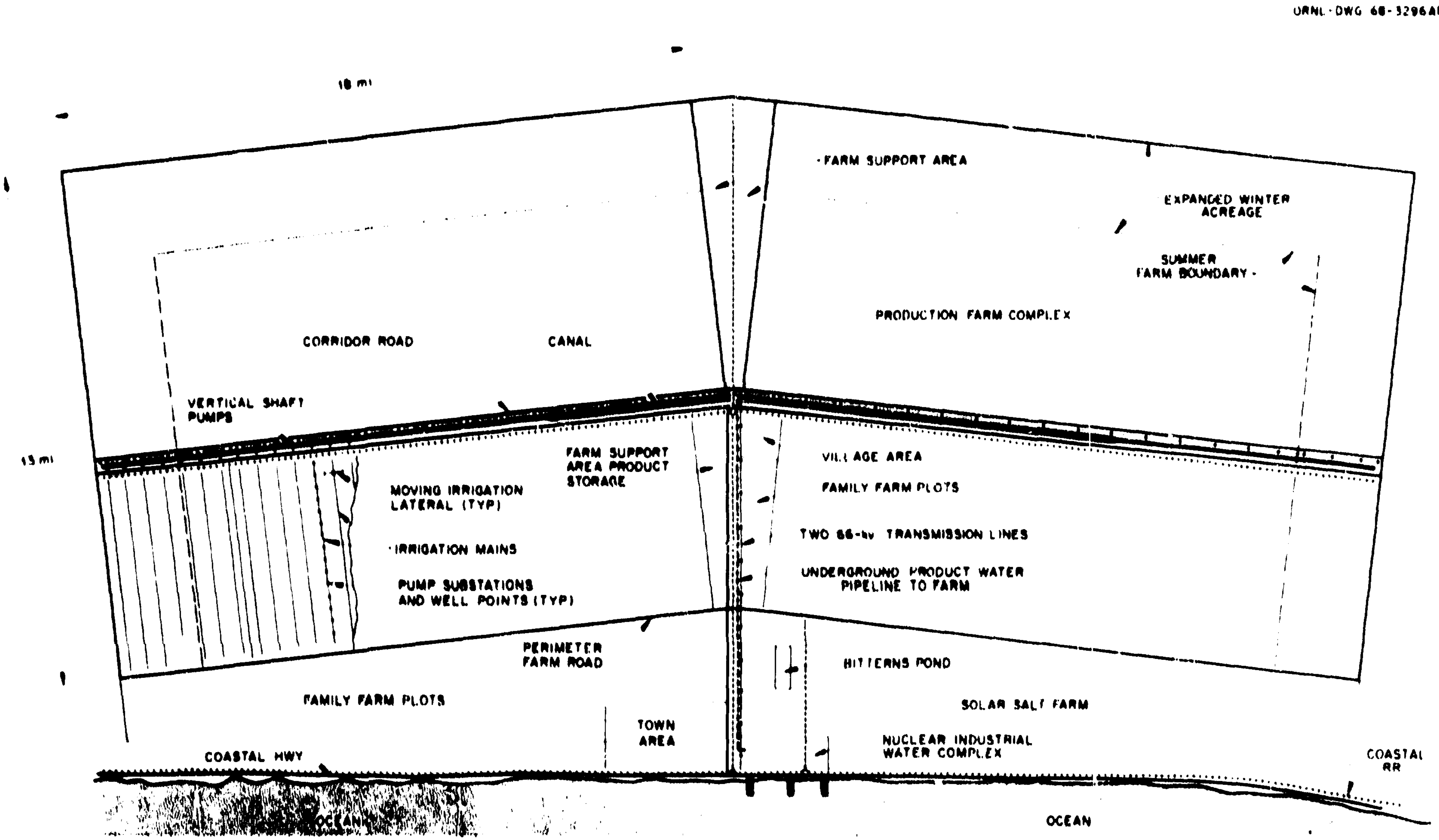

Fig. 18. Farm layout with a reservoir storage system.

include two types of surface irrigation: "Chapin-twin-wall," drip-tube, overhead sprinkler nozzles, and the "Micropor" porous plastic tube. The criteria for comparison will be yield and quality, as well as amount of water used (supplemental to rainfall) to maintain soil moisture levels at predetermined values.

IAEA Meetings

R. P. Hammond and J. W. Michel participated in a Study Group on Agro-Industrial Complexes at the International Atomic Energy Agency headquarters in Vienna, March 29 – April 2, 1971. Papers presented included:

Review of the Puerto Rico Energy Center Study, J. W. Michel

Review of Recent Agro-Industrial Complex Studies at ORNL, J. W. Michel

Comparative Study of Water-Only Desalting Plants, J. L. Jones

A Proposed Dual-Purpose Nuclear Desalting Plant Using Single-Effect Distillation, J. E. Jones and T. D. Anderson

The following week, April 5 – 7, a Panel on Storage and Transport of Water from Nuclear Desalting Plants was convened. The following ORNL papers were presented to this panel:

Alternatives for Storage of Desalted Water, J. W. Michel

Flexibility in Production of Power and Water from Nuclear Desalting Plants, I. Spiewak, J. K. Franzreb, and J. C. Moyers

The paper on "Alternatives for Storage of Desalted Water" included the results of work not previously reported. Three water storage systems were discussed: the underground aquifer (used in original studies), surface (cut and dike method), and floating plastic or rubber bag. Figure 18 shows (to scale) the circular surface storage reservoir as required to store about 25% of the annual water production on the plot plan of the farm design used in ORNL-4290. With an interest rate of 10%, water evaporation rate of 5 ft/year, and an initial water cost of 25¢ per thousand gallons, the total cost of this storage scheme is such as to cause an increase of 1.2¢ per thousand gallons in the production cost. This may be compared with 1.0¢ per thousand gallons for the aquifer/tube-well system. A floating or partially submerged plastic bag in a protected bay area also looks promising as an alternate storage system.

Other Meetings and Papers

Papers were also presented at two other conferences, the SINB annual meeting in Mobile, Alabama ("Status of Agro-Industrial Complex Studies at ORNL," J. W. Michel) and the Governors' Conference on Meeting Tomorrow's Energy Needs ("The Impact of Energy on the Location of Economic Activity," J. W. Michel). A survey of available literature on the subject of the use of heated water in open-field agriculture was prepared.

3.5 NUCLEAR DESALINATION INFORMATION CENTER

The Nuclear Desalination Information Center provides a means by which the scientist in the field of nuclear desalination can readily identify and retrieve complete information which has appeared in the literature and which is needed for his work. Numerous technical journals and publications from governmental agencies and educational institutions are scanned, and material pertinent to the work of the desalination program is selected by the Center. The material is then reviewed, abstracted, and indexed on a part-time basis by various specialists working with the desalination program. A computerized storage and retrieval system permits the retrieval of information from the storage system by author, company, or key words.

Publications

Four reports originated within the NDIC during the year; three of these were issued as ORNL-NDIC documents, while the fourth was printed by the U.S. Government Printing Office under an OSW label. Of the ORNL-NDIC reports, one was a review paper covering the state of the art of subsurface and trickle irrigation. This report by T. E. Cole is described in the section on "Agro-Industrial Complex Studies." A second report was an indexed bibliography-abstract document which continues the series of listings of abstracts which have been added to the storage and retrieval system. A revised index to all OSW R&D Progress Reports was also prepared, this time covering reports issued through July 1970. Since this form of index has such widespread acceptance and use, it will probably be updated annually. Since timeliness is important in such an index, it was printed and released by NDIC rather than through the Government Printing Office (which has a backlog of many months of work). However, the Government Printing Office did print, as an OSW report, a cumulative listing of abstracts in the storage and retrieval system. This covered the 1200 abstracts which had been listed in groups in the first five NDIC abstract reports.

The storage and retrieval system now includes abstracts of about 400 U.S. patents relating to the distillation process for desalting. A special report covering these patents has been prepared separate from the other literature covered by the system for the benefit of workers concerned with patentable inventions. A preliminary listing of about 250 patents had been circulated to a number of industrial organizations who in turn provided many additional patent numbers which were added to the storage system. A few copies of this report have been printed at ORNL; however, the regular distribution copies will be prepared by the Government Printing Office.

Thesaurus Development

In keeping with the needs of the Nuclear Desalination Information Center to be able to effectively index the material added to the system, changes have been made to the thesaurus of key words used. A number of new terms have been added as the need for them became evident, and some terms have been dropped or combined with others as experience showed that more effective indexing could be obtained by such a change. A revised thesaurus has been prepared and is now in use. Special consideration was given to making the words compatible with the terms used by the Water Resources Scientific Information Center and the Engineers Joint Council Thesaurus so that there would be an easy exchange of abstracts and indexing terms among NDIC and other systems. The computer system has automatically converted terms which had been assigned from the old listing to the new terms.

In connection with adding information to the storage system on the efficient use of water in agriculture, work is under way on the development of a suitable supplement to the thesaurus to cover this area of information. A preliminary listing of several hundred key words has been made, and assistance will be obtained from workers in agricultural science to determine which terms will be most likely to be useful for indexing. These key words will be used in addition to the listing already in use for the information system. While it is possible to add or delete terms from the system at a later date, the most effective indexing can be done with a list as near complete as possible at the start. The first material to be added to the system in the specific area of water use efficiency will be the references collected for the state-of-the-art irrigation report.

Location of Computer Files

A study is being made to determine the advisability of moving the storage and retrieval file from its present location at the Computing Technology Center at K-25 to the computer facilities at the X-10 site. It is understood that within the next 12 to 15 months the two IBM 7090 computers will be phased out at CTC, and all information work will be done on the System 360. This change will require reprogramming of the NDIC system and conversion of the storage tapes to the format required for I/O from the System 360. Since some kind of change must be made, we wish to consider the advisability of using the new facilities now available at the ORNL Computer Center. One major factor is that, for the eventual possibility of remote access to the storage files, the ORNL facilities can be coupled to public or FTS telephone lines, while security considerations require the use of dedicated lines into the CTC facility. The ORNL Computer Center has taken progressive measures to support remote terminals and provide versatile prepackaged programs to permit remote access. It is now possible, by public telephone, to communicate with the IBM 360/75 or the IBM 360/91 computer located at ORNL. Terminal access capability has also been extended to include true time-sharing exchanges with the recently installed PDP-10 computer at the ORNL facility. This remote access capability will be particularly advantageous as the Center's coverage is extended to cover material on the efficiency of water use in agriculture, since it will permit cooperating experiment stations and universities to obtain information directly from the current NDIC tapes.

Requests for Information

Requests for information or assistance from outside ORNL continue at the rate of about six or seven a month. There seems to have been a decrease in the appeal of desalting with school children, since the requests for booklets about desalting for term papers or science fair projects dropped from six or seven of last year to three this year. On the other hand, there were eight requests for information from graduate or undergraduate students at universities. Desalting topics are being investigated as thesis problems. Other requests indicate the consideration of desalting by groups which heretofore have not been involved; one such request was for several complete sets of abstracts by the Arizona Atomic Energy Commission. There are still requests for copies of some of the computer codes written for plant design studies.

4. Reports, Papers, Journal Articles, and Books*

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