ORNL-4668
UC-80 – Reactor Technology

NUCLEAR DESALINATION PROGRAM ANNUAL PROGRESS REPORT ON ACTIVITIES SPONSORED BY THE ATOMIC ENERGY COMMISSION FOR PERIOD ENDING OCTOBER 31, 1970

OAK RIDGE NATIONAL LABORATORY

operated by

UNION CARBIDE CORPORATION

for the

U.S. ATOMIC ENERGY COMMISSION

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NUCLEAR DESALINATION PROGRAM ANNUAL PROGRESS REPORT ON ACTIVITIES SPONSORED BY THE ATOMIC ENERGY COMMISSION FOR PERIOD ENDING OCTOBER 31, 1970

R. P. Hammond, Director

Report Compiled by
T. D. Anderson and A. B. Gill

APRIL 1971

OAK RIDGE NATIONAL LABORATORY
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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 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) 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

ORNL DWG 71 2311

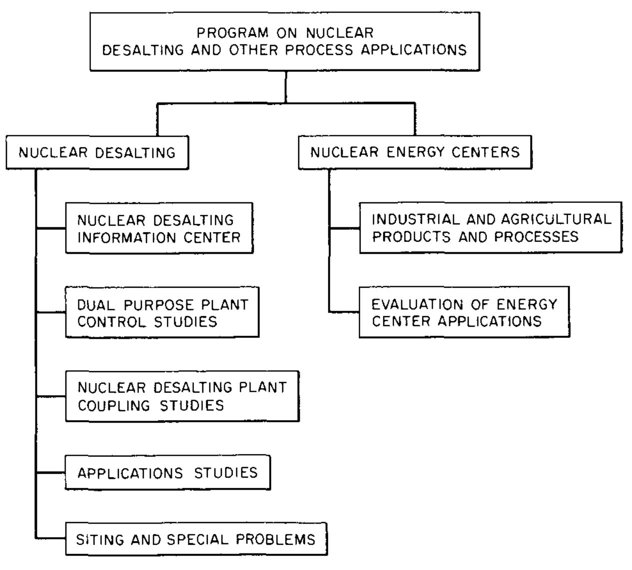

Fig. 1. Elements of program.

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 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, 1969, through October 31, 1970. 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

A preliminary study was made of a new concept for a dual-purpose plant which combines a conventional nuclear power plant and a single-effect vertical-tube evaporator The evaporator operates on very low-temperature (~109°F) turbine exhaust steam. The concept looks very promising for desalting applications in which a low water-to-power ratio is acceptable (e.g., municipal water supply).

A comparative study of alternate water-only desalting plants was completed. The study was based on the use of pressurized-water reactors as a heat source, both power reactors and low-temperature process heat reactors were considered From the study of several combinations of plants and cycles, it was concluded that a power reactor coupled with a hybrid desalting plant consisting of a vapor compressor and a vertical-tube evaporator was the clear choice for large water-only plants

An investigation of alternative coupling arrangements for a nuclear dual-purpose demonstration plant was initiated A reference coupling arrangement was developed which seems to meet most of the coupling criteria for a demonstration plant Further work will be required, however, to refine the system and to get a better understanding of the flexibility and dynamics characteristics

Investigations of the problems of controlling large nuclear desalting plants have continued to concentrate on multistage flash (MSF) evaporator dynamics Experiments were run on a test evaporator to determine the stage thermal and hydraulic operational characteristics for various design features Further studies using these data were made to predict overall plant behavior, controllability, and stability characteristics These studies made use of the ORNL digital simulator, which calculates the nonlinear time response behavior of large MSF plants This simulator has been found to be extremely useful, not only in plant design studies but in planning experimental programs. Work was begun on extending the simulator to include the turbine-generator and reactor plant behavior

2.2 NUCLEAR ENERGY COMPLEXES

While most processes that have been considered in nuclear energy center studies are electricity-intensive, industries that consume large quantities of steam would realize sizable advantages by being part of a nuclear-powered industrial complex An analysis of steam use by the main categories of United States industries was initiated.

A reanalysis of the basic assumptions used in past studies of the economic viability of using desalted water for agriculture was completed The main conclusion of this analysis is that the cost of desalted water is unlikely to become low enough for general agriculture using *conventional* farming methods, but the use of desalted water in *advanced* agriculture, such as that envisioned for agro-industrial complexes, appears very promising. The key to the successful use of desalted water on a large scale is the improvement in water use efficiency Sufficient improvements have been demonstrated on a pilot scale, and it seems only a matter of time until advancements in agriculture will make desalted water economically feasible for irrigation

Relative to the application of nuclear energy centers, ORNL provided information and technical assistance to the team from the Indian Atomic Energy Agency which is studying applications of agro-industrial complexes in India. Similar assistance was given on a study of an energy center for Puerto Rico which was sponsored by various agencies of the United States and Puerto Rican governments The ORNL study of large water-producing energy centers for areas of the Middle East was essentially completed

3. Summaries of Work Completed and in Progress

3.1 NUCLEAR DESALTING PLANT COUPLING STUDIES

Dual-Purpose Plant with Single-Effect Vertical-Tube Still

Preliminary evaluation of vertical-tube still. The proposed dual-purpose plant combines a conventional nuclear power plant with a single-effect vertical-tube still (VTS) which operates on very low-temperature (~109°F) turbine exhaust steam. A detailed examination of this concept may be found in ORNL-TM-2964.[1]

The reasoning behind the proposal for a single-effect plant stems from the relationship between heat cost and temperature for a dual-purpose plant For a nuclear electric power plant operating at a condensing pressure of, for example, 1.5 in. Hg (92°F), the value of exhaust steam is defined as zero As the turbine exhaust temperature is increased, the exhaust steam becomes more useful, but the turbine cycle becomes less efficient The nuclear steam supply must, therefore, provide more thermal energy to maintain the same electrical output. The incremental cost of producing this additional energy, expressed in terms of cost per unit of exhaust heat, is illustrated in Fig. 2, this figure is based on an investor-owned light-water reactor with a net production of 1000 MW(e) and enough exhaust steam for about 20 million gallons of water per day Although the cost of exhaust steam increases with temperature, the number of times the heat can be reused to evaporate water also increases with temperature (see Fig. 2).

The net result in terms of the contribution of heat cost to water cost is illustrated in Fig. 3. It will be noted that at relatively high temperature (>160°F) the heat cost contribution decreases with increasing temperature This well-known phenomenon accounts for the general interest in high-temperature multieffect and

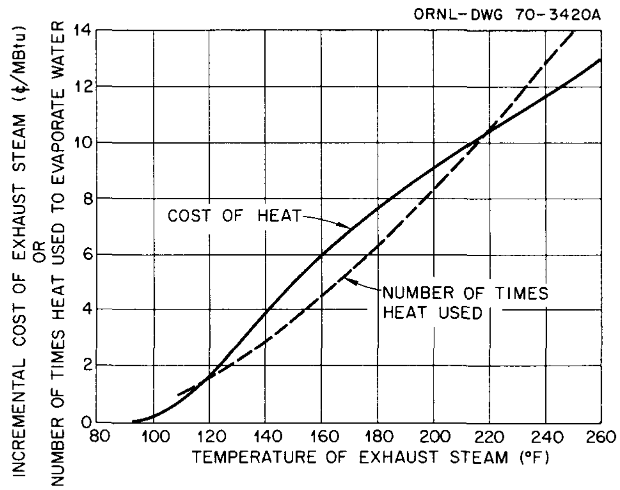

Fig. 2. Cost and use-efficiency of heat as a function of exhaust temperature.

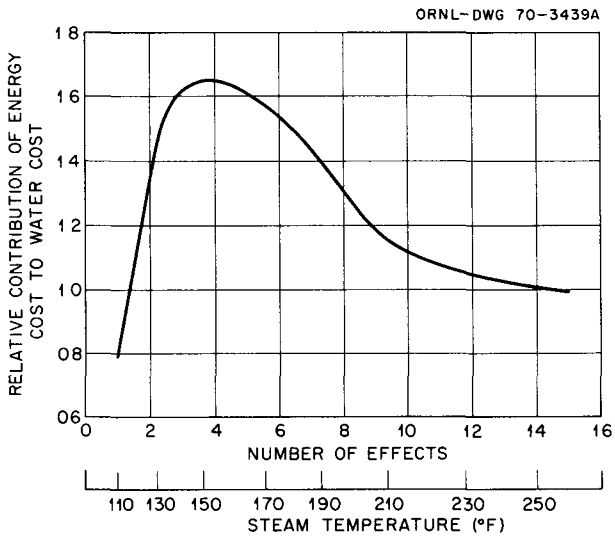

Fig. 3. Contribution of heat cost to water cost as a function of exhaust temperature.

1 J. E. Jones, Jr., and T. D. Anderson, *A Proposed Dual Purpose Nuclear Desalting Plant Using Single-Effect Distillation,* ORNL-TM-2964 (May 1970).

multistage evaporators However, it has not been recognized previously that at low temperatures the heat cost contribution decreases with decreasing temperatures (see Fig 3) It is this property which provided the initial incentive to examine the dual-purpose plant with a single-effect evaporator There are, however, several other technical and economic advantages of the low temperature single-effect plant These include (1) the possibility of using low-cost materials of construction such as aluminum tubes and concrete shells, (2) the elimination of seawater acid feed treatment, and (3) the simplification of coupling and control systems

A simplified sketch of the dual-purpose plant using the VTS is shown in Fig 4 Basically, the arrangement is a conventional nuclear power plant with one vertical tube evaporator effect placed between the turbine exhaust and the condenser

From the standpoint of cost, the VTS system looks very promising It is estimated that a dual plant producing 20 Mgd of water and 1000 MW(e) (net) of electricity would have a water production cost about 38% less with the VTS than with the next best alternative evaporator – a high-temperature VTE-MSF plant The cost savings result from (1) lower heat cost, (2) elimination of feedwater treatment, (3) reduced pumping power, and (4) the use of aluminum tubes and a concrete shell in the low-temperature VTS

Several technical and operational problems normally associated with dual-purpose plants appear to be alleviated by the VTS In the area of environmental pollution, the VTS effluent contains no added chemicals, no copper ions, and less heat than a similarly sized high-temperature plant Stability and control problems are substantially diminished with the use of only one effect and elimination of the flash feed heater Interface components, especially turbines and demineralizers, required are of the type normally used in power only stations Because of the low pressure differential (1 in Hg) between the exhaust steam and the brine, potential leakage between these streams should not be as serious a problem as with high-temperature evaporators

From this preliminary evaluation of the VTS, it is concluded that the concept has potential technical and economic advantages relative to high-temperature evaporators Although limited in application to developed regions because of the high power-to water ratio (50 MW(e)/Mgd), such regions (in the U S) are among the ones for which additional water supplies are needed

Study of optimum exhaust pressure In the preliminary evaluation described above, the turbine exhaust

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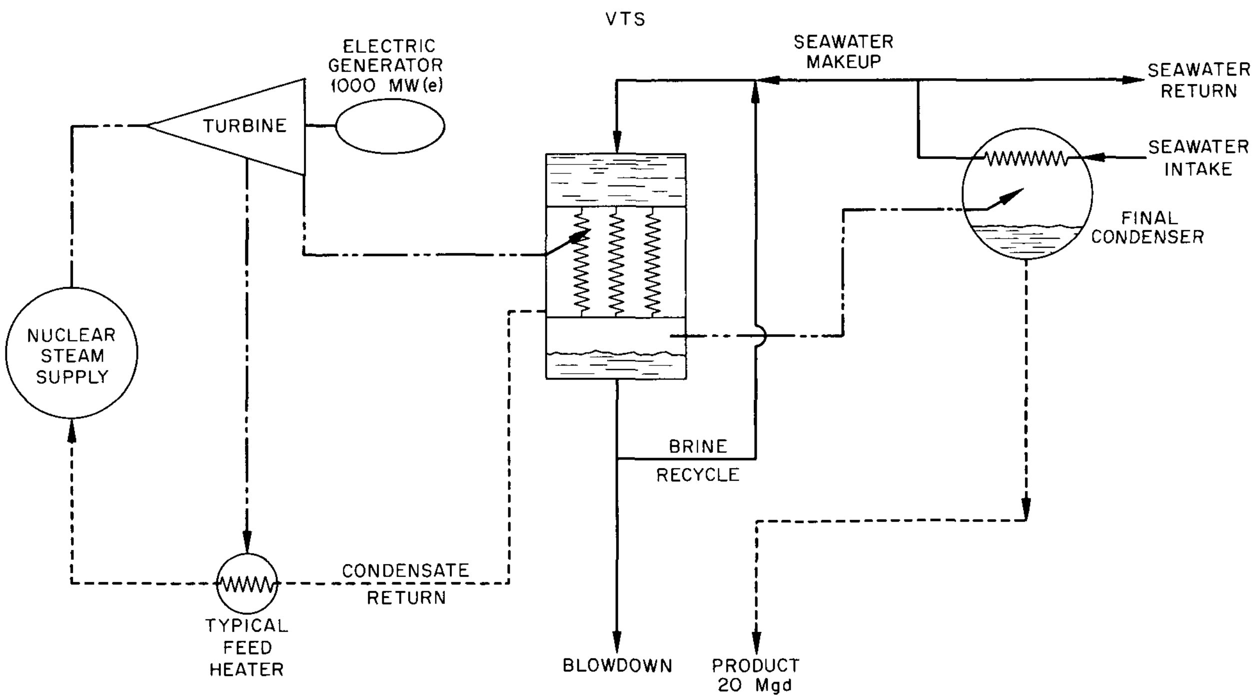

Fig. 4. VTS dual-purpose plant arrangement.

pressure (2.5 in. Hg) was selected more or less intuitively. Since this choice may have a very significant effect on the economics of the evaporator, a study[2] was made to evaluate the effect of exhaust pressure on the plant economics.

The design of a dual-purpose power desalting plant involves a compromise between electrical capacity and capital costs. This compromise was investigated for the specific case of an electrical plant of about 1000 MW(e) capacity and a single-effect vertical-tube still of about 20 Mgd capacity. As the turbine exhaust pressure is increased, the electrical capacity decreases, however, the heat transfer area required in the evaporator also decreases, resulting in a lower capital cost. The choice of the optimum exhaust pressure may be made in the following manner.

Define Y to be the total economic effect (in dollars) of a change from the reference condition Then

$$Y = [P(T_R) - P_0]\, V - [A(T_R) - A_0]\, S + C\,,$$

where T_R is the temperature measured from the reference value, $P(T_R)$ is the generator capacity at temperature T_R, P_0 is the reference generator capacity, V is the value of a kilowatt of capacity, $A(T_R)$ is the evaporator heat transfer area at temperature T_R, A_0 is the heat transfer area required at the reference condition, S is the evaporator cost expressed in terms of dollars per square foot of heat transfer area, and C is the difference in turbine cost between a given turbine and the reference. If we take the temperature derivative of Y and set it equal to zero we get

$$(T_R)_{\mathrm{opt}} = \left[-\frac{S\alpha}{UV}(T_R + 15.49) - \frac{S\,D(T_R)}{UV\,dP(T_R)/dT_R} \right]^{1/2} - 15\ 49\,,$$

where α = 3413 Btu hr^{-1} kW^{-1}, U is the coefficient of heat transfer, and $D(T_R)$ is the thermal capacity required in the evaporator at temperature T_R If S and V are allowed to vary as parameters, the equation may be solved by iterative techniques for the optimum temperature The optimum pressure and the economic effects can then be obtained. A small portion of the results obtained are shown in Table 1 to illustrate the information this procedure can generate. These results show a possible saving of up to $1.2 million, which demonstrates that such optimizations are worth while Other turbine-generator combinations covered in the study show even higher potential savings, ranging up to $2 5 million

Steam Cycle Efficiency for Dual-Purpose Plants

During this reporting period the report *Steam Turbine-Generator Cycle Efficiency for Desalting Applications*[3] was completed The previous annual report[4] provides some description of the study as it was being conducted Briefly, the report provides tables and graphs for rapid estimation of turbine cycle efficiency, heat rate, feedwater pumping power, throttle steam

2 F. G. Welfare, *The Optimum Turbine Exhaust Pressure for Use of a Single-Effect, Vertical-Tube Still Desalting Plant with a Steam Turbine Generator,* ORNL-TM-3291 (February 1971).

3. L. C. Fuller, *Steam Turbine-Generator Cycle Efficiency for Desalting Applications,* ORNL-TM-2909 (July 1970)

4. *Nuclear Desalination Program Annual Progress Report on Activities Sponsored by the Atomic Energy Commission for Period Ending October 31, 1969,* ORNL-4538 (May 1970)

Table 1. Optimization results for a 43-in. GE turbine

Value of a kilowatt (dollars)	Cost of heat transfer surface (dollars/ft^2)	Optimum exhaust pressure (in. Hg)	Optimum evaporator temperature (°F)	Total saving due to system change[a] (millions of dollars)
100	4	2.51	108 78	
100	6	2.67	110.92	0.077
100	8	2.81	112.64	0.264
100	10	2.92	114.09	0.527
100	12	3.03	115.36	0.845
100	14	3.13	116.50	1.207

[a]The saving is for operation of the system at the optimum pressure as compared with operation at 2 5 in Hg

flow, exhaust steam flow, and exhaust enthalpy for steam turbine-generator cycles.

In place of the usual detailed turbine cycle heat balance calculations, the tables and graphs can be used to make rapid determinations of performance data for steam turbines in power-only applications or in dual-purpose plants for desalting and power generation. The tables and charts cover throttle steam conditions for saturation to 300°F of superheat and for 400 to 2400 psia pressure, with exhaust at 1.5 in. Hg (abs), 15 psia, and 35 psia. The report includes cycle descriptions, flow diagrams, and the solution of a sample problem.

MSF Flexibility Analysis

An investigation was made to determine some of the requirements for an MSF process control system which would provide adequate brine level control with greater flexibility. It was found that for a given fixed interstage orifice configuration, with a given flow rate and vapor pressure differential and a given condensing system, there is only one temperature level at which this overall system will operate with constant brine levels. It follows that if, for example, the heat input load is changed, some other process parameter must be adjusted to rebalance the system at a different temperature level, or else the stage brine levels will vary. Any imbalance of the plant parameters is reflected in a brine level taper from stage to stage. This suggests a control mechanism wherein incipient brine level changes are detected, and the output of the detector is used to control a balancing variable. Since in a dual-purpose plant the heat load can most likely not be controlled, the control of the recycle flow rate appears logical. Other choices are, of course, possible.

There is experimental and analytical evidence that the level taper control concept is workable. One instance was the application of the system in a test by ORNL personnel in the OSW Baldwin-Lima-Hamilton three-stage facility at Wrightsville Beach, North Carolina.

A problem which might be encountered in level taper control is "bowing" of the level profile. Assuming that the nominal depth is controlled in a certain stage and that the first stage depth is controlled at the nominal value, the stages between might experience excessive or insufficient depths. Computer studies have been made to investigate this problem. Figure 5 shows some results of one such study which utilized the Oak Ridge Fixed Geometry MSF Code (ORFIG). In this study stage, brine levels were calculated for a wide range of off-design operating conditions including recycle flow rates of 0.8, 0.9, 1.1, and 1.2 times design, steam temperatures (to the brine heater) in increments of 5°F above and below design, and a range of steam flow rates. Figure 5 shows stage brine level profiles for the four off-design recycle flow rates and the combinations of other variables which gave the minimum variations from the nominal (design) 15-in. depth. Stage depths vary from 1.0 to 1.5 ft in most instances, and even the extreme spread does not appear intolerable.

These results are based on steady-state operating conditions without consideration of possible dynamic effects. A conventional plain (unbaffled) orifice flow equation was used, with an assumed flow coefficient. Nevertheless, it does indicate that there is at least a theoretical possibility that MSF stage brine levels can be

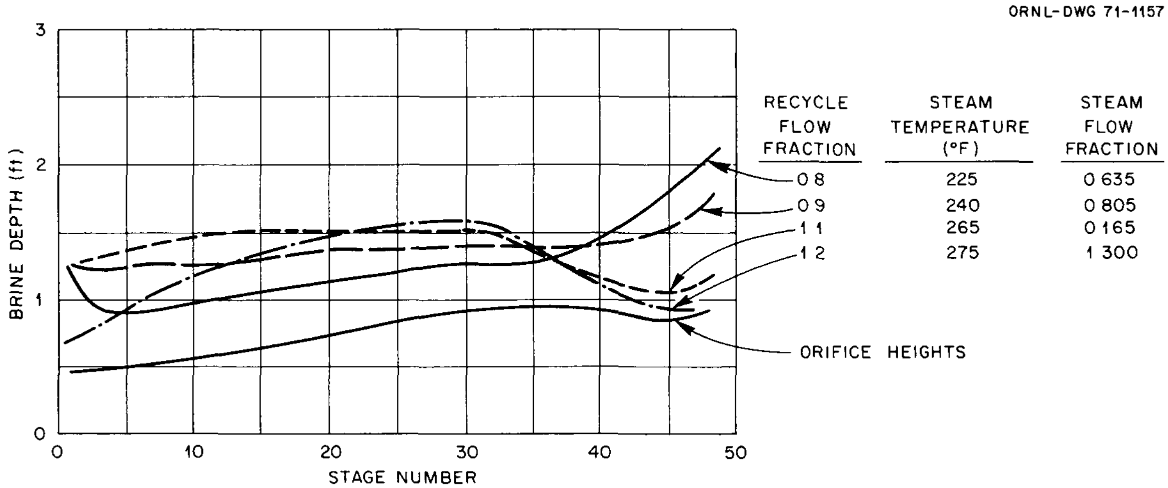

Fig. 5. Calculated variation of stage brine levels at off-design conditions up to ±20% design recycle flow rate.

properly controlled over a moderate range of operating conditions by properly adjusting external variables such as brine recycle flow and steam flow and temperature.

Comparative Study of Water-Only Plants

A comparative study of alternative water-only desalting plants has been completed. The study was based on the use of pressurized-water reactors as a heat source. Both power and low-temperature process heat reactors were considered. Two levels of PWR technology were considered as characterized by the type of fuel – oxide or metal. The three basic alternative cycles are listed below

Reactor	Coupling
1 Power	Prime steam → attemperator → evaporator
2 Power	Prime steam → vapor compressor → evaporator
3 Process heat	Process steam → evaporator

Preliminary results for cases 1 and 3 of this study were reported in the previous annual report along with the range of parameters and cost basis. The analysis of the vapor compressor case has since been completed. Table 2 provides a comparison of unit water costs for the alternative cases for the 250-Mgd plant. The larger plants, of course, have a slightly lower unit water cost, but the comparative results are similar.

The vapor-compressor-topped vertical-tube evaporator (VC-VTE) is significantly superior to the VTE or MSF plants using a power reactor with a cost advantage of 10% or more. This advantage is noted whether the financing is public or private and whether the fuel is uranium metal or oxide. However, a comparison of the VC-VTE with the VTE coupled to a process heat reactor shows an advantage for the VC-VTE plant of only 1.2 to 7.5%.

The actual advantage of the VC-VTE in this case may be larger because of two factors which do not show up in the summary table. First, the heat source for the VC-VTE plant is only about 1200 MW(t), which is in the size range where a fossil-fuel boiler would presumably be more economical Since our calculations considered only the PWR as a heat source, the prime steam costs may be high for this case. Second, the thermal heat exhausted from the VTE plant is approximately 70% more than that for the VC-VTE plant. Since the cost of waste heat disposal has increased sharply in many locations because of new regulations, the VTE plant would incur a much larger penalty for waste heat disposal than would the VC-VTE plant.

Although the apparent advantage of the VC-VTE plant is slight, it appears nonetheless to be the clear choice for large water-only plants.

Investigation of Coupling Arrangements for the Nuclear Dual-Purpose Demonstration Plant

It is evident that one or more moderate-sized prototype or demonstration plants will need to be constructed and operated prior to full commercial introduction of large dual-purpose desalting plants.

During this reporting period work was begun on development of the coupling and control characteristics of an assumed dual-purpose demonstration plant. Heat balances were made from numerous assumed turbine-generator cycles. Most of the cycles analyzed took their main characteristics from the TVA Sequoyah plant The heat rates of the various cycles analyzed did not vary by as much as 1%.

Figure 6 shows the cycle selected for further study. It was assumed that the evaporator plant will operate on

Table 2. Summary of unit water cost for water-only plants

Unit water cost (cents/kgal)					Reactor fuel	Type of financing
Process heat reactor		High-temperature reactor[a]				
Direct coupling, MSF	Direct coupling, VTE	Attemperator, VTE	Attemperator, MSF	Vapor compressor, VTE		
31 63	25.99	27.19	32.89	24.18	UO_2	Public
28.25	23.00	24.95	30.38	22 73	U	Public
48.68	39.78	41.70	50.67	37.38	UO_2	Private
45 59	37.01	39.97	48.74	36.40	U	Private

[a]The high-temperature reactors produce steam at conditions identical to present commercial PWR's.

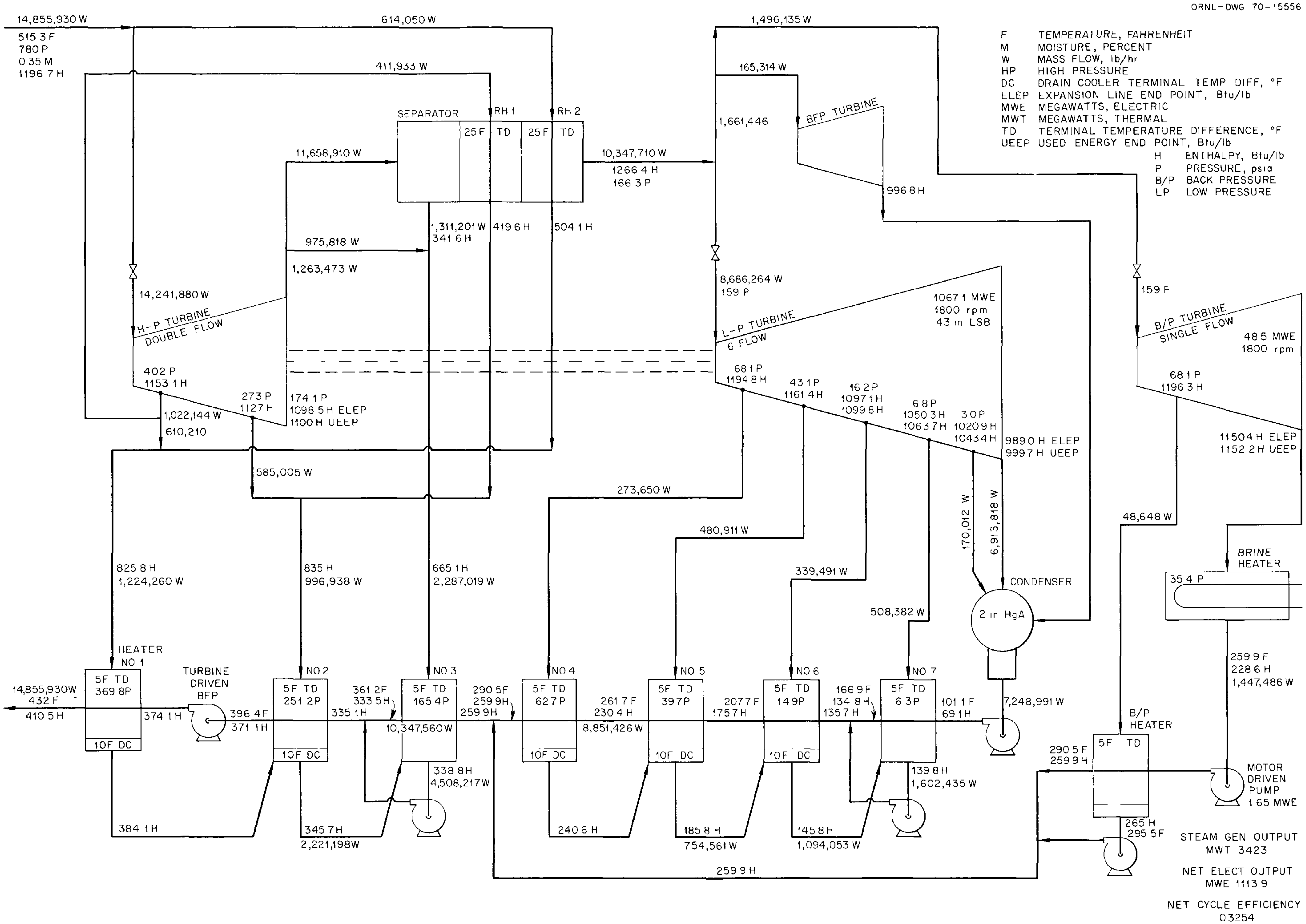

Fig. 6. Turbine-generator cycle heat balance.

260°F steam from a back-pressure turbine. The balance shown in Fig. 6 is for 50 Mgd with a performance ratio of 13. The "power" turbine-generator (H-P and L-P turbine sections on Fig. 6) was sized to provide the maximum electrical output obtainable using the reactor thermal power of Sequoyah and the requirement of 50 Mgd for the evaporator plant.

It is certainly desirable that the power portion of the plant be capable of producing full electrical output independent of the operating state of the evaporator. It is also desirable that the evaporator be capable of producing full design output independent of the operating state of the power turbine-generator. The changes required to make this possible will be studied.

Certain of the cycles were analyzed by the use of the ORCENT turbine-generator code. The cycle in Fig. 6, with its division of flow to a back-pressure turbine and a condensing turbine after the second stage reheater, required an additional computer program, which was used to arrive at the heat balance of Fig. 6.

The next step will be to look at the flexibility and dynamics characteristics of the back-pressure turbine/brine heater complex in more detail.

3.2 DUAL-PURPOSE PLANT CONTROL STUDIES

Introduction

Investigations of the problems of controlling large nuclear desalting plants have continued to concentrate on multistage flash (MSF) evaporator dynamics. Experiments have been run on an OSW test evaporator to determine the stage thermal and hydraulic operational characteristics for various design features. Further studies using these data have been made to predict overall plant behavior, controllability, and stability characteristics.

State of Technology

Experiments run on the Office of Saline Water/Baldwin-Lima-Hamilton (OSW/BLH) Wrightsville Beach test evaporator have produced sufficient data and have yielded good correlations for describing the behavior of MSF stages over limited ranges of operation for a few simple stage designs. However, more data, covering the entire flashing range and including various flash enhancer and baffle designs, need to be obtained and analyzed. Similar experiments on the full-scale MSF module at San Diego are also required to verify the pilot data.

Analytical methods for describing the overall dynamics and controllability of large MSF plant designs have been developed further and applied to specific plants. The MSF digital simulator developed at ORNL provides a convenient means of predicting MSF plant dynamics for varieties of user-supplied models, parameters, and plant design features.

Experimental Investigations of MSF Evaporator Operating Characteristics and Dynamics

Trend tests. The derivation of empirical correlations for describing stage nonequilibrium losses (Δ') and tray brine hydraulic behavior is a crucial aspect of the problem of predicting overall plant operating characteristics. In both cases the behavior is very sensitive to variations in several parameters; hence, when correlations are derived, it is important that changes in behavior are properly attributed to variations in each parameter.

The idea of the "controlled trend" test method is to first establish a given set of operating conditions and then slowly vary one parameter while holding others (where possible) constant. The response of the pertinent evaporator conditions is logged continuously, resulting in a "curve" showing the change in behavior with the varied parameter. The important features, then, are:

1. *Deviations* in behavior are more apt to be properly attributed to *deviations* in a measured parameter, rather than having to base the relationship on differences between absolute measurements made on different days, with perhaps other significant differences in conditions not apparent from the measurements.
2. Data can be taken continuously, and hence much more efficiently, since it is necessary for the test stage, but not the entire plant, to be "settled out" before recording data.
3. With a recorder available, the general characteristics of the trends are readily apparent to the experimenter right on the spot, and he can usefully exercise his judgment in controlling the experiments.

One of the built-in problems in the trend (or steady-state) test method is that it is not possible to vary just one input parameter at a time. In order to develop a parametric expression for one aspect of stage behavior (Δ', for example) it would be helpful to be able to do this. However, the consideration of secondary parameter variations is done in the analysis, though not in the execution phase of the experiment.

The additional instrumentation and control hardware required for implementing trend tests on the BLH plant was installed and checked out, and testing and analysis procedures were developed and tried. Tests were run on a 15-ft-long test stage in February 1970 and on a 7-ft-long stage in August 1970 While the February tests were primarily "shakedown runs," much useful information was obtained which led to improved measurement, data collecting, and experiment design techniques applied to the later tests.

Accurate empirical correlations for both the Δ' behavior and the interstage orifice flow relationships were derived from the August test data Several special techniques were required to obtain consistent, reproducible data for the Δ' correlations, including statistical weighting of the temperature data containing significant temperature fluctuation "noise," use of heat-balance-derived tray brine temperatures rather than direct brine temperature measurements, and special in situ temperature probe calibration techniques Special tests were also run to note the effects of varying antifoam and acid concentrations and condenser venting rates on stage performance.

An empirical correlation equation for Δ' for the plain-hole test stage, applicable over a wide range of brine flow rates and levels and a brine temperature range of 125 to 160°F, was derived which fits the data to within 0 25°F root mean square error. Δ' was found to have a strong negative dependence on flashdown and a positive dependence on brine level The brine level effect appeared to be both level- and temperature-dependent, level changes being less effective at higher temperatures and at higher absolute levels. An additional term was included to account for the effect of the presence of acid.

A correlation equation of the same form, but with different coefficients, was also derived for the inlet stage Δ', this one fitting the data to within 0 2°F rms error While the inlet stage is quite atypical, particularly due to the brine flow entering from the side, the fact that the form of the two equations is the same suggests that this form might be applicable to Δ' performance for a wide class of stage geometries.

The significant effects of brine level changes on Δ' were also seen to be important to the hydraulic behavior For example, as the level of a stage decreases, its Δ' decreases Since a smaller Δ' means the vapor temperature is closer to the brine temperature (i e , hotter), the corresponding vapor pressure increases This is in opposition to the inherent inventory control mechanism in open channel brine flow, where, for example, a decrease in inventory (brine level) decreases the static head in the stage and thus increases the inlet flow and decreases the outlet flow Hence a positive dependence of Δ' on level results in a destabilizing tendency and indicates that flash enhancer and baffle designs which minimize this dependence would help to improve the hydraulic stability. Later tests run by BLH on the 7-ft stage with several different flash enhancer devices installed indicated just such desirable reductions in the dependence of Δ' on level A comparison made of measured Δ' values and those computed with the empty-stage correlation equation showed little improvement in low-brine-level Δ' values but showed significant improvements at higher levels

An empirical correlation equation for the test stage inlet tray brine flow rate was derived which accounts for most of the significant trends in the flow data taken in the August tests. Data were taken during ten trend tests in which brine flow rate was held constant and other parameters (such as levels and flashdown) were varied. These data showed that as the upstream level is increased, the required total head increases markedly and the relative effectiveness of the vapor pressure difference decreases. An empirical flow equation based on this observed behavior was made to fit the data from the ten runs to within 2.7% rms error. Data from all 17 sets of flow tests, including those in which the recirculating flow was varied, were fitted to 3.2% rms error

Figure 7 shows the characteristics of the resulting equation for particular orifice height (8.5 in.), flow, and level conditions The significant features of the curves are the large positive slopes of the total head vs upstream level curves, the fact that the slopes are greater with higher flow rates, and that at higher levels, the spread increases between the curves for the same flow but with different level differences.

It may be seen that the normal flow stabilizing effect in open channel flow relating the flow and levels is substantially altered. For example, an increase in inlet flow rate to stage 1 makes its level, L_1, increase, thus increasing the total head, ΔP_T, and causing the flow rate out of stage 1 to increase accordingly. However, the steeper the slopes of the total head vs L_1 curves, the greater the increase in total head required to make the proper adjustment in flow out. Thus steeper slopes indicate a greater destabilizing tendency in the inherent flow control mechanism, and the results show this tendency to be more prevalent at the higher flows

The increased spread between the curves for $L_2 - L_1 = 2$ in and $L_2 - L_1 = -2$ in. at higher brine levels represents a stabilizing effect on the inherent flow control (This can be seen by hypothesizing various changes in operating points between the solid and dashed curves)

From preliminary observations, it also appears that the importance of downstream level, L_2 (relative to L_1 and ΔP_{vapor}) is quite high over much of the operating

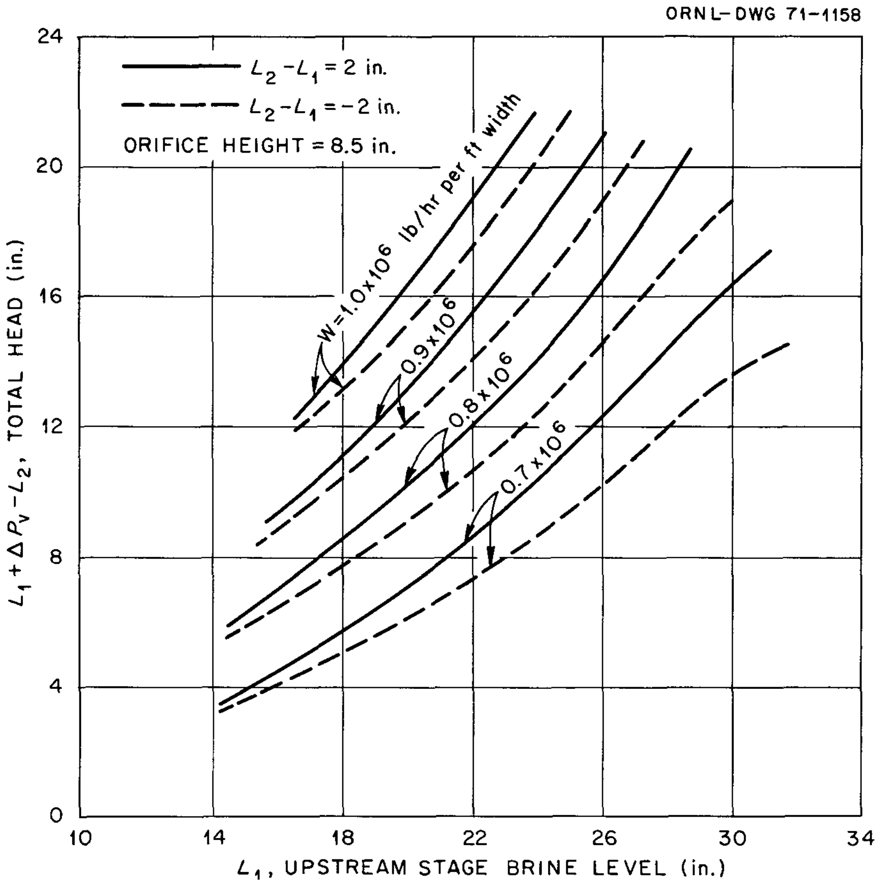

Fig. 7. Baldwin-Lima-Hamilton 7-ft plain-hole test stage inlet orifice flow equation – total head vs upstream level for constant flow and level differences.

range, which means that potentially serious overall plant stability problems would be likely.

It may be noted that the particular stage design tested (7 ft long with plain orifice) had quite poor operational and efficiency characteristics and would clearly be undesirable for use in a production plant. The correlations and observations derived from the test data are significant, however, in that they demonstrate the kinds of problems which may be encountered in a well-designed stage. The destabilizing tendencies of both the Δ' behavior with stage brine level and the inherent flow control mechanism effects noted above are important operational features which should be tested for any seriously considered stage design.

Dynamics tests. A variety of dynamics tests were run, including large-perturbation pulse-type inputs of recirculating brine flow rate and inlet temperature and frequency response tests utilizing pseudorandom binary sequence (PRBS) perturbations.

Analyses of the pulse tests have utilized the new ORNL hybrid computer. Digitized temperature, flow, and level data recorded on magnetic tape during the tests are stored in the digital computer, and a model of the evaporator dynamics is set up on the analog computer. Input signal perturbations corresponding to the measured test inputs are sent to the analog model, and the measured test outputs are then compared with the response of the analog model to these input signals. The hybrid system is set up so that variations in the model parameters are made to minimize the differences between the predicted (model) response and the measured response. Parameter variations may be made manually or automatically using a gradient search algorithm. Visual monitoring of the convergence is afforded by a large-screen oscilloscope, which shows the individual time response signals and error signals, plus typewriter printout of the statistical errors. The resulting optimized model information is to be used in developing models for the overall plant dynamics simulator

The PRBS test is an efficient method of obtaining a wide spectrum of frequency response information, which is useful in determining the small-perturbation (linear) dynamics characteristics of a stage A particular type of PRBS signal known as the "*n* sequence" was used in the latest tests The *n* sequence is an antisymmetric test signal containing only odd harmonics and has been shown to discriminate against system nonlinearity effects, which would otherwise contaminate the results PRBS tests were run using both brine heater steam flow rate and brine recirculating flow perturbations Analyses of the steam perturbation tests have yielded interesting and useful information on stage brine and vapor temperature dynamics Analysis of the recirculating brine perturbation tests, however, has so far failed to yield rational results, and further studies of the data are being made.

Blowthrough tests. One group of experiments run in August was designed to study fluid flow characteristics of flashing brine during blowthrough conditions Blowthrough (or blowby) occurs when the upstream brine level is less than the height of the orifice opening between stages In this condition, vapor as well as brine is transported through the interstage orifice Of particular interest were the flow characteristics during the transitions between normal flow, in which the orifice is submerged, and the blowthrough state

Twelve definable separate instances of blowthrough were recorded. These occurred at several different flow rates, orifice heights, and system temperatures. The transitions from normal flow to blowthrough were induced several different ways by lowering the tray brine levels, by raising the orifice height, by increasing the seawater flow through the brine cooler, by increasing the steam flow to the brine heater, and by decreasing the recirculating brine flow rate through the evaporator. In order to get out of blowthrough, the above processes were reversed.

While the original intent of the blowthrough tests was just to obtain orifice flow correlations for the behavior during the transitions into and out of blowthrough, two other interesting aspects of the blowthrough state were noted. First, there was an apparent hysteresis effect from a given set of operating conditions (flow, levels, flashdowns, etc.) the plant would tend to slip easily into blowthrough, but to get the plant out of blowthrough, the operating conditions had to be altered substantially beyond that point from which blowthrough originally occurred. In other words, the plant would tend to "lock in" on a blowthrough state, implying that the supercritical flow conditions characteristic of blowthrough yield a very stable mode of operation. The second observation was that there were very low values of Δ' associated with the low brine levels during blowthrough and that this increase in stage efficiency tended to compensate for the reduced efficiency due to the interstage vapor leakage. In fact, over the limited temperature range of the tests (130–160°F), the net efficiency was not perceptibly reduced These observations imply that pursuit of the idea of intentional blowthrough, with additional built-in means of reducing interstage vapor leakage, is clearly worth while

Theoretical Studies of MSF Plant Dynamics

Several improvements were made to the MSF digital simulator program, which is used to calculate nonlinear time response behavior of large MSF plants A more sophisticated model for the brine heater and the time variations of salt concentrations in each stage are now included.

The simulator was used to investigate the effects of various changes in assumed models and parameters It has thus been useful in planning the experimental programs, indicating those aspects of the stage models to which overall plant dynamic behavior is particularly sensitive.

Special modifications of the simulator were made to include features peculiar to the nine-stage MSF module in San Diego. The simulation is operational and can be used to help plan proposed future module dynamics tests. A special-purpose steady-state code was developed for calculating module initial conditions, whereas the standard version of the code uses the output from a stage-by-stage MSF design code

Work was also begun on extending the simulator to include the turbine-generator and reactor plant behavior

Conclusions

Resolution of control and operational problems of MSF plants is a requirement for the design of large-scale plants, including large demonstration plants such as that being jointly studied by the state of California and OSW. Further development of the MSF models and extensions of the MSF simulator to include the rest of the dual-purpose plant are also required.

Application of MSF control technology to the combined VTE-MSF (hybrid) plant designs is also anticipated While preliminary work was done on VTE dynamics, with particular application to the VTE-X in San Diego, this work is being conducted at a low level since the MSF concept is of higher priority.

3 3 NUCLEAR DESALTING APPLICATIONS STUDIES

To aid in planning future directions for the AEC program on the applications of nuclear energy, studies are being made to determine the kind of nuclear desalting technology needed and to identify the timing and the role of such technology in meeting present and future water needs A preliminary survey of California's water resources is being undertaken as the first part of a series of planned regional studies to identify the conjunction of nuclear desalting technology and water needs for the United States The water problems of California are generally characterized by the following situations

1 Most of the rain falls in the high mountain regions of the northern and eastern portions of the state, but greatest water needs are in the farming and urban areas of central and southern California

2 Throughout the state 80 to 90% of the rainfall occurs in the winter months, from October through March, whereas the periods of greatest water consumption, especially for irrigation farming, occur during the summer growing season

These situations require the construction of reservoirs to catch water when it is available and hold it until it is needed, plus conveyance facilities to transport water from the reservoirs to the cities and the irrigated farming areas Far-reaching water resource development projects have been undertaken in California by municipalities to obtain city water supplies, by the federal government, and by the state

Table 3 summarizes information concerning major conveyance facilities in California but does not reflect the thousands of miles of canals and distribution channels provided by the local irrigation districts (1600 miles in the Imperial Valley alone)

The forecasts of water requirements for the state depend most strongly on assumptions regarding population growth and the increase in farm acreage under irrigation The gross irrigable farming area in the state is about 22 7 million acres, of which about 9 million now receive irrigation water If large quantities of water could be made available at sufficiently low cost, the irrigation of additional acreage could utilize as much as 35 million acre-feet (MAF) per year, which is 50% more than the entire state's water usage in 1960 Studies by the state of California indicate that the state's water resources can provide an average of about 50 MAF/year when fully developed Table 4 summarizes the water requirements and sources of supply projected by the State Department of Water Resources for the next 50 years [5] The water projects presently authorized by the state and federal governments are expected to meet most of the anticipated needs through 1990

Costs of water from various supply agencies are not computed by standard methods and therefore are not directly comparable Nevertheless, to obtain a measure of water charges with which desalting would have to compete, present water rates in California have been surveyed and methods of computing water costs reviewed

The availability of water has a great influence on the value of land and property, especially in southern California, and it is a common practice for water districts to impose an assessment on all property in the district based on the valuation of the property The very large Metropolitan Water District of Southern California (MWD), which supplies water to the coastal regions from Ventura and Los Angeles to San Diego, has a total valuation of $24 billion for property within its service area and imposes an annual tax of 16¢ per $100 of the valuation When a new area is admitted to the District, a special additional tax is levied to cover the privilege of receiving water from the system In 1969, MWD tax revenues were $47 million, while water sales produced revenues of $40 million [6]

Among the 109 irrigation districts covered by the State Controller's *Annual Report of Financial Transactions Concerning Irrigation Districts of California,*[7] 79 of the districts imposed property taxes at rates ranging from 7¢ to $15 per $100 valuation, with the average being $2 60 per $100 valuation However, land valuations vary from $50 to $3000 per acre, also. For these 109 irrigation districts, tax levies yielded a revenue of $14 million, while water sales amounted to $23 million

Water rates cover a similarly wide range and a variety of methods of charging for water, including flat-rate charges on a per-acre basis regardless of the quantity of water used, different per-acre charges based on the crop being grown, and quantity usage charges ranging from 50¢ to $35 per acre-foot [8] The rates charged by the

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5 *Implementation of the California Water Plan* Bulletin No 160-66, State of California, Department of Water Resources, Sacramento, Calif , 1966

6 *Thirty First Annual Report 1969* The Metropolitan Water District of Southern California, Los Angeles, Calif , 1969

7 Houston I Flournoy, *Annual Report of Financial Transactions Concerning Irrigation Districts of California, Calendar Year 1966,* State of California, Office of the Controller, Sacramento, Calif , 1967

8 *Summary of Water Rates 1960,* Irrigation Districts Association of California, Sacramento, Calif , 1960

Table 3. Major water conveyance facilities in California

System	Responsible agency and area served	Length (miles)	Capacity at intake (cfs)	Construction period	Cost (dollars)	Type of conveyance structure	Dimensions	Water motive power
All American Canal	Bureau of Reclamation, Imperial Valley	80	15,155	1934–1940	25,000,000	Open canal	230t 160b 20d[a]	Gravity
Coachella Canal	Bureau of Reclamation, Imperial Valley	124	2,500	1938–1948		Open canal	100t 60b 10d	Gravity
Colorado River aqueduct to Los Angeles	Metropolitan Water District of Southern California	242	1,605	1932–1940	209,900,043	Open canal		Five pumping stations, 1619 ft total lift
San Diego branch aqueducts	Los Angeles–San Diego Metropolitan Water District							
1st barrel	San Diego area	35	85	1945–1947	7,200,000	Closed conduit	4–6 ft diam	Gravity
2nd barrel	San Diego area	31	95	–1954	8,275,000	Closed conduit	4–6 ft diam	Gravity
Second San Diego aqueduct	Metropolitan Water District, San Diego area	34	250	–1960	15,200,000	Closed conduit and canal	6 ft diam	Gravity
Owens River–Los Angeles aqueduct								
1st barrel	City of Los Angeles	176	440	–1913	25,000,000	Closed conduit		Gravity
1st barrel extension to Mono Lake	City of Los Angeles	100		–1940	22,500,000	Closed conduit		Gravity
2nd barrel	City of Los Angeles	176	210	–1970		Closed conduit		Gravity
Hetch-Hetchy aqueduct	City and county of San Francisco	135		–1934		Closed conduit		Gravity
enlargement			455	–1970		Closed conduit		Gravity
East Bay aqueduct	East Bay Municipal Utility District	95						
1st barrel	Communities on the Oakland side of San Francisco Bay		170	–1929	29,000,000	Closed conduit		Gravity
2nd barrel			70	–1944	12,000,000	Closed conduit		Gravity
3rd barrel			260	–1965	68,200,000	Closed conduit		Gravity
Central Valley Project	Bureau of Reclamation, Central Valley							
Delta-Mendota Canal	West side of San Joaquin Valley	115	4,600	1946–1951	63,700,000	Open canal	186t 100b 14d[a]	Pumped lift, 197 ft
Friant-Kern Canal	East side of San Joaquin Valley	151	4,000	1945–1951	61,500,000	Open canal	74t 36b 15d	Gravity
Madera Canal	East side of San Joaquin Valley	36	1,000	1940–1945	3,400,000	Open canal	46t 20b 9d	Gravity
Contra Costa Canal	Contra Costa county	48	350	1937–1948	15,600,000	Open canal	64t 24b 6d	Four pumping plants, 127 ft total lift
Corning Canal	West side of Sacramento Valley	21	500	1954–1959	7,750,000	Open canal	50t 22b 7d	Pumped lift, 55 ft
Tehama-Colusa Canal	West side of Sacramento Valley	24	2,530	1965–1969	80,800,000	Open canal	72t 24b 16d	Gravity

Table 3 (continued)

System	Responsible agency and area served	Length (miles)	Capacity at intake (cfs)	Construction period	Cost (dollars)	Type of conveyance structure	Dimensions	Water motive power
California Water Project, California aqueduct	State of California							
Delta Peripheral Canal	Sacramento River – San Joaquin River delta	43	21,800	1971–1976		Open canal	400t 300b 30d	Pumped lift, 13 ft
North Bay aqueduct	San Francisco Bay area	28	117	Phase I–1968	16,100,000[b]	Pipeline and canal		Two pumping plants, 414 ft total lift
South Bay aqueduct	San Francisco Bay area	51	363	–1968	47,500,000[b]	Pipeline and canal		Two pumping plants, 583 ft total lift
Main California aqueduct	Delta to San Bernardino, Riverside, and San Diego	444	10,000	1964–1972	1,163,400,000[b]	Open canal	238t 110b 33b	Eight pumping plants, 4132 ft total lift
Coastal branch	San Luis Obispo and Santa Barbara	100	450	–1980	67,600,000[b]	Pipeline and canal		Five pumping plants, 1756 ft total lift
West branch	Los Angeles	22 5	3,129	1967–1971	272,000,000[b]	Pipeline and canal	30 ft diam	Pumped lift, 227 ft

[a]t = top width of canal at water surface, ft, b = bottom width of canal, ft, d = normal depth of water, ft

[b]Portion of total cost assigned to conveyance, excludes costs assigned to flood control, recreation, and other uses

Table 4. Summary of California water requirements and sources of supply[a]

	1960 (actual)	1990 (estimated)	2020 (estimated)
	x 10^3	x 10^3	x 10^3
Population[b]	15,717	35,330	54,300
Urban land use, acres	2,068	4,240	5,960
Urban water use, acre-ft/year	3,257	8,480	14,000
Irrigable land, acres	22,550	20,770	19,140
Irrigated land, acres	8,085	9,564	10,775
Agricultural water use, acre-ft/year	28,482	32,320	35,705
Total net water requirements, acre-ft/year[c]	23,106	31,470	38,000
Needs met from local supplies, acre-ft/year	15,481	15,480	17,048[d]
Imported water supplies, acre-ft/year	7,625	15,990	18,147
Projected supplemental needs, acre-ft/year			2,805[e]

[a]From California Department of Water Resources Bulletin No 160-66, ref 5

[b]1970 Census shows California population as 19,715,000

[c]Allowing for some reuse

[d]Increase in 2020 reflects greater usage of underground water supplies

[e]Supplemental needs forecast for the following areas (acre-ft/year)

South coast, Los Angeles – San Diego	1,540,000
Central coast, San Francisco – Los Angeles	490,000
San Joaquin Valley, Central Portion	300,000
Southern end of Central Valley	300,000
Imperial Valley region	175,000
Total	2,805,000
Additional supplies for Imperial Valley, if water cost is low enough	2,700,000

California State Water Project are "wholesale" rates in that they reflect the cost of water to the water distribution agencies rather than to the ultimate users, but these rates still may be the most meaningful for comparison with desalted water costs, because they allow full recovery of capital, interest, and operating costs in the price charged for water The California Water Project rates include a delta water charge, which covers the water storage reservoirs and other facilities required to assure a dependable year-round supply of water at the Sacramento–San Joaquin delta, where the California Aqueduct conveyance begins Additionally, there is a proportionate-use capital charge for the facilities involved in delivering water to each customer Operating costs for the facilities involved in delivering water to users are also charged on a proportionate-use basis Table 5 gives the average water rates for users in major distribution areas, but it should be noted that in actual practice a specific water charge is calculated for each user [9] The rates apply to untreated water, as it is pumped from the Sacramento River, with a total dissolved solids content usually in the range of 150 to 300 ppm

The charges for water from present supply systems in California, even those involving long-distance conveyance, are quite low, and there is no economic incentive to pursue desalting where present water supplies are adequate However, there are areas where additional needs cannot be met from presently available water supplies and where desalting plants might be attractive There are desert and arid areas where the water that is available locally requires desalting to be acceptable for municipal or agricultural use

In the Imperial Valley and the San Joaquin Valley, drainage tiles are laid under fields to prevent salt accumulation of the soil The Imperial Valley drainage

9 *The California State Water Project in 1970* Bulletin No 132-70, State of California, Department of Water Resources, Sacramento, Calif , 1970

Table 5. Average water charges to distribution agencies for California aqueduct water

Distribution area	Delta water charge (dollars/acre-ft)	Transportation charge (dollars/acre ft)	Total charge for untreated water[a]	
			(dollars/acre ft)	(cents/1000 gal)
North Bay aqueduct area	10 10	20 65	30 75	9 4
South Bay aqueduct area	10 10	22 45	32 55	10 0
San Joaquin Valley area	10 10	11 01	21 11	6 5
Coastal branch service area	10 10	70 36	80 46	24 7
Southern California area	10 10	50 19	60 29	18 5

[a]These costs include amortization of facilities over a 50-year period and interest at a rate of 4 021%/year

flows into the Salton Sea, which has no outlet Salt concentrations in the Salton Sea are now a little higher than seawater, and the lake, which has been stocked with saltwater game fish, is an important tourist and recreation attraction Continued increases in the salt concentration of the Salton Sea would spoil the fishing and recreational uses Salt removal from about 150,000 acre-ft/year would stabilize the lake at about seawater concentration Since Colorado River water has a salt concentration averaging about 1000 ppm when it comes into the Imperial Valley, the high-quality product water from a desalting plant would be welcomed by municipalities, especially if the water cost is not too high

A separate agricultural drainage channel is being constructed in the San Joaquin Valley to carry off the leached salts from irrigated fields so that they will not contaminate local or imported water supplies Desalting of this water for reuse may become attractive at some future date The drainage is expected to amount to 600,000 acre-ft/year, with a salt concentration of 2500 ppm

Geothermal brackish waters with temperatures ranging from 400 to 700°F have been found at depths of several thousand feet under the Imperial Valley and in other places in California These potential water supplies are now being investigated If they prove to be extensive, as some early estimates indicate, the hot brackish water might be suitable for very economical desalting

On the Pacific coast from San Francisco southward, local water supplies have been rather fully developed in most areas, and obtaining significant quantities of additional water will probably necessitate development of new sources from seawater desalting, waste water reclamation and reuse, or additional imports The U S Interior Department's Office of Saline Water has entered into contracts for the construction and operation of test modules of large seawater desalting plants using the multistage flash and the vertical-tube evaporation processes The state of California is developing plans for a prototype desalting plant for the southern California coast They intend to present a proposal for state and federal support of a jointly sponsored desalting plant of about 30 to 50 Mgd capacity, the size depending on the supplemental water needs in the service area selected

The Colorado River is the source of about three-fourths of the water now used in the coastal and desert regions of southern California Present uses and planned projects which depend on Colorado River water require more water than the average flow of the river in dry years The Mexican Water Treaty guarantees Mexico 1 5 MAF/year of water from the Colorado River as a first priority The 1964 Supreme Court decision on a suit filed by the state of Arizona apportioned the first 7 5 MAF/year available in the Colorado River flow as follows Arizona 2 8, California 4 4, and Nevada 0 3, with excess flows above 7 5 MAF/year divided 50-50 between Arizona and California

California's usage of Colorado River water had increased to 5 3 MAF/year during the 1960's, so the state has had to make arrangements to permit them to reduce their usage of Colorado River water in years when the river's total flow is low They plan to reduce the MWD imports through the Colorado River aqueduct from 1 2 MAF/year to 0 55 MAF/year by supplying additional water from northern California and to reduce usage in the Imperial Valley region by 0 3 MAF/year if low flows in the Colorado River make such a reduction necessary To date, the lowest recorded Colorado River flow was 5 6 MAF in 1934, although average flows are usually in the range of 14 MAF/year

Evaporation losses in reservoirs and return flows from upstream irrigation projects are causing the salinity of the Colorado River water to increase The current salt content is about 1000 ppm and has increased 30% in the past 20 years Even with increasing use of underground tile drains to permit better flushing of salt from the soil, Imperial Valley is experiencing decreases in crop yields and withdrawals of land from crop production because of salinity [10] Desalting of the irrigation drainage flows may become necessary all along the Colorado River system to keep salt out of the river and improve water quality Desalting of seawater at the Colorado River delta could provide water to replace the Colorado River supply in that region, allowing more Colorado River water to be used upstream

The joint U S –Mexico–International Atomic Energy Agency study[11] forecasts a growing need for water in the lower Colorado River region and describes opportunities for the desalting of seawater to contribute important new water supplies to this arid region By 1980 supplemental water from a desalting plant will be needed to meet anticipated demands, and by the year 2000 additional water needs are expected to exceed 7 MAF/year (6 4 billion gallons per day) The extent of the water shortages of the region, the closeness of a seawater supply, the concurrent needs for electric power which would make a dual-purpose plant attractive, and the flexibility of planning afforded by interrelationships between the Colorado River and other sources of water in the region, all make the lower Colorado River region one in which there is a challenging opportunity for seawater desalting to provide significant benefits in meeting water requirements

3 4 AGRO-INDUSTRIAL COMPLEX STUDIES

Process Steam Consumption

While most of the industry-related studies have been concerned with power-intensive processes, it has been recognized that industries which consume large quantities of steam could probably realize sizable advantages by being part of a nuclear-powered industrial complex Indeed, this appears to be the case for the recently completed study of an energy center for Puerto Rico (see below) which would produce some 540 MW(e) and 5×10^6 lb of steam per hour for use in an adjacent industrial complex

An analysis of steam use by the main industrial categories for 1966 and projected to 1980 is summarized in Table 6 The chemical industry uses the greatest amount, 37% of the total steam used, and is projected to increase its consumption by 1980 by the largest amount, 80% This steam use represents the production of a wide variety of chemicals Table 7 lists chemicals which use a significant amount of steam, ~10% of the total industry usage, and shows a breakdown of the steam pressures utilized As indicated in this table, more than 80% of the steam consumed is at a pressure below 200 psig

Agriculture

A reanalysis of the basic assumptions used in past studies of the economic viability of using desalted water for agriculture has been completed The main conclusion of this analysis may be stated as follows The likelihood that the cost of desalted water will become low enough for use in *conventional* agriculture now seems remote, while its use in *unconventional* agriculture as envisioned in the food factory concept in an agro-industrial complex appears promising

A review of the irrigation water balance from the 1967 study[12] is shown in Fig 8, which indicates the water use and the associated costs For example, a 1000-Mgd plant produces 1 0 million acre-feet of distilled water per year (at a 90% load factor) with a capability of producing more than 1 1 million acre-feet, thus losing about $11 million per year in reduced sales, of which $7 5 million represents a true loss (charges against capital) These losses are based on a water value of 30¢ per 1000 gallons (For a water value of 20¢ per 1000 gallons the losses and maximum allowable investments would essentially be two-thirds of the values given) By capitalizing this annual loss at 10%, investing up to about $75 million to eliminate this loss would be justified Similarly, almost $35 million could be invested to eliminate canal leakage losses, and up to $25 million could be invested to eliminate storage losses

The assumption of 80% irrigation efficiency in the original study implies a loss of nearly $19 million per year and a justification for an expenditure of up to $630 per acre to eliminate this loss Finally, the amount of water productively used by the crops is only about 34% of the installed plant capacity, or about half of the water applied to the land, and represents a loss of $38 million per year, or an equivalent capitalized investment of $1260 per acre

Means of reducing the losses in some of these categories appear possible, for example, switching from

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

11 *Nuclear Power and Water Desalting Plants for Southwest United States and Northwest Mexico* U S Mexico-IAEA Report TID-24767, National Technical Information Service, Springfield, Va 22151 (September 1968)

12 *Nuclear Energy Centers Industrial and Agro Industrial Complexes* ORNL-4290 (November 1968)

Table 6. Summary of industrial steam consumption

Industry	1966 steam consumption (lb)	Percent of total	Estimated 1980 steam consumption (lb)	Percent increase over 1966
	$\times 10^{11}$		$\times 10^{11}$	
Chemical	16 8	37	30 2	80
Petroleum	11 2	24	18 9	69
Paper	8.2	18	14.4	76
Food	6 1	13	8 5	39
Textile and rubber	3 5	8		

Table 7. Estimate of steam consumption and pressure distribution for ten steam-significant chemicals in 1965–66

Chemical	Annual consumption of chemical (tons)	Unit steam consumption (lb per pound of chemical)	Annual steam consumption (10^{10} lb)				
			450–1000 psig	200–450 psig	100–200 psig	≤100 psig	Total
	$\times 10^3$						
Alumina	5884	3 3	0 58		1 78	1 51	3 87
Aluminum sulfate	673	3 5				0 47	0 47
Ammonium nitrate	5637	2 8			3 16		3 16
Ethyl alcohol	1945	3 0		0 23		0 94	1 17
Formaldehyde	1857	2 2			0 41	0 41	0 82
Phosphoric acid	4548	0 78		0 18		0 53	0 71
Potassium chloride	4003	1 3				1 04	1 04
Sodium carbonate	5090	2 3		2 3			2 3
Sodium hydroxide	7616	2 9			4 42		4 42
Sodium sulfate	1445	1 8				0 52	0 52
Total			0 58	2 71	9 77	5 42	18 48
Percent			3	15	53	29	100

a sprinkler irrigation system to drip tubes or porous underground tubes could approach a 100% irrigation efficiency. Also, these systems, perhaps coupled with the use of a reflective ground mulch, could eliminate most of the nonproductive water evaporation losses. Additional developmental work and economic analyses are required, however, to verify and optimize these potential gains. It does appear that a 1000-Mgd desalting plant could serve a much larger irrigated farm than was assumed for the 1967 study *or* a sizable reduction in the amount of water required per crop can be realized.

Figure 9 indicates the sort of yield increases that result from increasing the atmospheric concentration of CO_2 in a greenhouse. Rice yield is nearly doubled when the level of CO_2 is increased from 300 to 2400 ppm, while the yield of sorghum is increased by a factor of $3\frac{1}{2}$. With several on-site by-product sources of CO_2 available in an agro-industrial complex as shown in Table 8 and making dual use of the water distribution piping network also for CO_2 distribution, yield increases approaching those obtained in greenhouses may be attainable This table shows a range of a factor of 5 in the CO_2 available from the electric-furnace phosphorus process. Actually, CO is the waste product, the lower figure represents the amount of CO_2 available merely by burning the CO in air, while the larger value is the amount available from burning with surplus oxygen from the electrolytic ammonia process and using the heat produced to calcine limestone to give additional CO_2 plus CaO. The next largest source of CO_2 is from wheat straw, being over 50 million cubic feet per day.

Shown in Table 9 is an estimate of the amount of CO_2 which might be consumed by two typical crops Comparing this usage with that potentially available, it

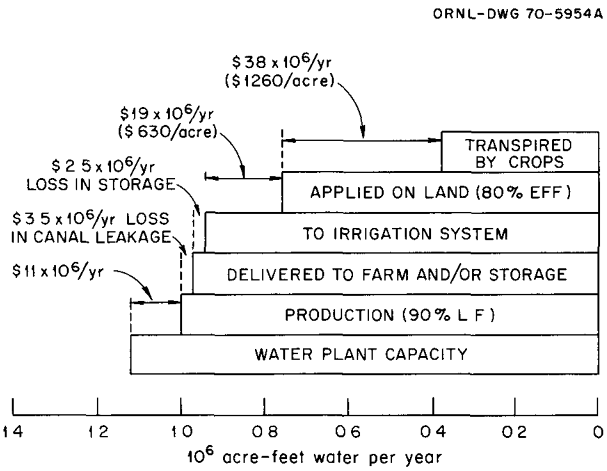

Fig. 8. Irrigation water balance from 1000-Mgd desalting plant (water value = 30¢/1000 gal).

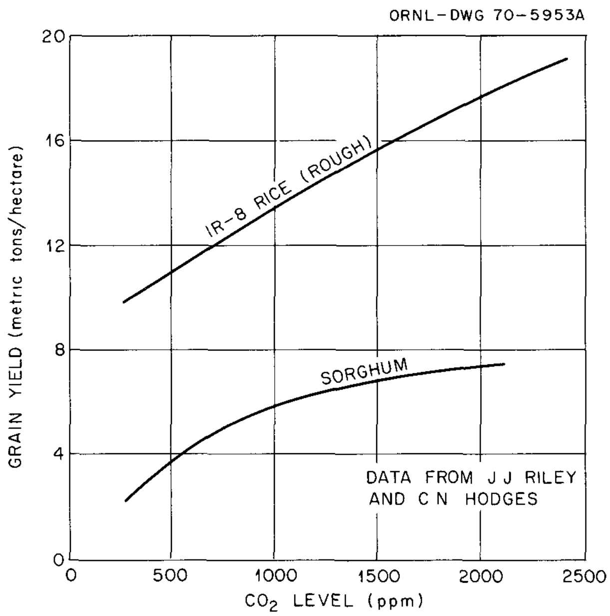

Fig. 9. Effect of CO_2 concentration on yields of two grain crops.

would appear that the crop requirements could be met from on-site supplies of CO_2, provided the efficiency of application is high and the atmospheric mixing losses are kept low

The importance of reducing nonproductive water losses and achieving yield increases in relation to their effect on the allowable water price is obvious Reducing the water use by one-half is equivalent to doubling the allowable cost for water to grow a crop, while doubling the yield using the same quantity of water would

Table 8. Carbon dioxide sources in an agro-industrial complex

Source	CO_2 available per unit of primary product	Total CO_2 from a typical complex
Industry		
Electric furnace phosphorus	2 2 lb per lb P	30 150
Aluminum smelting	1 5 lb per lb Al	18
Seawater pretreatment		
Acid (decompose HCO_3^-)	0 4 lb per 1000 gal	8
Farm		
Wheat straw	1 5 lb per lb straw	54
		110–230

Table 9. Carbon dioxide consumption in an agro-industrial complex

Crop	Peak consumption (ft^3 $acre^{-1}$ hr^{-1})	Requirement for 300,000 acres (ft^3/day)
Rice	800	51×10^6
Corn	1600	102×10^6

permit the cost for water to increase by a factor of nearly 4 If the investment is increased by 50% to allow for CO_2 cleanup and the higher cost distribution system, the allowable increase in the cost of water for the latter case would be a factor of about 3

There are further possibilities foreseen to improve the overall economics of the food factory approach using desalted water Genetic development and production optimization of tropical crops appear to provide yield gains similar to those obtained through intensive research on wheat and rice Growing high-value seed crops would seem to fit into the intensive management concept implied for an agro-industrial complex With year-round growing climates it should be possible to exploit the ratooning characteristic of many plants, that is, obtaining a second or third crop from a single planting, thus reducing operating costs

Meeting of panel on irrigation water use efficiency The nation's leading experts in various aspects of irrigation water use efficiency participated in a two-day meeting at ORNL in July This meeting summarized the current state of knowledge affecting water use efficiency and discussed many aspects of the feasibility of achieving greatly increased crop yields by applying all the latest techniques. Reports on the status of current research projects were discussed by the panel members together with their comments on areas needing more work. Very large gains in crop yields are being achieved in many areas not normally considered arid by providing irrigation water as needed to maintain optimum growth. Some progress has been made in developing mathematical models which can be used to predict crop yields under various conditions, but much more work is needed to make this a generally useful tool. There was considerable discussion of the relative amounts of water lost from the soil surface.

Application Studies

India. *Review of India study.* Technical assistance to the Indian Study Team on Nuclear-Powered Agro-Industrial Complexes has continued. Their final report was issued and has been reviewed. Two projects are analyzed in this report: (1) an industrial complex with agriculture based on the use of desalted water and located in the Kutch-Saurashtra section of Gujarat and (2) an industrial complex with agriculture based on natural groundwater from some 25,000 tube wells and located in the eastern part of Uttar Pradesh (U.P.). Table 10 gives a summary comparison of the two proposed projects. The U.P. tube well project provides additional cereal grains sufficient to meet the food needs of approximately a 3-year population increase for the entire country or a 12-year increase for U.P. alone. If some of the sugarcane acreage (20% of the total) were used for food grains, a still greater impact would be realized.

Although much of the data and methodology used in the appraisal of the project was quite conservative, the returns on investment are attractive. Two critical assumptions, however, were made and appear to require further attention: (1) a high load factor (two to four times as large as the current average well operating factors) for the operation of the tube wells and (2) use of high-performance water electrolysis cells in the ammonia plant.

Interim Power Study. A study of various methods of providing an interim source of power for the proposed tube well project in Uttar Pradesh was completed. Inasmuch as the construction period for a nuclear power generation station of the size contemplated is at least five years, it appears that earlier benefits from tube wells for irrigation could be obtained by providing an interim power source which could be completed in a shorter time period than the nuclear station.

Capital and operating cost information on various means of supplying power for the tube wells was accumulated, and a model which will allow an economic comparison of the cost of the various methods was developed. Direct-drive engines of several types were considered; light-duty air-cooled gasoline and air-cooled diesel and heavy-duty water-cooled kerosene and diesel engines were compared. Electric generating sets included diesel-powered sets ranging from 550 to 4250 kW, gas turbines to 40 MW rating, and, for comparative purposes, coal-fired steam plants of about 50 MW capacity at an assumed cost of $200 and $300 per kW(e) of capacity.

Several interesting observations were made, although lack of detailed information from India prevented the drawing of definite conclusions:

1. The very high cost of the transmission and distribution system, approximately $3750 per well on the average, gave a heavy bias toward use of direct-drive engines in comparison with interim electric generating sets. This was found to be true even though the model for both cases ended with the transmission and distribution system built and in operation. The use of direct-drive engines permitted construction of most of the electric grid to be deferred for about four years, thus leading to a reduction in the present worth of the costs. In a more detailed analysis it is believed that this bias would be offset by benefits in addition to those directly resulting from supply of power for tube wells alone.

2. An analysis of costs by the Government of India Working Group indicates that most farm products can profitably be raised using tube well irrigation with power costs as high as 6 to 7¢/kWhr and that some crops would be profitable at a much higher cost. Power costs for an interim power source are well below this figure using either direct-drive engines or electric generating sets, provided that fuel costs are not much greater than the 20¢/gal for diesel oil or $10.00 per ton for coal delivered, at railside, assumed for this preliminary analysis.

3. Details on the existing and projected power grid and generating stations should be factored into the analysis, as it is probable that the units provided for interim power for the tube wells could be retained as peaking or standby units complementary to the grid. Such use would permit evaluation over a longer time period than considered in the present analysis and thus would lead to a reduction in estimated interim power costs.

4. The use of coal-fired steam generating units for interim power (and possibly for longer term use) seems attractive, since coal is apparently much less expensive than liquid fuel in this region. Furthermore, it would appear that foreign exchange requirements would be

Table 10. Comparison of the proposed Indian agro-industrial complex projects

Item	Kutch Saurashtra			U P tube wells		
	ROI[a] (%)	Investment (dollars)	Size (power required)	ROI[a] (%)	Investment (dollars)	Size (power required)
		$\times 10^6$			$\times 10^6$	
Power (two reactors)	5 3	363	5800 MW(t) [1200 MW(e)]	10 3	316	3800 MW(t) [1200 MW(e)]
Water						
Desalted	6	78	180 Mgd or 0 166 $\times 10^6$ acre-ft/year			
Pumped				6 5	90 (elect distr) 158 (tube wells)	13 6 $\times 10^6$ acre-ft/year [300 MW(e)]
Industry	31	292		28	243	
NH_3			2200 tons/day [751 MW(e)]			1650 tons/day [558 MW(e)]
NH_4NO_3			3200 tons/day [19 MW(e)]			2400 tons/day [14 MW(e)]
P_4 (P_2O_5)	(Note 0 4% of NH_3 and 1 2% of DAP consumed within the project)		900 tons/day [264 MW(e)]	(Note 89% of N and 80% of P_2O_5 consumed within the project)		688 tons/day [200 MW(e)]
DAP			2000 tons/day [~3 MW(e)]			1500 tons/day [~3 MW(e)]
Al (fab)			150 tons/day [125 MW(e)]			150 tons/day [125 MW(e)]
NaOH			150 tons/day [25 MW(e)]			
NaCl			3300 tons/day			
Agriculture	20	35 (875/acre)		128[b]	511[c] (205/acre)	
Acreage			40,000 acres [12 MW(e)]			3,700,000 acres
Subtotal (foreign exchange)		768 (174)			1318 (295)	
Total (including infrastructure)	15	879		70	1559	

[a]Return on investment

[b]Based on total investment including tube wells and electric distribution system but not including crop storage (~$82 million)

[c]Mechanized farming, at 300% cropping intensity The cost per acre includes the cost of the electrical distribution system and the tube wells, without these costs, this figure becomes $138 per acre

much less for both the capital and the operating costs of a coal-fired plant. Foreign exchange considerations have not been factored into the present model, however, it is clear that a more detailed analysis should do so.

Puerto Rico Energy Center Study. Technical assistance was provided for the study of applying the energy center concept to the island of Puerto Rico This study was jointly supported by the U.S. Federal Government and the Commonwealth Government of Puerto Rico, involving several departments of each. It was carried out under a contract with Burns and Roe, Inc , and the Dow Chemical Company and resulted in a proposed complex of the following major elements:

Power and Water Production

Electrical power	700 Mw(e)
Process steam	400 psig – 400,000 lb/hr
	150 psig – 3,000,000 lb/hr
	40 psig – 1,600,000 lb/hr
Desalted water	20 Mgd

Note On-site generation of steam and 540 MW(e) from a 2875-MW(e) reactor, estimated investment = $161 million

Industry Use of Power

Aluminum, 384 tons/day	223 MW(e)
Caustic/Cl_2, 1470 tons/day (Cl_2)	180 MW(e)
Refinery and petrochemicals, 60,000 lb/day	113 MW(e)
Salt recovery, 2800 tons/day	1 6 MW(e)
Utilities and reverse allowance	182 4 MW(e)

Total investment including site, harbor, docks, etc = $476 million

Agriculture

A study of agricultural enterprises and the potential need and economics of the use of desalted water for irrigation revealed a need for general crop diversification and a conclusion that water at 45¢ per 1000 gal was in most cases too expensive to use for irrigation in Puerto Rico

The main conclusion drawn by Burns and Roe was that this proposed energy center is economically viable in Puerto Rico, with the industry showing an acceptable discounted cash flow of more than 15%.

Middle East. The Middle East Study Project, which is being conducted at ORNL, was initiated in response to Senate Resolution 155. This resolution recommended an examination of the concept of large water-producing energy centers in areas of the Middle East as a means for providing (1) new jobs for refugees, (2) an increase in agricultural productivity of existing wastelands, (3) a broad base for cooperation between Arab and Israeli governments, and (4) a further demonstration of the United States efforts to find peaceful solutions to areas of conflict. The study is near completion.

State of Texas. Technical assistance in the form of supplying information on past studies in both reports and personal meetings has been given to a study team formed at Texas A&M University. This team is evaluating the Nuplex concept for possible application in the state of Texas. It is anticipated that two to three years will be needed to complete the project.

The Economic Impact of Energy Centers

As part of the advanced educational program in cooperation with the University of Tennessee, a Ph.D. dissertation on the economic impact of energy centers was completed. An economic model was developed for determining (1) an optimum combination of industrial activities for a nuclear energy center as a function of energy cost and (2) the economic impact of the center on its region. The model was derived from the coupling of two research techniques, separable programming and input-output analysis, in a mutually consistent manner. Separable programming (IBM MPS-90 system) was used to optimize the mix of energy-intensive industries proposed for an energy center; maximization of premium worth at a 10% minimum acceptable rate of return was adopted as the optimization criterion. The program used energy cost as a parameter in order to study the variations in industrial activity and total energy demand as a function of energy cost.

Results of the separable program served as the data for an input-output program which examined the effect of the center on its economic region in terms of increases in gross product, employment, and capital demands. A feedback of information from the input-output program permitted adjustment of the capital and employment constraints in the separable program, so that consistent relationships were maintained between the project demands and the resources of the economy. Projection of the input-output data to show the effects of an energy center over both short- and long-term time periods was developed employing a dynamic procedure which took into account the changes in the final demands of the economy as a function of the growth of gross product.

Puerto Rico was selected as a test region for this model. Industrial activities considered for the energy center included the production of elemental phosphorus, aluminum, magnesium, chlorine, caustic, vinyl chloride monomer, pig iron, steel, ammonia, and fresh water (seawater desalting). The feasibility of installing industrial activities at an energy center was established by comparing individual processes with competitive and, in some cases, non-power-intensive processes located elsewhere in Puerto Rico or on the United States mainland

One of the interesting results of this study is illustrated in Fig 10, which indicates the elasticity of demand for power as a function of its cost

American Institute of Chemical Engineers Symposium

A two-session symposium on "Energy Centers" was organized for the American Institute of Chemical Engineers National Meeting in Atlanta, February 15–18, 1970 The following papers were presented

Part I. Large-Scale Desalting Technology and Applications

J A Hunter, Chairman

Operating Experience with a Large Multistage Flash Desalination Module, L T Taylor

Desalting Potential, Technology and Costs, H L Sturza et al

Principal Factors Relative to the Selection of Single-Purpose and Dual-Purpose Desalting Plants, W A Homer et al

Use of Desalted Water in Agriculture, R P Hammond

Opportunities for Augmenting Water Supplies through Desalting, J J O'Brien

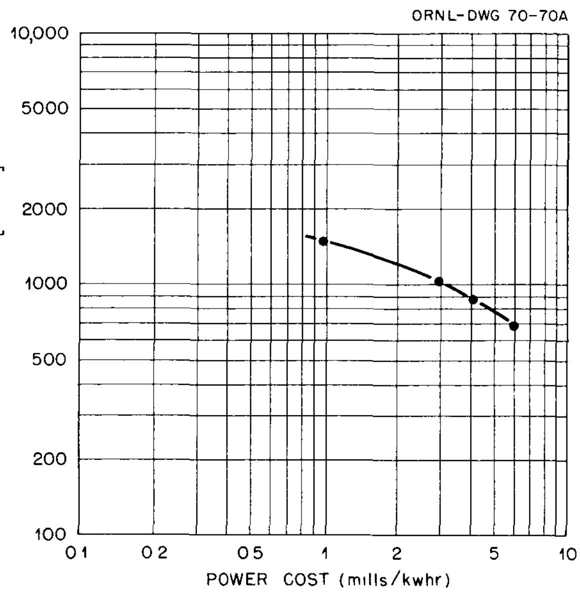

Fig. 10. Effect of power cost on optimum energy center power demand.

Part II. Nuclear Powered Agro-Industrial Complexes

J W Michel, Chairman

Projected Cost of Energy, J A Lane

Energy Intensive Industry, H E Goeller

Seawater Utilization in an Energy Center, W C Yee

The Energy Center Concept, J W Michel and J E Mrochek

3 5 NUCLEAR DESALINATION INFORMATION CENTER

Since 1966, the Nuclear Desalination Information Center, under the sponsorship of the USAEC, has collected and condensed information from the literature and has provided the means by which the scientist in the field of nuclear desalination can readily identify and retrieve the information Publications from the open literature, governmental agencies, and educational institutions are scanned, and material pertinent to the desalination program is selected by the Center The material is reviewed, abstracted, and indexed on a part-time basis by technical specialists on the Nuclear Desalination Program staff Retrieval of information by author, company, and key words is possible through the use of a computerized storage and retrieval system

The Distillation Division of the OSW provides support for a portion of the information activities concerned with the distillation process

Publications

One new indexed bibliography[13] (with abstracts) of nuclear desalination literature was issued during the year, and a second is in preparation These will bring the total number of references in the Center's storage and retrieval system to about 1300 Another publication[14] provides an alphabetical index by title, authors, and company to all research and development progress reports which have been issued by the OSW This, of course, covers a much wider area than nuclear desalination or the distillation process, since the OSW is concerned with several methods for desalting The index has been updated annually and used locally for several years, but enthusiastic use by members of both the Nuclear Desalination Program staff and the Water

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13 K O Johnsson *Indexed Bibliography of Nuclear Desalination Literature – 5,* ORNL NDIC-7 (September 1970)

14 K O Johnsson, *Title Author Company Index to Reports Published by the U S Department of the Interior Office of Saline Water* ORNL-NDIC-8 (November 1970)

Research Program staff indicates that it should have wider distribution.

The versatility of the computer system for specalized bibliographies was shown by a report[15] prepared at the request of the OSW. For this report the entire master file of the Center was scanned for abstracts of U.S. patents pertaining to the distillation of seawater. These abstracts were then printed as a separate listing along with author and key-word indexes. A revision of this interim report will be made when additional patents (as suggested by industrial organizations which received the interim report) have been abstracted and added to the storage system.

15. K. O. Johnsson, *U.S. Patent Abstracts and Indexes Covering the Technology of Distillation Processes for Saline Water Conversion (Interim Report)*, ORNL-TM-2841 (March 1970).

Requests for Information

Members of the Nuclear Desalination Program staff are informed of new articles in their area of investigation which they may have overlooked. This is done on an individual basis as well as by circulating lists of reports received by the Center. Other services provided include the preparation of specialized lists or literature searches of the computer storage system as needed by staff members to aid in their study of specific problems. Requests from outside ORNL, by letter and by telephone, continue at the rate of six or seven per month. The distribution of requests remains about the same as in previous years, with one-third from industry, one-third from academic institutions, and the remaining portion equally divided between U.S. governmental agencies and foreign groups.

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

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