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**NUCLEAR DESALINATION PROGRAM
ANNUAL PROGRESS REPORT
ON ACTIVITIES SPONSORED BY
THE ATOMIC ENERGY COMMISSION
FOR PERIOD ENDING OCTOBER 31, 1969**

OAK RIDGE NATIONAL LABORATORY
operated by
UNION CARBIDE CORPORATION
for the
U.S. ATOMIC ENERGY COMMISSION

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R. P. Hammond, Director

Report Compiled by
T. D. Anderson and W. E. Thompson

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MAY 1970

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1. Introduction

The general objectives of the Atomic Energy Commission's Nuclear Desalting Program are (1) to explore the possible applications of nuclear energy to water desalting and other process uses; (2) to define the nature, range, and potential of nuclear desalting applications and the locations where they offer greatest promise; and (3) to cooperate with industry and other government agencies in developing the technical understanding and the hardware to implement desalting applications. The AEC-supported program is carried out at ORNL, where closely related desalting research and development is supported by the Office of Saline Water (OSW) under an Interagency Agreement between the Department of the Interior and the AEC. The general guideline is that AEC supports activities concerned with the production and application of low-cost energy from nuclear fuels, while OSW supports research and development related to desalting process technology. ORNL has shown the advantages and range of application of nuclear energy for dual-purpose plants producing both electric power and desalted water and has shown that these advantages can be extended to other processes and operations which benefit from low-cost heat and electricity.

ORNL developed the idea of an agricultural-industrial complex using desalted water for irrigation and low-cost heat and electricity for industrial processes and has shown the idea to be attractive in many ways. In the past year effort has been devoted to further development of the agro-industrial complex concept, including the evaluation of new industrial processes for inclusion in the complex, the study of new crops and food-

processing methods, and the investigation of possible uses of warm water waste streams for raising fish, shrimp, or other marine crops. ORNL has also assisted in studies by others to explore applications of agro-industrial complexes in developing countries.

Study of reactors to produce very low-cost heat for desalting applications has shown the promise of uranium-metal fuels in an unclad metal breeder reactor with liquid-metal coolant and in a clad fuel element for pressurized-water reactors. Methods of handling the coupling of the reactor steam system to the electric power generators and to the desalting plant brine heaters have been studied. Flexibility of operation is an important factor, since the demands for electricity and water can change independently whereas production cannot. How to achieve minimum cost, greatest flexibility, and most dependable operation is a complex question which is being studied in greater depth.

The operation of the Nuclear Desalination Information Center (NDIC) aids the work on all aspects of desalting. As the reputation of the Center spreads, more information is supplied to the Center and more information is requested from it. 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.

This report summarizes ORNL's work under the AEC Nuclear Desalting Program for the period from November 1, 1968, through October 31, 1969. More complete information can be found in the scientific and engineering reports listed in Section 4.

2. Highlights of Progress

The emphasis of the AEC program on dual-purpose nuclear desalting plants is on developing the technology needed for coupling commercial reactors with desalting units and on integrating the many subsystems into an operable unit. Significant progress was made in the past year on developing both steady-state and dynamic computer simulations of desalting plants. In cooperation with the OSW, experimental work was conducted on evaporator plants to develop and refine the models used in the simulations. These test runs also yielded valuable experience on instrumentation techniques and requirements for large evaporators.

Exploratory work was completed on two advanced reactor concepts for desalting applications. The uranium-metal-fueled PWR, which was previously examined for low-temperature process heat production, was found to have significant potential advantages in higher temperature applications, including electric power production and dual-purpose desalting.

Experimental scoping studies were completed for the Unclad Metal Breeder Reactor (UMBR). Loop tests showed excellent compatibility between flowing liquid sodium and uranium metal and uranium-thorium alloys; this result confirms tests at Dounreay, and gives further encouragement that an unclad metal fuel may be acceptable in a standard sodium-cooled fast breeder reactor. Small-scale fuel fabrication experiments indicate that a number of fabrication methods are feasible. The work has reinforced previous indications of significant reductions in desalted water cost using this type of energy source.

In continuing development of information for agro-industrial complexes, the application of improved electrolytic cells in the production of ammonia was found to be a route to important savings. When ammonia production and hydrogen storage are combined so that

off-peak electric power is used, economic gains result for the electric power system as well as for ammonia production. The Tennessee Valley Authority has joined Oak Ridge National Laboratory in a study of this overall subject.

The D-LM process for electrolytic smelting of partially reduced iron ore offers promise of low-cost production even at plant capacities as low as 500 tons/day, which may be important in a developing country where markets for pig iron may be limited. Ordinary blast furnaces are considered uneconomic if the size is much below 2000 tons/day.

New agricultural data have permitted the design of improved agro-industrial complexes with higher returns per unit of water consumed. The work showed that rice production and poultry fed on wheat were especially attractive. Potato storage and processing into dehydrated granules was found to be economically rewarding where the market is large enough.

ORNL has provided information and technical assistance to the team from the Indian Atomic Energy Agency which is studying applications of agro-industrial complexes in India. Under the plains of the Ganges River are large aquifers from which fresh water can be pumped without requiring desalting. In this region a nuclear power plant with the necessary distribution system to bring electricity to pumps in every field could provide water for crops to be grown the year around rather than just during the monsoon season. The system cost appears to be about equal to the value of the extra food thus produced each year. Electricity might also be used for industrial applications, especially fertilizers. The Indian study team is also evaluating agro-industrial complexes for the Kutch-Saurashtra area on the arid west coast of India.

3. Summaries of Work Completed and in Progress

3.1 DESALTING PLANT SYSTEM COUPLING STUDIES

Computer Code Development

Computer codes are used in the design of desalination plants and in the design of systems for coupling these plants to nuclear heat sources. There are several advantages to the use of codes: (1) they facilitate parametric studies, (2) they allow problems to be reexamined easily and quickly so that the codes can be adapted to new purposes (the code may also be used as a record of the design assumptions and ground rules), and (3) they solve complicated optimization problems and evaluate the gains of new developments. Work on computer codes consisted of developing new codes and upgrading existing codes.

The conceptual design of a 250-Mgd vapor-compressor water-only desalting plant was used as a base to write a computer design code. The final cost information is presently being checked in the cost subroutine. A draft report on this code has also been written.

The cost information in the computer codes for the combined VE-MSF plant and plain MSF plant, ORSEF and ORVE, was updated to be consistent with cost estimates by the Bechtel Corporation.^{1,2} In addition, a draft report on the ORVE code was written and is being reviewed. A reactor subroutine was added to ORVE and ORSEF which has the flexibility of computing both dual plants and water-only plants. The cost estimates in the ORSEF code were modified to give results for small plants (2.5–10 Mgd) that are in agreement with current available costs.

Comparative Study of Water-Only Desalting Plants

Most of the money and effort put on the development of commercial nuclear energy has been, and will

¹Bechtel Corp., *Conceptual Design of 250 Mgd Desalting Plant*, OSW 14-01-0001-534 (July 31, 1968).

²E. C. Hise and S. A. Thompson, *Conceptual Design Study of a 250 Mgd Combined Vertical-Flash Evaporator Desalting Plant*, ORNL-4260 (August 1968).

continue to be, directed toward electrical power plants. With such plants it is necessary to achieve a good thermodynamic efficiency, and this requires high-temperature steam. For distillation of seawater it is not necessary to produce high-temperature steam, since with present distillation technology the maximum allowable temperature of the process steam is 260°F. Thus, this raises the possibility of a less costly reactor that produces low-temperature process heat for desalting plants.

Studies have been made of both oxide- and metal-fueled pressurized-water reactors for process heat production. These studies indicate that, relative to their high-temperature counterparts, process heat PWR's show significant economic advantages when judged on the basis of energy cost. This simple economic index is not, however, sufficient to show whether or not there is an incentive to develop low-temperature reactors for water-only desalting plants. The reason for this is that there are alternatives to process heat reactors for providing the energy for water-only desalting plants.

To provide a rational basis for future development programs it is essential that we decide whether or not to continue work on process heat reactors. More generally, we want to know what approach offers the best possibility for water-only desalting plants. A comparative study is under way to resolve this question. For the present the study will concern itself with pressurized-water reactors, but two levels of PWR technology will be considered, as characterized by the type of fuel — oxide or metal. For each type of fuel the following coupling arrangements will be compared on the basis of equal water production:

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

All of the above coupling arrangements have been oversimplified since, in each case, provisions will be

made for generating enough electric power for on-site needs. Case 1 is probably not interesting in itself, but its main purpose is to provide a reference by which the other arrangements can be judged.

Results are now available on two of the three coupling schemes to be investigated in the comparative study. These include the process heat reactor case and the power reactor case where prime steam is attenuated to process conditions. A turbine-generator plant sized to provide auxiliary power requirements is included in both cases. The range of plant types and parameters considered is shown in Table 1. The equations for the reactor, turbine, and operation and maintenance costs are given in Table 2.

Figures 1 and 2 present the estimated water cost trends as a function of plant size for the parameters considered. It must be recognized that there are uncertainties in cost data for all parts of the plant (reactor, turbine-generator, and evaporator). The band presented for each case represents the effect of a 30% increase in the nominal reactor and turbine plant capital cost. The significant result is the relative difference in cost between the cases considering power and process heat reactors for each set of parameters. The process heat reactor provides lower water cost for all cases, with its advantage being somewhat greater with the uranium metal fuel and with private financing for either evaporator type.

Turbine-Generator Cycle Efficiency Survey for Dual-Purpose and Power-Only Plants

A suitable means for estimating the turbine-generator cycle efficiency is necessary for studies involving both dual-purpose plants and power-only plants. Although high turbine cycle efficiency is not quite as important in dual-purpose plants, since turbine exhaust steam has value when delivered to the evaporator plant, the turbine cycle data should be reasonably accurate in order to allow comparison of tentative cycles with existing cycles documented by detailed heat balances.

Previous work on turbine cycles within the Laboratory and also at Sargent and Lundy Engineers^{3,4} covered throttle conditions from 400 psia (saturated) through 2400 psia (1000°F) and evaluated each cycle at

³ Nuclear Desalination Program Annual Progress Report on Activities Sponsored by the Atomic Energy Commission for Period Ending October 31, 1966, ORNL-4087 (March 1967).

⁴ Sargent and Lundy Engineers, Large Turbine Performance and Turbine Plant Cost Study, SL-317 (December 1965).

Table 1. Range of Parameters for Comparative Study of PWR's

Reactor type	PWR
Fuel	UO ₂ , U metal
Evaporator type	MSF - ORNL 2 level. Bechtel cost estimate ^a VTE - ORNL design. Bechtel cost estimate ^b
Evaporator size, Mgd	250, 500, 1000
Financing	Public - 7% FCR ^c Private - 12% FCR
Capital cost estimate range for nuclear and turbine island	+30-0%
Plant load factor	90%

^aBechtel Corp., *Conceptual Design of 250 Mgd Desalting Plant*, OSW 14-01-0001-534, (July 31, 1968).

^bE. C. Hise and S. A. Thompson, *Conceptual Design Study of a 250 Mgd Combined Vertical-Flash Evaporator Desalting Plant*, ORNL-4260 (August 1968).

^cFCR = fixed charge rate.

exhaust pressures of 1.5 in. Hg(abs) and 14, 35, and 78 psia. This early work was intended to give an approximate efficiency for preliminary studies.

The next step in the program was to develop a computer code which calculates steam turbine-generator performance and turbine cycle heat balance for steam conditions typical of present-day water reactors. This resulted in development of the code ORCENT.⁵⁻⁷ ORCENT is based on equations presented in a General Electric report⁸ which is a standard reference for evaluating turbine plant performance.

During the last reporting period, a turbine-generator cycle efficiency survey⁹ was conducted to provide a more accurate estimate of efficiency for dual-purpose

⁵Nuclear Desalination Program Annual Progress Report on Activities Sponsored by the Atomic Energy Commission for Period Ending October 31, 1967, ORNL-4239 (April 1968).

⁶Nuclear Desalination Program Annual Progress Report on Activities Sponsored by the Atomic Energy Commission for Period Ending October 31, 1968, ORNL-4409 (April 1969).

⁷H. I. Bowers, *ORCENT: A Digital Computer Program for Saturated and Low Superheat Steam Turbine Cycle Analysis*, ORNL-TM-2395 (January 1969).

⁸F. G. Baily, K. C. Cotton, and R. C. Spencer, *Predicting the Performance of Large Steam Turbine-Generators Operating with Saturated and Low Superheat Steam Conditions*, General Electric Company, GER-2454A, American Power Conference, Chicago, Ill., Apr. 25-27, 1967.

⁹L. C. Fuller, *Turbine Generator Cycle Efficiency Survey for Dual Purpose and Power Plants*, ORNL-TM report, to be issued.

Table 2. Cost Basis for Comparative Study of Water-Only Desalting Plants

1968 dollars

1. Fuel Cost, $\text{\$/10}^6$ Btu					
Fuel	Process Heat Reactor		Power Reactor		
	Public Financing	Private Financing	Public Financing	Private Financing	
Uranium metal	5.18	7.18	5.67	7.33	
UO ₂	9.67	11.13	10.38	11.64	
2. Financing					
	Private	Public			
Annual charge rate	0.12	0.07			
3. Reactor cost, \$					
CAPR = $(a \times \text{MWT} + b) \times 10^6$					
	Power Reactor		Process		
	Private Financing, UO ₂ Fuel	Public Financing, UO ₂ Fuel	Private Financing, U Fuel	Public Financing, U Fuel	
a	0.0127043	0.0119982	0.0159043	0.0151982	0.01012754
b	33.59923	33.37449	33.59923	33.37449	29.30464
4. Turbine Cost, \$					
CAPP = $K(\text{MWEG})^n \times 10^6$					
MWEG Range	n	Power Reactor		Process Reactor	
		Private K	Public K	Private K	Public K
<200	0.38885	2.31908	2.23791	2.8696	2.7692
200-350	0.47937	1.43558	1.38533	1.77640	1.71422
350-800	0.72114	0.348295	0.336101	0.430984	0.415892
>800	0.916	0.094679	0.091365	0.117160	0.113060
5. Operating and Maintenance Cost of Reactor, \$/year					
O&MR = $(0.890381 + 1.72816E - 4 \text{ MWT} + 2.12822E - 10 (\text{MWT})^2) \times 10^6$					
6. Operating and Maintenance Cost of Turbine, \$/year					
Less than 1000 MW(e):					
O&MT = $[0.122133 + 7.89142E - 4(\text{MWEG}) - 5.85735E - 7(\text{MWEG})^2 + 2.19304E - 10(\text{MWEG})^3] \times 10^6$					
Greater than 1000 MW(e):					
O&MT = $(0.00022 \times \text{MWEG} + 0.32) \times 10^6$

Fig. 1. Water Cost vs Plant Size for Water-Only Plants Using Uranium-Metal Fuel.

Fig. 2. Water Cost vs Plant Size for Water-Only Plants Using UO_2 Fuel.

and power-only plants over the range of interest for current nuclear plant concepts. Figure 3 shows gross turbine cycle efficiency as a function of throttle steam pressure with various condensing or back-pressure conditions and with various temperatures at a given pressure. The range of parameters considered included throttle pressures from 400 to 2400 psia, condensing pressures of 1.5 in. Hg(abs), 15 psia, and 35 psia, and up to 300° superheat for throttle steam pressures over 1200 psia. The ORCENT code, which was used for all calculations, was not intended to be used at pressures above 2000 psia. The curves resulting from calculations at pressures above 2000 psia, however, do appear reasonable and are almost certainly more accurate than hand calculations at high pressure.

The ranges of superheat cycles considered in this study were 0 to 100°F superheat for 400- to 1000-psia cycles and 100 to 300°F superheat for 1200- to 2400-psia cycles. Higher values of superheat would have been run for the higher throttle pressures except that the design limit of ORCENT was 200°F superheat and 300°F was believed to be as far as it could be extended with any degree of accuracy.

A set of calculations was made with 35 psia back pressure both with and without regenerative feedwater heaters. It was thought that this might be practical for a dual-purpose plant since the fraction of total thermal energy that is rejected at the turbine exhaust is not wasted to the environment in dual-purpose cases but rather is used to drive the evaporator plant. The economically optimum degree of feedwater heating should be less in dual-purpose than in power-only plants. While Fig. 3 would indicate that the effect of regenerative feedwater heating on efficiency would vary from 1/2 to 3%, it should be noted that the higher-pressure cases had higher final feedwater temperatures to begin with and thus there was more room for loss of efficiency when feedwater heaters were eliminated.

The break in all the curves between 1000 and 1200 psia represents the transition from nonreheat to reheat cycles. All high-pressure cases employ primary reheat but no external moisture separation. All low-pressure cases use an external moisture separator but no reheat. The curves could be extrapolated to determine an approximate percentage change in efficiency with a change from reheat to moisture separation.

Fig. 3. Gross Turbine Cycle Efficiency.

All of the low-pressure cases were run with 1800-rpm tandem-compound 6-flow (38-in. last-stage blade length) turbine-generators. The high-pressure cases used 3600-rpm tandem-compound 6-flow (33.5-in. last-stage blade length) units. A more detailed description of each cycle calculated is given in ref. 9, which also shows tables and/or graphs of electrical output, gross turbine cycle heat rate, gross turbine cycle efficiency, power required by motor-driven feedwater pump, turbine throttle steam flow, and turbine exhaust steam flow.

It is not anticipated that these results would take the place of a heat balance calculation for a specific application but rather that it would give preliminary general information and would be followed up with direct application of ORCENT, which is quick, accurate, and complete. The output of ORCENT includes all the information normally shown on steam turbine cycle heat balance diagrams.

Survey of MSF Coupling and Control Problems

The function of the coupling and control system of a nuclear dual-purpose MSF distillation plant is, briefly, to mate the reactor, electrical power plant, and water plant so that they all operate efficiently and economically over the specified load ranges. The reactor-electrical-plant combination has much background experience, but coupling to the water plants is relatively new. The water plant characteristics are therefore of primary importance in designing the overall system. Experience with current water plants for which detailed operating data are available indicates that the technologies of heat transfer (condenser bundle design), interstage brine flow control, and overall plant instrumentation and control are not highly developed. The extent to which these technologies are interrelated in the MSF evaporator is probably not generally recognized. The failure to recognize the interrelationships inhibits the adequate development of all three technologies.

A surprising gap exists between the condenser bundle design state of the art in the distillation and electrical power industries. It is generally accepted that power plant condensers are routinely designed for, and achieve, overall heat transfer coefficients (U) of about $700 \text{ Btu hr}^{-1} \text{ ft}^{-2} (\text{°F})^{-1}$. In terms of distillation plant tube materials this should correspond to about $U = 600$ at comparable temperatures. Yet distillation plant values at these low temperatures are typically below 500. Power plant condenser bundles utilize steam lanes to limit the number of tubes in vertical rows in a flow path to prevent tube inundation. The flow paths are

tapered to maintain adequate steam velocity for efficient noncondensable gas sweeping, and efficient venting is provided at the ends of all flow paths. Many distillation plant bundles are designed without some or all of these features.

Even though an efficient bundle layout may be provided for an MSF evaporator, fouling factors derived from less sophisticated plants are usually applied, with the result that the bundle is oversized. This overdesign may not be reflected simply in a reduced log mean temperature differential. The bundles are in effect underloaded at the design operating conditions and may fail to produce the superior heat transfer coefficients of which they are capable. At low steam flow rates the steam velocity necessary to provide adequate noncondensable gas sweeping may not be provided in the later rows of tubes, leading to noncondensable gas fouling of these tubes. This effect has been observed experimentally in some test facilities.

The design and operational characteristics of interstage flashing devices are not well defined. Each equipment manufacturer typically utilizes a particular hardware combination of plain orifices, baffles, liquid head devices, and/or turbulence promoters which he has evolved through experience. These configurations vary widely, and performance data and calculational procedures for comparing them are almost nonexistent. There is no way to determine which interstage device is best for a given facility, and the configuration ultimately utilized typically depends on which manufacturer is awarded the contract. Orifice sizes are usually adjusted in the field in an effort to obtain the design flashing brine levels at the design operating conditions. This objective is frequently not realized because the hardware configuration may not be compatible with the available driving force for propelling the brine through the hardware. Excessive brine depths are often encountered in the low-temperature stages, where the stage-to-stage pressure differential is minimal. The cumulative level buildup can be counteracted further upstream, where interstage vapor pressure differentials are greater. Stage brine levels may be excessive or insufficient as a result of unstable flow characteristics through the flashing devices. The tendency toward instability seems to be greater at low brine levels.

Basic instrumentation in MSF evaporators is often inadequate. Temperature elements for this purpose should provide at least a good mixed mean flashing brine temperature near the outlet of each stage, reliable condenser stream temperatures between vessels, reliable vapor temperatures for each stage, and brine heater outlet and scawater temperatures. In practice, flashing

brine temperatures, for instance, are frequently read by a single thermocouple per stage even when stage width may be many feet. Also, the temperature and pressure instruments are generally not adequate to provide the accuracy needed to analyze the process. Typically the flashdown between stages may be 3° . A $\frac{1}{2}^{\circ}$ error in temperature readout would represent a 16% error in the calculated flashdown. Precision-grade instrumentation systems are needed to evaluate the performance of MSF evaporators.

In view of the inadequate basic instrumentation, it is not surprising that control systems are rudimentary. Most plants are controlled manually, with little or no effort expended toward improving the stage-by-stage performance.

Because of the circumstances discussed above, great nonuniformity exists between various stages of many operating evaporators. One stage inlet orifice may be deeply submerged by brine, so that little flashing occurs, the flashdown being only 1 or 2°F . The condenser is far underloaded and exhibits a coefficient below $300 \text{ Btu hr}^{-1} \text{ ft}^{-2} (^{\circ}\text{F})^{-1}$; stage production is far below design. Another stage may have a low brine level and produce 6 or 7° flashdown. The condenser is overloaded according to the design but, owing to its conservative surface area design, operates efficiently and produces a heat transfer coefficient of well above $800 \text{ Btu hr}^{-1} \text{ ft}^{-2} (^{\circ}\text{F})^{-1}$. Production is of course well above design.

MSF evaporators typically attain their design operational requirements in spite of these chaotic operating conditions. This can only mean that if the design and control of the process were improved, performance could be substantially increased.

These considerations have important ramifications in economic comparisons of the MSF and other desalting processes. They are also very significant in terms of coupling a large MSF evaporator with a large nuclear power plant. The performance characteristics of the reactor and power plant are well defined at the design point as well as for off-design conditions. The MSF performance characteristics are not well defined even at design-point conditions. Such a large plant will almost surely have to be automatically controlled to a large extent. Neither the ability to accomplish this nor the instrumentation required has been demonstrated on current MSF plants.

It appears that a general upgrading of MSF technology is prerequisite to the developing of a realistic dual-purpose plant. The upgrading must include the interrelated technologies of heat transfer, fluid flow, and instrumentation and control.

3.2 DUAL-PURPOSE PLANT CONTROL STUDIES

Introduction

The objectives of the control studies are to investigate the problems involved in the operation of large nuclear desalting plants and to develop general-purpose methods for solving these problems. Implicit in the economic studies made of large desalting plant designs is the assumption that the resulting "optimum" plant can be operated satisfactorily. What often happens, however, is that the more effective the economic optimization becomes, the less tractable the eventual plant control and operation tend to become. In fact, predictions made to date on the dynamics of several very large MSF plant designs have, unfortunately, borne out this "rule of thumb." Resolution of the overall plant dynamics and control problems in advance of the final plant design (and construction), therefore, is clearly a necessity.

State of Technology

Several methods have been developed for predicting the dynamic behavior and controllability of large MSF plant designs. These techniques are general purpose to the extent that the detailed design features of a particular plant, for example, as generated by an ORNL design code, may be used directly as input data to the dynamics codes for studying specific control features. While the simulator codes themselves are operable, debugged, and internally consistent, the mathematical models used in the codes are not yet sufficiently accurate to make reliable predictions of plant behavior. Hence the major effort to date has been to obtain experimentally derived models and parameters to be used to upgrade the predictions. Of particular importance are the relationships that govern both the flow of tray brine through the interstage orifices and the extent to which the tray brine reaches equilibrium with the stage vapor.

Experimental Investigation of MSF Evaporator Dynamics

The derivation of models and parameters to be used in the prediction of MSF plant performance has been a goal of considerable OSW- and AEC-supported research, including that undertaken in this task. Unfortunately, the long-sought-after relationships describing this complex process have proven very elusive. There are several reasons for this: first, the basic processes involved (such as open-channel flashing flow and steam condensation

in very large condenser tube bundles) are not well understood, and so experiments and measurement systems are set up on a more or less cut-and-try basis, often resulting in noncorrelatable data, and second, the measurement and data-collecting problems themselves are quite difficult, since they require high accuracy under adverse conditions.

Our attempts at obtaining correlations for the brine flow rate through plain interstage orifices (i.e., with no baffles) are a case in point. We have obtained a considerable amount of operating data on the Baldwin-Lima-Hamilton (BLH) three-stage evaporator at Wrightsville Beach, North Carolina, both from our own tests and from tests run by BLH personnel. After considerable effort, using trial-and-error methods for deriving "optimum" forms of flow equations along with least-squares nonlinear regression fit computer codes to seek out the best coefficients for the equations, we were able to come up with two quite different expressions, each of which "fitted" the data to within a 10% standard deviation error. Alternative use of these two expressions in the dynamics codes, however, resulted in significantly different predictions of overall plant behavior. The major problem is that while these correlations can predict nominal flow rates fairly well given a basic set of operating conditions, they do not predict the effects on flow of *trends* in the various controlling parameters such as tray brine level. For example, low-temperature tests were run on the BLH evaporator in August 1969 in which the plant inventory, and hence the test stage level, was gradually decreased as the flow rate, flashdown, and tray brine inlet temperature were held constant. For deep (>18 in.) test stage brine depths, the net head loss (ΔP_T) decreased with decreasing level in a manner very similar to the nonflashing behavior. Further lowering of the test stage level, however, caused the inlet jet to be less submerged and the initial flashing region to move back toward the orifice, and ΔP_T increased with decreasing level. At shallow test stage depths (~13–14 in.), further reductions in inventory (and test stage level) had no effect on upstream level. A plot of net head loss vs test stage level for this test is shown in Fig. 4. Also shown is the variation in error in predicted flow rate by the two correlations noted previously, which points out their inability to predict trends.

In terms of previous overall plant stability calculations,¹⁰ the behavior shown in Fig. 4 indicates that a

plant with plain orifices would tend to be more stable operating with shallow brine depths.

To overcome these problems, the approaches we are now taking are to investigate the basic characteristics of the tray brine flow in order to better plan the experiments and measurements, and to run series of tests which permit direct measurement of the effects of trends in the controlling parameters. The "controlled trend" techniques are also to be used in determining relationships for describing nonequilibrium losses.

Basic studies of the flow characteristics have been made using the "flow box," a nonflashing three-stage MSF evaporator mockup. The intent here is to consider differences between the flashing and nonflashing cases as perturbations on the simpler nonflashing model. Correlations have been derived for which the standard deviation of the error in predicted nonflashing flow rate is 2½% over a wide range of operating conditions. Velocity distribution measurements made in the flow box have also aided the understanding of the changes in flow behavior that take place at different operating

Fig. 4. Parameter Trend Test Showing Effect of Stage Level on Net Head Loss and Inadequacy of Flow Correlations in Predicting Flow During Variation Sample Correlations Used in Simulator.

¹⁰S. J. Ball, *Nuclear Desalination Dual-Purpose Plant Control Studies. Interim Report*, ORNL-TM-1618, Part 1, p. 42.

conditions and have helped to confirm the assumption that data taken in 1- to 2-ft-wide channel rigs could be used to estimate wide-channel (i.e., full-scale plant) performance.

The dynamics tests which were run on the BLH evaporator in September 1968 were analyzed to attempt to determine the transfer functions relating test stage parameters to variations in inlet tray brine temperature and flow rate. Because of insufficient signal-to-noise ratios, nonlinear effects, deficient operations of the data logger, or a combination of these, the resulting analyses typically resulted in functions with poor coherence. Subsequent experiments are planned in which these problems will hopefully be solved.

Further investigations were also made of basic temperature and level measurement problems and of data-logging techniques at the OSW test facilities at Wrightsville Beach and San Diego.

Theoretical Calculations of MSF Plant Dynamics

A digital computer program for calculating nonlinear time-response solutions for large MSF plant designs has been developed at ORNL to study plant control and coupling problems. The simulator employs a variation of the matrix exponential technique.¹¹ The approximation is made in the *model* that during each calculational time step, each stage is effectively decoupled from its neighboring stages. This permits the transient solution for a 50-stage evaporator, for example, to consist of 50 sets of eighth-order equations instead of 400 coupled equations. The validity of this approximation has been checked out by an independent frequency-response calculation, as well as by successive reductions of the calculational time step used in the simulator.

The simulator has been debugged and is operating smoothly and efficiently. Errors in overall plant heat and mass balances are less than 1%, indicating sufficient internal consistency. Typical running times are of the order of 15 times real time (e.g., the simulation of a 1-hr-long transient for a 50-stage plant is run in about 4 min of IBM 360/91 computer time). An automatic plotting routine is used to plot time responses of selected parameters.

Although the models and parameters used in the simulator are internally consistent, they are not yet

sufficiently representative of actual plant behavior. Simulation runs using various models have been helpful, however, in pinpointing areas in need of further experimental data. For example, the tray brine levels in the high-temperature stages are quite sensitive to changes in flashdown, since a small change in temperature is equivalent to a large pressure change (13 in. H₂O head per degree at 250°F). The extent to which blowby would occur in the higher-temperature stages was found to be very sensitive to the assumed form of the flow equations as the brine levels approach the orifice heights. Consequently, experiments are being planned to obtain these data.

An example of the high sensitivity to small temperature changes is shown in Fig. 5, which plots the response of tray brine levels in several stages to a step increase of only 1°F in brine heater steam temperature. The successive emptying out of the upper stages is quite apparent. It is significant that the flow correlations used were for plain-hole orifices, which have been observed to be unstable at high operating temperatures as the brine levels are lowered. This is because as the difference between an upstream level and orifice height is reduced, there is successively less momentum loss due to the flow stream's striking the interstage barrier, until finally no loss due to the barrier is incurred as the level equals the height of the opening. For the case of a baffle just downstream of the orifice impeding the flow, however, this destabilizing effect is reduced since the flowing stream still experiences a significant momentum loss at the low levels. This has clearly indicated the desirability of using baffling in the higher-temperature stages.

Conclusions

Solutions of the MSF dynamics and control problems are required for direct application to large-scale MSF demonstration plant designs and, later, in conjunction with vertical-tube evaporator (VTE) controls studies, for application to combined VTE-MSF (hybrid) plant designs.

Experimental work on evaporator dynamics is being coordinated with OSW. ORNL has developed the capabilities for setting up and running dynamics tests on OSW experiments and for logging and analyzing the resulting test data. The MSF controls studies will incorporate further tests on the OSW-BLH three-stage plant at Wrightsville Beach and on the OSW nine-stage module in San Diego.

Analytical and experimental studies of VTE control problems will be initiated in early 1970 and coor-

¹¹S. J. Ball and R. K. Adams, "MATEXP," *A General Purpose Digital Computer Program for Solving Ordinary Differential Equations by the Matrix Exponential Method*, ORNL-TM-1933.

ORNL-DWG 70-3206

Fig. 5. MSF Digital Simulator—Response of Tray Brine Levels in Stages 1 to 6 and 10 to a 1°F Step Increase in Brine Heater Steam Temperature at Time Zero.

minated with OSW-sponsored design efforts. Eventual studies of hybrid plants will incorporate the individual technologies of both the MSF's and VTE's. Primary test vehicles proposed for the VTE work are the VTE pilot plant at Wrightsville Beach and the VTE-X at San Diego. Analytical studies of VTE dynamics will make use of the new ORNL hybrid computer as well as ORNL's large digital computers.

The technology developed in this task, in particular the dynamics codes, will be applied directly to specific demonstration plant designs as the needs arise.

3.3 TRADEOFFS BETWEEN ELECTRIC POWER GENERATION AND TRANSMISSION FOR LARGE NUCLEAR DESALTING PLANTS

This investigation into tradeoffs between electric power generation and transmission costs for large nuclear desalting plants is a part of the continuing studies of alternative technological and economic choices for satisfying water and energy needs conducted by the Nuclear Desalination Program at ORNL. These studies are directed toward establishing a basis for determining where the emphasis should be placed in the development of nuclear desalting technology. Special attention is being given to the role of desalting plants in relation to overall resource requirements for satisfying regional water and energy needs.

The total annual cost incurred in producing both products (water and electricity) from a dual-purpose

plant is considerably less than that from separate single-purpose plants producing the same quantities of both products. This saving is attributable to the cost-size scaling effect for the nuclear heat source, to the common facilities that are shared by the power- and water-producing portions of the dual-purpose plant, and to the maximum utilization of the available energy of the prime steam by the series arrangement of the turbine plant and the evaporator plant. The difference in annual costs is even more pronounced if the single-purpose plant requires supplemental cooling facilities such as cooling towers. This difference can be applied to delivering the electric energy to a load center via high-voltage transmission lines.

Two alternative means for satisfying base-load water and electric power requirements were investigated and compared, as illustrated in Fig. 6. The first situation is shown on the upper half of the figure above the heavy dashed line: a single-purpose water desalting plant located at a coastal site supplies water for use near the coastal site, and a separate single-purpose electric generating plant located near a load center supplies electric power for the load center. The second situation is shown on the lower half of the figure below the heavy dashed line: a dual-purpose plant at a coastal site supplies water for use nearby and supplies electric power to the remote load center over high-voltage transmission lines.

The immediate question to be answered is: What is the break-even transmission distance, X , between the

Fig. 6. Alternative Means for Producing Water and Electricity.

dual-purpose plant and the remote load center? The answer to this question is an indication of the economic incentive for considering dual-purpose plants or, alternatively, separate single-purpose water and electric plants.

Break-even electric power transmission distances were determined solely on the basis of total annual costs. When electric power transmission is combined with a dual-purpose plant, the break-even distance is defined to be the length of transmission line for which total annual costs for the dual-purpose plant plus transmission line are equal to the total annual costs for the single-purpose electric plant plus single-purpose water plant.

Annual costs were estimated for the plants and systems listed below, assuming multistage flash distillation plants, light-water reactors, 90% plant capacity factor, and both public and private financing.

Single-purpose water plants of 250, 500, and 1000 Mgd capacity

Single-purpose electric plants of 500, 1000, and 2000 MW(e) net capacity provided with once-through cooling, evaporative cooling towers, and nonevaporative cooling towers

Dual-purpose plants of equivalent combined capacity

Electric power transmission lines of 500, 1000, and 2000 MW(e) capacity

All costs were estimated in terms of 1968 dollars based on ideal siting conditions, a 40-hr work week for construction labor, no local sales tax, and no escalation during the construction period. Fixed charge rates for public financing were assumed to be 7% on depreciating capital and 5% on nondepreciating capital; those for private financing were 12% on depreciating capital and 10% on nondepreciating capital.

Water plant costs were based on computer extrapolations¹² of a design and cost study¹³ of a 250-Mgd multistage flash plant made by ORNL and Bechtel Corporation for OSW. Reactor plant costs for single-purpose water plants were based on an ORNL conceptual design of a low-temperature process heat reactor.¹⁴ Power reactor costs and turbine plant costs were based on ORNL estimates for PWR plants. Evaporative and nonevaporative cooling towers were assumed to increase the cost of single-purpose electric plants by \$10.00 and \$25.00 per kilowatt (electrical) respectively.

Fuel-cycle costs shown in Table 3 were based on studies by Rahe, Jones, and Robin¹⁵ using economic

Table 3. Fuel-Cycle Costs

	Cost (¢/MBtu)	
	Process Heat Reactor	Power Reactor
Net uranium burnup and losses	8.23(8.23) ^a	8.70(8.70)
Fuel fabrication	1.73(1.73)	1.88(1.88)
Fuel processing and reconversion	0.47(0.47)	0.41(0.41)
Fuel shipping	0.15(0.15)	0.15(0.15)
Inventory	1.17(2.31)	1.03(1.99)
Working capital	0.32(0.64)	0.29(0.59)
Gross fuel cycle	12.07(13.53)	12.46(13.72)
Credit for fissile Pu	2.40(2.40)	2.08(2.08)
Net fuel cycle	9.67(11.13)	10.38(11.64)

^aParenthesized numbers are for private ownership.

ground rules predicted to be representative of the year 1985.

Electric power transmission system costs were based on average costs for the United States for overhead alternating-current lines.^{16,17}

Cost estimates are summarized and compared in Tables 4 and 5. The upper portion of each table shows total annual costs expressed in millions of dollars. Each entry is the sum of three components: (1) annual fixed charges on capital investment, (2) annual operation and maintenance costs, and (3) annual fuel-cycle costs. Line 1 shows total annual costs for single-purpose water plants; line 2 shows total annual costs for single-purpose electric plants with the three types of heat rejection (run of river, evaporative cooling towers, and nonevaporative cooling towers); and line 3 shows the total

¹²C. T. Mothershed, *ORSEF: A Fortran Code for the Calculation of Multi-Stage Flash Evaporation Desalination Plant Designs*, ORNL-TM-1542 (March 1966).

¹³S. J. Senatore and J. A. Smith, *Study of 250 Mgd Multistage Flash Distillation Plant with Two-Level Brine Flow*, ORNL-4214 (January 1969).

¹⁴T. D. Anderson et al., *A Study of Metallic Uranium Fueled Pressurized-Water Reactors for the Production of Process Heat or Electric Power*, ORNL-TM-2451, to be published.

¹⁵E. P. Rahe, Jr., J. E. Jones, Jr., and T. T. Robin, *A Fuel Cycle Economic Analysis of Oxide Fueled Power and Process Heat PWR's for Seawater Desalination*, ORNL-TM-2046 (January 1969).

¹⁶H. I. Bowers, Oak Ridge National Laboratory, internal memorandum.

¹⁷L. D. Van Hees and E. L. Kelley, Jr., *TRANCO: A Computer Program for Estimating the Cost of Electrical Power Transmission*, BNWL-743, Pacific Northwest Laboratory (May 1968).

of lines 1 and 2 and corresponds to the first alternative situation shown in Fig. 6, a single-purpose water plant and a separate single-purpose electric plant. Line 4 shows total annual costs for dual-purpose plants of the same combined capacities. Line 5 is obtained by subtracting line 4 (total annual costs for dual-purpose plants) from line 3 (total annual costs for separate single-purpose plants) and shows the savings in total annual costs that dual-purpose plants provide when compared with separate single-purpose plants. It is this

difference that was assumed to be available to pay for electric power transmission from the dual-purpose plant to the remote load center.

The lower portion of each table shows break-even electric power transmission distances that can be paid for by the difference, or savings, tabulated on line 5. If all the electric power is transmitted via a single full-capacity line, the break-even distances for all cases are greater than 500 miles, as shown on line 6. If, for added reliability, it is assumed that the electric power is

Table 4. Comparison of Total Annual Costs for 7% Fixed Charge Rate and Indicated Plant Capacity

	250 Mgd, 500 MW (Electrical)			500 Mgd, 1000 MW (Electrical)			1000 Mgd, 2000 MW (Electrical)		
	No CT ^a	Wet CT ^b	Dry CT ^c	No CT ^a	Wet CT ^b	Dry CT ^c	No CT ^a	Wet CT ^b	Dry CT ^c
Annual Costs, \$/year $\times 10^{-6}$									
1. Single-purpose water plant	24.5	24.5	24.5	44.0	44.0	44.0	81.8	81.8	81.8
2. Single-purpose electric plant	12.0	12.6	13.7	19.9	21.0	23.1	35.6	38.0	42.3
3. Total single-purpose plants	36.5	37.1	38.2	63.9	65.0	67.1	117.4	119.8	124.1
4. Dual-purpose plant	29.1	29.1	29.1	53.1	53.1	53.1	99.7	99.7	99.7
5. Difference	7.4	8.0	9.1	10.8	11.9	14.0	17.7	20.1	24.4
Break-Even Transmission Distance, miles									
6. One full-capacity line carrying full load	>500	>500	>500	>500	>500	>500	>500	>500	>500
7. Two full-capacity lines each carrying half load	410	450	500	420	460	>500	470	>500	>500

^aSingle-purpose electric plant with no cooling towers (once-through or run-of-river cooling).

^bSingle-purpose electric plant with evaporative cooling towers.

^cSingle-purpose electric plant with nonevaporative cooling towers.

Table 5. Comparison of Total Annual Costs for 12% Fixed Charge Rate and Indicated Plant Capacity

	250 Mgd, 500 MW (Electrical)			500 Mgd, 1000 MW (Electrical)			1000 Mgd, 2000 MW (Electrical)		
	No CT ^a	Wet CT ^b	Dry CT ^c	No CT ^a	Wet CT ^b	Dry CT ^c	No CT ^a	Wet CT ^b	Dry CT ^c
Annual Costs, \$/year $\times 10^{-6}$									
1. Single-purpose water plant	37.3	37.3	37.3	67.5	67.5	67.5	125.7	125.7	125.7
2. Single-purpose electric plant	16.9	17.9	19.4	27.5	29.3	32.7	48.9	52.5	59.4
3. Total single-purpose plants	54.2	55.2	56.7	95.0	96.8	100.2	174.6	178.2	185.1
4. Dual-purpose plant	43.8	43.8	43.8	80.3	80.3	80.3	151.0	151.0	151.0
5. Difference	10.4	11.4	12.9	14.7	16.5	19.9	23.6	27.2	34.1
Break-Even Transmission Distance, miles									
6. One full-capacity line carrying full load	>500	>500	>500	>500	>500	>500	>500	>500	>500
7. Two full-capacity lines each carrying half load	370	400	450	360	400	480	390	450	>500

^aSingle-purpose electric plant with no cooling towers (once-through or run-of-river cooling).

^bSingle-purpose electric plant with evaporative cooling towers.

^cSingle-purpose electric plant with nonevaporative cooling towers.

transmitted via two full-capacity lines each carrying half load, break-even distances range from about 370 miles to over 500 miles, as shown on line 7. If the single-purpose electric plants are required to bear the additional costs of cooling towers, break-even transmission distances are increased 30 to 60 miles for wet evaporative-type cooling towers and 80 to more than 100 miles for dry nonevaporative-type cooling towers.

The preceding discussion assumes that all the savings in total annual costs are available to pay for electric power transmission. This assumption implies that water produced by the dual-purpose plants has the same economic value and can be sold for the same price as water produced by the single-purpose water plants. The other extreme is to assume that electric power produced by dual-purpose plants has the same value as electric power produced by single-purpose electric plants and to apply all the savings to reducing water costs. In actual practice it is unlikely that either extreme will be possible. It seems that both products should show an economic advantage to assure that the producers of water and electric power will cooperate in building and operating dual-purpose plants.

The present study serves only to indicate the maximum break-even electric power transmission distances assuming that water produced by the dual-purpose plants has the same economic value as water produced by the single-purpose water plants. Under these conditions and the other assumptions of this study, it is concluded that there is a very strong economic incentive to consider dual-purpose plants as opposed to separate single-purpose water and electric plants.

3.4 UNCLAD-METAL-FUELED BREEDER REACTOR FOR DESALTING OR POWER

Previous work^{18,19} has shown considerable economic promise for a sodium-cooled fast breeder reactor with unclad metal fuel. Eliminating the cladding from fast reactor fuels reduces markedly the diluent materials in the reactor, hardens the neutron spectrum, and substantially improves the neutron economy and nuclear performance. Principal uncertainties involve the fuel fabrication methods and cost estimates and the fuel stability under design service conditions. Experimental

work in these two areas during the year is described below.

Materials Compatibility

A test loop was operated to evaluate the compatibility of Th and Th-20% U specimens with sodium in a type 304 stainless steel system. The test loop was operated isothermally at 800°F for 200 hr. Specimen exposure times were 500, 1000, and 2000 hr. Sodium velocity past the specimens was 15 fps. The loop is shown schematically in Fig. 7.

The sodium was cold trapped and then hot trapped in the loop prior to the start of the test. The indicated O₂ content of the sodium was less than 10 ppm when the specimen exposure began. No difficulties were encountered during the operation, and the O₂ level in the sodium remained below 10 ppm, as indicated by a plugging meter and an amalgamation analysis. Upon completion of the test the specimens were removed from the loop, and the residual sodium was removed by cleaning with liquid ammonia.

Examination of the specimens revealed no physical evidence of corrosion. The maximum amount of reaction product film was less than 0.1 mil. The weight gains accounted for by interstitial element changes exceeded the net weight gain of the specimens, thus indicating some very small metal loss. This was substantiated by electron microprobe analysis, which showed a slight increase of uranium at the surface of the thorium specimens. There was no apparent time effect, nor was there any notable difference between the two types of specimen. The average weight change for 2000 hr was less than 0.1 mg/cm².

Metallographic examinations were made on test specimens exposed 500 and 2000 hr and on specimens representing before-test material and specimens exposed to simulated cleaning operations. The examination showed that a thin (<0.1 mil) reaction product layer had formed on the exposed specimens. (Again there was no detectable difference between the 500- and 2000-hr specimens.) The examination showed that there had been no intergranular corrosion.

Fuel Fabrication Development

Thorium and uranium metal are prepared commercially as powders, and plutonium can be readily obtained in powdered form. These powders can be blended together to form a uniform alloy composition in any desired ratio. Well-developed methods exist for such blending and for compacting and pressing the

¹⁸R. P. Hammond et al., *Unclad-Metal Breeder Reactor (UMBR) for Desalting or Power*, ORNL-4202 (January 1969).

¹⁹*Nuclear Desalination Annual Progress Report on Activities Sponsored by the Atomic Energy Commission for Period Ending October 31, 1968*, ORNL-4409.

Fig. 7. Uranium-Metal Fast Breeder Reactor Corrosion Loop.

mixture into coherent form. This powder compact then becomes the starting material for fuel element production, for which several fabrication routes appear feasible. These fall into two categories, depending on whether the compact is melted or fabricated directly. The experiments reported here were performed with thorium-uranium alloys only, but the addition of plutonium in the small amounts required is not expected to affect the fabrication results.

Casting Experiments. — Small-scale experiments were initiated to determine the basic feasibility of casting to shape, casting a billet, and then forming into component shapes of which the fuel element can be constructed. One possible problem in casting appeared to be hot tearing due to the low-melting uranium-rich eutectic. An H-shaped section was drop cast into a water-cooled copper mold to determine the extent of hot tearing in this "worst-case" configuration. A cross section of the H is shown in Fig. 8. Although there are some small cracks in the inside corners, it appears that hot tearing would not be a problem in properly designed castings. Investment casting techniques have been used to cast stainless steel prototype components which can be assembled to form the fuel element shape. Lengths of the thin-walled sections up to 9 in. appear to

be practical with the steel. Compatibility of the mold materials with the thorium-uranium alloy has not been tested. It was demonstrated that the Th-20 wt % U alloy can be rolled from an ingot into sheet and then formed into component shapes of which the fuel element can be constructed. The ingots used thus far have been arc-melted and drop cast into water-cooled copper molds.

The microstructure of this casting is shown in Fig. 9. The lightest phase is a thorium-rich phase, the intermediate phase is the uranium-rich eutectic, and the darkest gray particles are oxide. This structure should give good irradiation performance, since most of the fission fragments from the uranium will land in the more damage-resistant isotropic thorium phase. After rolling to reductions of up to 90%, the uranium phase appears as very small discrete platelets uniformly dispersed in the thorium matrix. This structure should offer the same good irradiation performance.

Preliminary wetting experiments in vacuum have shown that the Th-20 wt % U alloy is wetted by some of the high-temperature brazing alloys previously developed at ORNL for joining refractory metals. Initial electron beam welding trials are also encouraging. Joining of component shapes into an integral fuel

Y-91484

Fig. 8. Cross Section of Th-20 wt % U Casting. 5X. As polished.

Y-91494

0.002 INCHES
IS 500X

Fig. 9. Microstructure of Cast Th-20 wt % U Alloy. 500X. As polished.

element appears feasible; however, design of the shapes and holding mechanisms could eliminate any need for joining if desired.

Direct Fabrication Experiments. — The powder compacts, which were cylindrical in shape, were placed in close-fitting copper containers closed with copper lids threaded or welded in place. It was found that these assemblies could be successfully extruded with a reduction in area of 8:1 and that the copper maintained a complete protection from the atmosphere as well as serving as a die lubricant. Thus the extrusion press used could be conventional and would not have to be provided with inert-gas surroundings or remote handling.

The alloy bars produced by extrusion were found to be full-density ductile metal. They are presently being subjected to chemical and metallurgical analysis and then will be rolled down into 0.054-in. sheet metal for bend tests and shaping tests. The same extrusion process could be modified to produce hollow draw stock, which could then be drawn into hexagonal tubes suitable for final assembly of fuel elements. However, this route would require extensive die development and is not being pursued at this time. The sheet metal route is equally feasible and serves well enough as a demonstration that a fuel element can be successfully fabricated.

3.5 METAL-FUELED PRESSURIZED-WATER REACTOR

Introduction

It has long been recognized that the use of metallic uranium as a reactor fuel offers neutronic advantages relative to other, lower density, fuels such as uranium dioxide. However, irradiation-induced swelling at relatively low burnup levels has previously eliminated uranium metal fuel from consideration in commercial applications. Recent developments in uranium metal fuel technology have greatly extended the allowable burnup; the improvements in irradiation performance have been achieved through (1) the use of "adjusted" uranium (uranium containing a few hundred parts per million carbon, aluminum, iron, and silicon), which substantially reduces the uranium swelling, and (2) the use of externally clad hollow-core metallic uranium fuel elements to allow expansion space for moderate swelling without cladding distortion. Development work on the hollow-core concept was done at the Pacific Northwest Laboratory.²⁰⁻²²

Our studies on the application of metallic uranium fuel to pressurized-water reactors indicate that the use of this fuel may lead to significant improvements in the fuel-cycle performance and economics. Most attempts to improve the fuel cycle through better neutron economy result in completely new advanced reactor concepts. The use of metal fuel may, however, lead to an improved fuel cycle while retaining the fully developed system technology of current commercial reactors.

The initial emphasis of our work was on the study of low-temperature process-heat reactors for single-purpose desalting.²³⁻²⁵ During the course of this study it became apparent that the potential usefulness of metal fuel may not be limited to low-temperature reactors; the scope of work was therefore broadened to include the application of metallic uranium fuel to power and dual-purpose reactors.

General Description

The metal-fueled reactors considered are essentially identical in overall concept to commercial PWR plants. The only change in technology is the use of high-density metallic uranium fuel in place of the conventional uranium dioxide fuel. Two core configurations were examined to determine the potential usefulness of metal fuel. Table 6 shows a comparison of various design parameters for the two metal fuel cores, with values of the reference oxide-fueled Diablo Canyon reactor²⁶ also presented for comparison.

²⁰R. D. Leggett *et al.*, "Irradiation of Metallic Uranium Hollow Core Fuel Elements to 1 at. % Burnup," *Trans. Am. Nucl. Soc.* 11, 153 (1968).

²¹R. D. Leggett, J. C. Tverberg, and C. R. Hann, Pacific Northwest Laboratory, Richland, Wash., personal communication.

²²W. E. Gurwell, Pacific Northwest Laboratory, Richland, Wash., personal communication.

²³T. D. Anderson, J. E. Jones, Jr., and C. M. Podeweltz, *A Study of Metallic Uranium Fueled Pressurized Water Reactors for the Production of Process Heat or Electric Power*, ORNL-TM-2451 (December 1969).

²⁴T. D. Anderson, J. E. Jones, Jr., and C. M. Podeweltz, "A Metallic Uranium Fueled PWR for Single-Purpose Desalting," *Trans. Am. Nucl. Soc.* 11, 355 (1968).

²⁵E. P. Rahe, Jr., J. E. Jones, Jr., and T. T. Robin, *A Fuel Cycle Economics Analysis of Oxide Fueled Power and Process Heat PWR's for Seawater Desalination*, ORNL-TM-2046 (January 1969).

²⁶Pacific Gas and Electric Co., *Nuclear Plant - Diablo Canyon Site, Preliminary Safety Analysis Report*, vols. I and II, Docket No. 50-275.

Table 6. Summary of Uranium Metal Power Reactor Characteristics^a

	Direct Replacement ^b Uranium Metal Core	Reference Uranium Metal Core	Diablo Canyon UO ₂ Core
Reactor power rating, MW			
Thermal	3250	3250	3250
Net electrical	1050	1050	1050
System pressure, psia	2250	2250	2250
Coolant inlet temperature, °F	539	539	539
Coolant outlet temperature, °F	602	602	602
Core materials			
Fuel	Uranium metal	Uranium metal	UO ₂
Cladding	Zircaloy	Zircaloy	Zircaloy
Grid structure	Inconel	Inconel	Inconel
Fuel element			
Length (active), ft	12	12	12
Outside diameter, in.	0.422	0.672	0.422
Clad thickness, in.	0.022	0.036	0.024
Fuel OD/ID, in.	0.378/0.154	0.600/0.245	0.367/solid
Void fraction, % of fuel volume	20	20	
Fuel assembly cross-sectional dimensions, in.	8.475 × 8.475	12.650 × 12.650	8.475 × 8.475
Fuel-to-water volume ratio (unit cell)	0.528	0.667	0.593
Number of fuel assemblies	193	115	193
Effective core diameter, ft	11.06	12.76	11.06
Reactor vessel			
Design pressure, psig	2500	2500	2500
Nominal inside diameter, in.	173	196	173
Basic shell thickness, in.	8.50	9.11	8.50
Containment vessel			
Design pressure, psig	47	47	47
Nominal inside diameter, ft	140	144	140
Overall height, ft	212	216	212
Basic shell thickness, ft	3.5	3.6	3.5

^aCharacteristics of the reference Diablo Canyon UO₂ reactor are included for comparison.^bDirect replacement for oxide-fueled reactor.

The first of these cores, designated as "direct replacement uranium metal core,"²⁷ is indeed suitable for direct replacement in current oxide-fueled reactors. The rod size (0.422 in. OD) and fuel-to-water volume ratio (0.528) yield a lattice configuration identical to that of the reference oxide core.

The second core, designated as "reference uranium metal core," provides a larger (0.672 in. OD) rod in a relatively drier (fuel-to-water volume ratio of 0.667) lattice. This core is larger in diameter and yields a lower power density but benefits from the reduced fuel

fabrication costs and improved conversion ratio associated with larger pins and a drier lattice.

It should be noted that neither of the aforementioned cores represents an optimum. The reference core, however, is closer to the optimum configuration than the direct replacement core.

The fuel elements are cylindrical coextruded rods with Zircaloy clad around the "adjusted" uranium metal fuel and a central void (20% of fuel volume) in the fuel region to absorb the irradiation-induced swelling. The individual fuel elements are arranged in a 15 × 15 array and mechanically fastened together to form a canless fuel assembly. Figure 10 shows a partial section of a typical fuel assembly.

The metal-fueled reactors are essentially identical to current commercial PWR plants except for the interior

²⁷F. G. Welfare and J. E. Jones, Jr., *Physics, Thermal-Hydraulic, and Fuel Cycle Cost Analyses of a Metallic Uranium Direct Replacement Core for PWR's*, ORNL-TM-2493 (to be published).

of the fuel pin. However, for the reference uranium metal core the power density is less, dictating a larger-diameter core. Therefore, both the reactor and the containment vessel must be slightly larger for this core. The capital cost penalty associated with the increase in size is discussed in the economics evaluation.

Fig. 10. Partial Section of Typical Fuel Assembly.

Core and Fuel-Cycle Characteristics

Each core was analyzed at a number of different exposures. The equilibrium cycle length was held at about one calendar year, and the exposure was varied by changing the number of cycles for which each fuel assembly remained in the core. The fuel-cycle data are equilibrium values. An average exposure of 13,200 MWd per metric ton of uranium (MWd/MTU) has been adopted as the reference value. This average exposure would imply a maximum exposure of about 18,000 MWd/MTU. Core and fuel-cycle characteristics of the two designs at the reference burnup are summarized in Table 7, with comparable data presented for the UO_2 core.

The fuel cycles are characterized by low values of feed enrichment (1.3 to 1.5 wt % ^{235}U) and high ratios (~ 0.8 to 0.9). These characteristics indicate the excellent neutron economy which results from the use of high-density metallic fuel.

Economics

The economic ground rules used in the evaluation are summarized in Table 8. Basically, these ground rules are intended to characterize a set of economic conditions that would apply, as an effective lifetime average, to a reactor started up in the early 1980's. The assumption of when the reactor is to be started affects the size of the fuel industry and, therefore, the unit costs of fuel

Table 7. Core and Fuel-Cycle Data for Uranium Metal Power Reactors^a

	Direct Replacement ^b Uranium Metal Core	Reference Uranium Metal Core	Diablo Canyon UO_2 Core
Burnup, MWd/MTU	13,200	13,200	33,100
Reactor throughput, MTU/year	80.9	80.9	32.3
Reloading interval, years	1.04	1.00	1.00
Fraction of core reloaded	$\frac{1}{2}$	$\frac{1}{3}$	$\frac{1}{3}$
Specific power, kW(t) per kg feed U	19.3	13.4	28.7
Power density, kW(t)/liter	97.0	74.3	97.0
Feed ^{235}U enrichment, wt %	1.50	1.29	3.30
Discharge ^{235}U enrichment, wt %	0.61	0.57	0.81
Discharge plutonium, g per kg feed U			
Total Pu	6.85	6.73	6.21
Fissile Pu	5.13	5.13	4.36
Conversion ratio	0.78	0.86	0.56
Average heat flux, $\text{Btu hr}^{-1} \text{ft}^{-2}$	207,000	218,000	207,000
Maximum fuel temperature, $^{\circ}\text{F}$	926	1098	~ 4100
DNB (burnout) ratio	1.422	1.423	1.422
Average mass velocity, $\text{lb hr}^{-1} \text{ft}^{-2}$	2.59×10^6	2.17×10^6	2.59×10^6

^aCharacteristics of the reference Diablo Canyon UO_2 reactor are included for comparison.

^bDirect replacement for oxide-fueled reactor.

processing and fuel fabrication. All cost estimates are made in terms of 1968 dollars.

A breakdown of the fuel-cycle costs for the two metal-fueled reactors at the reference burnup of 13,200 MWd/MTU is given in Table 9, with data for the UO_2 core presented for comparison. The principal differences in fuel-cycle costs for the two uranium metal cores appear in the lower fuel fabrication costs associated with the reference uranium metal core. The lower fabrication cost results from the use of larger fuel rods. The lower net uranium fissile burnup and losses result from less ^{235}U feed enrichment required and the higher conversion ratio. A somewhat higher inventory charge is applied to the reference uranium metal core because of

its lower specific power. The estimated total equilibrium fuel-cycle costs for electric power generation of 13,200 MWd/MTU are 0.93 mill/kWhr for the direct replacement core and 0.73 mill/kWhr for the reference core.

In our depletion analysis of the metal-fueled reactors we assumed spatially uniform, "scatter" reloading. Considering this same reloading assumption for the Diablo Canyon oxide-fueled reactor, we calculated an initial enrichment approximately 20% lower than that reported by the manufacturer. This discrepancy is due in part to the nonuniform out-to-in radial zone reloading scheme reported by the manufacturer and may also be the result of some conservatism in their estimate in order to provide a guaranteed burnup.

Assuming a comparable amount of optimism in our predictions of metal fuel enrichments, we have for comparison calculated the fuel-cycle cost for a 20% increase in initial enrichment of the reference uranium metal fuel case. The results of this adjustment may be seen in Figs. 11 and 12, where sensitivity analyses are presented to show how oxide and metal fuel-cycle costs vary with two important ground rule assumptions: U_3O_8 cost (Fig. 11) and industry size (Fig. 12). The lower boundary of the shaded area defines the fuel-cycle costs calculated from our prediction of initial feed enrichments, while the upper boundary defines the fuel-cycle cost associated with the 20% increased enrichment.

Figure 11 reveals that the fuel-cycle cost difference between the reference oxide and metal designs is 0.37 to 0.50 mill/kWhr(e) for the assumed ground rules. However, the reference uranium-metal-fueled reactor

Table 8. Summary of Economic Ground Rules

Fuel materials	
Cost of natural U_3O_8 , \$/lb	8.00
Cost of separative work, \$/kg	26.00
Uranium tails enrichment, % ^{235}U	0.200
Cost of conversion, U_3O_8 to UF_6 , \$ per kg of U	1.35
Value of fissile Pu, \$/g	9.08
Industry size	
Industry served by a single-purpose fuel fabrication plant, MW(t)	75,000
Nominal rating of multipurpose processing plant, metric tons/day	10
Reactor plant capacity factor, %	90
Fixed charge rate on depreciating capital, %/year	
Reactor plant	12
Fabrication and processing plant	22
Fixed charge rate on nondepreciating capital, %/year	10

Table 9. Equilibrium Fuel-Cycle Cost for Metallic-Uranium-Fueled Power Reactors^{a,b}

Cost Component	Cost [mills/kWhr(e)]		
	Direct Replacement ^c Uranium Metal Core	Reference Uranium Metal Core	Diablo Canyon UO_2 Core
Net uranium fissile burnup and losses	0.719	0.560	0.920
Fuel fabrication	0.279	0.203	0.198
Fuel processing and reconversion	0.110	0.110	0.043
Fuel shipping	0.021	0.021	0.016
Inventory	0.197	0.230	0.211
Working capital	0.056	0.058	0.062
Gross fuel-cycle cost	1.382	1.182	1.450
Credit for fissile Pu	-0.454	-0.454	-0.220
Net fuel-cycle cost	0.928	0.728	1.230

^aAverage core exposure is 13,200 MWd/MTU for uranium metal and 33,100 MWd/MTU for UO_2 .

^bCharacteristics of the reference Diablo Canyon UO_2 reactor are included for comparison.

^cDirect replacement for oxide-fueled reactor.

Fig. 11. Fuel-Cycle Cost Components as a Function of U_3O_8 Cost.

Fig. 12. Fuel-Cycle Cost as a Function of Industry Size.

has a lower power density and therefore a larger-diameter core, which results in a capital cost penalty; components affected by power density are the reactor vessel and the containment vessel. The capital cost penalty for these components was estimated to be \$3.1 per kilowatt (electrical). This may be translated into an energy cost penalty of 0.05 mill/kWhr(e). The reference uranium-metal-fueled reactor would, therefore, have a net economic advantage of 0.32 to 0.45 mill/kWhr(e) relative to the oxide-fueled reactor.

Uranium Ore and Diffusion Plant Requirements

The same characteristic of metal-fueled cores that leads to low fuel-cycle costs (i.e., the high conversion ratio) also results in more efficient use of uranium ore resources and diffusion plant capacity. In evaluating the ore and separative work requirements for the nuclear industry, the fissile plutonium produced is an important consideration. It may be either recycled or used in other reactor types (e.g., fast breeders). In our analysis of ore and separative work requirements, plutonium recycle was assumed, and the direct replacement core was evaluated based on metal fuel being introduced in 1976. For comparative purposes, similar data relative to fuel utilization were derived for current technology UO_2 -fueled PWR's. A summary of separative work and ore requirements to satisfy the AEC-projected domestic nuclear industry up to 1990 is presented in Table 10 for these two cases.

It will be noted that the introduction of metal fuel would result in more than a threefold reduction in separative work capacity needed and a 30% reduction in ore requirements by 1990. Another interesting aspect of the plutonium-recycle case with metal fuel is that after eight to nine years of operation, the uranium feed requirements could be satisfied with natural uranium. This mode of operation could be very attractive for countries without diffusion plants.

Table 10. Comparison of Separative Work and Uranium Ore Requirements for Oxide- and Metal-Fueled FWR's^a

	UO ₂ Fuel	Metal Fuel ^b (Direct Replacement Core)
Separative work consumption, kg/year × 10 ⁶ (average rate for year)		
1980	21	9
1985	34	11
1990	50	14
Cumulative ore consumption, MTU × 10 ³ (to end of year)		
1980	150	130
1985	320	240
1990	560	380

^aBased on AEC-projected domestic nuclear industry and recycle of plutonium for both fuels.

^bAssumes that metal fuel would be introduced in 1976.

Fuel Technology

Since the only advancement in technology considered is the use of metallic uranium fuel, it is pertinent to discuss the current state of metal fuel technology.

Irradiation Stability

Recent experimental results from the Pacific Northwest Laboratory^{20,21} have shown that fuel elements of the type assumed in this study can achieve up to 18,000 MWd/MTU with no increase in external volume and no indication that the burnup limitation has yet been approached. The present study was based on achieving similar results. It is evident, however, that much more irradiation experience, especially with longer rods in rod bundles, will be required to establish confidence in the irradiation stability of uranium metal as a commercial fuel.

Fabrication

Coextrusion of clad uranium metal fuel elements is a well-developed process. Gurwell²² and his co-workers at PNWL have coextruded 6-ft-long hollow-core fuel rods containing adjusted uranium and externally clad with a zirconium alloy. Twelve-foot-long rods of a similar design have been fabricated for the NPR at Hanford. Therefore, fabrication of the 12-ft-long rods proposed in the present evaluation appears to be feasible with established technology. We do not suggest, however, that no fabrication development would be required.

It is clear that both the irradiation stability and the corrosion behavior are dependent on the alloy content, the heat treatment, and the general fabrication procedure. Furthermore, a high degree of reliability will be required for metal fuel elements to avoid the economic penalty associated with the occurrence of defective fuel elements.

Corrosion

Uranium metal reacts with water to form uranium dioxide and hydrogen, and the reaction rate is quite sensitive to temperature. The corrosion rate for unalloyed uranium is approximately 2 mils/min at 572°F and only about 1 mil/day at 212°F. Preliminary results on adjusted uranium indicated that it is less corrosive by a factor of about 4.

Defective fuel element experiments with uranium metal were reviewed, and it was concluded that the criterion for reactor shutdown with this fuel must be entirely different from that generally applied to oxide fuel. With oxide fuel the criterion for shutdown is a limiting contamination level in the coolant or in the waste disposal system. With metal fuel the reactor will probably be shut down upon an initial indication that a cladding defect has developed. If reactor cooldown starts when the defect is detected and proceeds at a rate of 100°F/hr, our calculations indicate that less than 20 g of uranium could be corroded. If all the oxidized fuel were distributed in the primary coolant, the gross gamma activity level of the coolant would be about 1 μCi/cc. Based on experience with presently operating reactors, this is not an unusually high activity level.

The preceding interpretation of the consequences of fuel failure is tentative. The data available on defective element behavior are based on unalloyed and unirradiated uranium in solid rods. Rods with a central void space may exhibit a different corrosion behavior as compared with solid rods, but no evidence is available to indicate what the difference may be. Likewise, irradiated fuel may be different from unirradiated fuel relative to corrosion behavior. It is evident that much more corrosion data on metal fuel are needed.

Conclusions

The present evaluation shows the interesting possibility of significantly improving the fuel cycle of pressurized-water reactors through the use of metallic uranium fuel. Although the work was done specifically for pressurized-water reactors, it is reasonable to assume that metal fuels would also be applicable, with similar advantages, to boiling-water reactors.

A fuel-cycle cost reduction, relative to oxide fuel, of 30 to 40% was estimated for the reference metal-fueled reactor. Furthermore, the evaluation was based on a rather arbitrary set of core-lattice parameters; optimization of the metal-fueled reactor should result in even better economics.

The use of metal fuel also has important implications relative to fuel resource utilization and diffusion plant requirements. For example, indications are that the introduction of metal fuel would reduce the separative work requirement, relative to that for oxide fuel, by a factor of 3 or more.

There are a number of uncertainties that must be resolved before metal fuel becomes commercially useful. Of particular concern is the corrosion of uranium

metal in water should a cladding defect occur. Our analysis of defective-element corrosion data indicates that to effectively limit the corrosion the reactor must be shut down upon detection of a defect. Thus, the cladding integrity must be quite good to avoid an economic penalty because of reduced availability. It appears, however, that the potential advantages of uranium metal fuel provide a very strong incentive for further development to demonstrate the reliability of this fuel.

3.6 GENERAL STUDIES OF AGRO-INDUSTRIAL COMPLEXES AND OF AGRICULTURAL AND INDUSTRIAL PROCESSES

Costs of Power and Water

The costs of nuclear power stations in the United States were updated to a mid-1969 basis by applying suitable factors to allow principally for increases in material and labor costs and escalation (construction period increased from 4 years to 5½ years). Table 11 shows a comparison of the power costs used as a base case in ORNL-4290 (1967 basis)²⁸ and the estimated mid-1969 costs. Decreasing the construction period for the mid-1969 case by one year, that is, to 54 months, gives a decrease in power cost of 0.2 mill/kWhr; decreasing the load factor from 90 to 85% increases the power costs by about 0.1 mill/kWhr.

The effect of an increase in the cost of power on the economics of the basic industrial processes considered

²⁸Nuclear Energy Centers: Industrial and Agro-Industrial Complexes, ORNL-4290 (November 1968).

Table 11. Comparison of Reactor (LWR) and Power Costs for a 1034-MW(e) [3200 MW(t)] Station

	ORNL-4290, ~1967	Mid-1969 Cost Basis
Base capital investment, \$/kW(e)	122	161
Investment including interest during construction at 9%, ^a \$/kW(e)	139	207
Construction period, months	48	66
Power costs, mills/kWhr		
Capital charges ^b	1.88	2.80
Operation, maintenance, and insurance	0.26	0.30
Fuel cycle	1.57	1.57
Total	3.7	4.8

^aCompounded quarterly.

^bAssumes cost of money at 10%, load factor of 90%, interim replacements at 5% of total cost replaced after 15 years; remaining plant has 30-year life.

Table 12. Changes in Manufacturing Costs Caused by a 1.0-mill/kWhr Increase in Power Cost

Product	Percent Increase in Manufacturing Costs	Equivalent Increase in Product Price
Aluminum	3	1.0¢/lb (\$20/ton)
Phosphorus	6	0.3¢/lb (\$5.5/ton)
Chlorine	9	0.2¢/lb (\$3.3/ton)
Ammonia	17	0.4¢/lb (\$8/ton)

in ORNL-4290 is indicated in Table 12. For most of these products the market price has also increased during this same time period, and the increase appears to more than balance the added production costs that could be attributed to the increase in power cost.

The effects of the increased reactor costs as well as increased evaporator costs (relative to the 1967 study) on the cost of desalted water have also been estimated and are illustrated in Fig. 13. In the earlier ORNL study it was assumed that the near-term technology would be a light-water reactor coupled with a multistage flash evaporator. Current thinking is that within the context of an agro-industrial complex the combined MSF-VTE evaporator coupled with an LWR may be considered as "near term."

As indicated in Fig. 13, the cost increases from 1967 to 1969 are nearly balanced (at 5 to 10% cost of money) by a shift in the evaporator technology. On the basis of the same technology, that is, LWR-VTE, the cost increase (allowing for both reactor and evaporator) amounts to about 45% at a cost of money of 10%.

Due to increased interest in the evaluation of smaller desalination plants, the cost of water was computed as a function of plant size from 5 to 1000 Mgd and is given in Fig. 14 for two costs of money. The water costs from plants of 5 to about 100 Mgd were based on purchasing electricity and extraction steam at constant cost from an equivalent 500-MW(e) nuclear power station. For the range 150 to 1000 Mgd, a dual-purpose plant concept is adopted, using steam from a back-pressure turbine for the brine heater. Over this range the size scaling laws for both the reactor and the evaporator apply, and the water costs shown are computed by the difference method,²² thus accounting for the step change which is shown in Fig. 14.

To show the relative influence of the various component costs on the cost of desalted water, Fig. 15 was

²²For example, water costs are based on the cost difference between a dual-purpose plant and a power-only plant producing the same amount of salable electricity.

Fig. 13. Incremental Cost of Water vs Cost of Money for 1000-Mgd Plant (Load Factor = 90%).

prepared. The cost of the evaporator is the largest single item, accounting for about 43% of the total cost for water under the conditions listed on this figure.

Industrial Processes

Ammonia. — Work on industrial processes which appear attractive for inclusion in an energy center has entailed further refinement of the earlier building block data and the development of technical and economic data for several additional processes.

The effect of using commercial water electrolyzers on the manufacturing cost of ammonia was evaluated. A comparison of the characteristics of these units is given in Table 13, and the associated manufacturing costs of ammonia are shown in Fig. 16, where a comparison with the use of two advanced systems, Allis-Chalmers and General Electric cells, is given. These costs are based on the use of a 9% fixed charge rate (15-year life) except for General Electric Cells (12.3% and 10-year life), a 600-ton/day plant at 95% load factor, and an oxygen credit of \$4.00 per ton. In the absence of this oxygen credit the NH_3 cost would be increased by about \$5.70 per ton of NH_3 .

A study was made of the economics of integrating an electrolytic ammonia plant with a power station and

Fig. 14. Cost of Desalted Water vs VTE Plant Size (Load Factor = 85%).

Fig. 15. Components of Water Cost.

Fig. 16. Manufacturing Cost of Ammonia Using Electrolytic Hydrogen.

Table 13. Commercial Water Electrolyzers

Cell	Type	Temperature (°C)	Pressure (atm)	Current Density (A/ft ²)	Power Consumption (kWhr/Mscf H ₂) ^a	Maximum Module Size (scf H ₂ /hr)	Estimated Plant Investment ^b (millions of dollars)
Hydro-Pechkranz	Bipolar diaphragm	80	1	140	120	12,200	19.6
Zdansky-Lonza	Bipolar diaphragm	90	30	115	120	28,150	32.7
De Nora ^c	Bipolar diaphragm	90	1	280	109	27,500	16.2
Bamag	Bipolar diaphragm	80	1	230	121	17,600	
Stuart	Unipolar tank-type diaphragm		1	200	147	626	18.1
Trail	Unipolar tank-type diaphragm	24	1	80	145	172	18.5

^aDry gas at 60°F and 30 in. Hg absolute pressure; 378 scf of gas per pound-molecular volume.

^bIncludes 10% allowance for engineering, 10% for general overhead, and 5% for contingencies; where estimates were for equipment purchase only, an allowance of 10% was made for erection of the plant. Plant size is 40 Mscf of H₂ per day, equivalent to 600 tons of ammonia per day.

^cImproved version of their water electrolyzer; however, it has not been operated on a large commercial scale.

with a power grid. In this type of operation it is assumed that the water electrolysis plant operates with off-peak power at variable current density depending on the power plant or system load curve. In the case of the conjunctive operation with a power plant, it is further assumed that the power plant can operate at a 90% load factor and that the water electrolysis plant can only obtain power when this load factor decreases. Figure 17 shows a case of a 1000-MW(e) [two 500-MW(e) units] station operating with a 300-ton/day ammonia plant assuming a \$4.00 per ton credit for the co-produced oxygen. (A comparably sized air liquefaction plant could produce oxygen for \$6.00 per ton. The lower credit assumed was to compensate for delivery costs.) This figure gives the required price for ammonia such that the total annual cost of the conjunctive (NH₃ and power) plant operation is equal to that of the power plant alone operating at the indicated reduced load factors. The amount of power sold to the grid would be identical for both power plant operating modes. The minimum price for NH₃ of \$47.00 per ton shown in the figure may be compared with a price of \$57.00 per ton delivered to a farm in northeastern Iowa during the summer of 1969, thus indicating an allowance of ~\$10.00 per ton for hauling to farms.

The integration of an electrolytic ammonia plant with a grid was evaluated for the case of the Western India grid, which has a peak load of about 1700 MW(e) and a

minimum load of 860 MW(e). The proposed 1200-MW(e) (two unit) nuclear power station would be connected to this grid and could supply the peaking power requirements by reducing or interrupting the operation of the water electrolysis cells. This in turn could allow the closing down of some of the currently used high-fuel-cost small peaking stations. If the saving in fuel costs (between the new nuclear station and the old small stations) were applied to the cost of producing ammonia, it would amount to \$11.00 per ton and thus reduce the costs shown in Fig. 4 to values well below the cost of importing ammonia into this agricultural region.

Since many of the above processes for electrolytic-based ammonia depend on further successful development of the porous electrode concept, some efforts have been made to interest industrial firms and the TVA Fertilizer Development Laboratory at Muscle Shoals to continue this effort. In addition, the long-term savings available through additional cell design changes have been estimated. For example, if the asbestos matrix now required for separating the plate electrodes could be eliminated, perhaps by use of concentric porous tube electrodes with electrolyte flow through the tube walls, a 40% reduction in the production costs for NH₃ appears attainable. TVA personnel are currently reviewing the status and potential of the water electrolysis route to ammonia

Fig. 17. Ammonia Sales Price Required for the Combination of a 1000-MW(e) Nuclear Power Station and Electrolytic Ammonia Plant to Break Even with the Same Power Station Operating at the Indicated Load Factors.

before recommending any further development programs.

Phosphorus. — Additional data on the electric-furnace phosphorus process indicate that for some types of phosphate rock, the rock pretreatment required could introduce an appreciable increase in the plant investment cost. For example, if the rock requires a pelletizing operation, the overall plant investment cost given in ORNL-4290 could increase by as much as 33%. Also, recent cost estimates (late 1968) obtained from Gulf Design Corporation indicate that the plant costs previously used may be 28% too low. Capital investment data for the wet acid process obtained from this firm were also higher, about 45%, than those used in ORNL-4290. The overall effect of using these cost increases on the comparison of the two processes is small since they are offsetting.

Acetylene. — The production of acetylene has recently been extended to include the electric arc (Du Pont) process.³⁰ In many parts of the world acetylene

is being replaced by ethylene obtained from cracked petroleum and naphtha since the ethylene is a lower-priced feed stock, partly due to the local demand for the associated by-products. In some countries which may have natural gas but little petroleum or where there is little demand for gasoline and the many other products obtained from cracking petroleum or naphtha, the arc processes may be desirable. The manufacturing cost of acetylene as a function of the cost of power for several plant sizes and costs of money is given in Fig. 18. The use of acetylene for vinyl chloride manufacture (the largest single use) is compared in Fig. 19 with vinyl chloride made using ethylene as the feed stock. For a plant size of 328 tons of vinyl chloride per day (corresponds to 144 tons of acetylene per day) and a 10% cost of money, a break-even power cost of about 5 mills/kWhr is obtained when this process is compared with ethylene-based vinyl chloride. This corresponds to an acetylene manufacturing cost of about \$116 per ton, or 5.8¢/lb (Fig. 18), which, in turn, is equivalent to ethylene at 2.8¢/lb. Since this process is not in large-scale operation, the associated costs are subject to further evaluation.

D-LM Process for Production of Pig Iron. — In the D-LM process,³¹ developed by McDowell-Wellman Engineering Company for operation at Mobile, iron ore, coal, and limestone are ground together and formed into balls or pellets. The green pellets are hardened and partially reduced on a traveling grate, with the coal forming part of the fuel and natural gas or gas from the smelting operation providing the remainder. As the self-fluxing pellets leave the traveling grate, in which approximately half of the oxygen combined with the iron has been eliminated, they are charged hot into a submerged-arc smelting furnace. It is claimed that less than 100 kWhr per ton of pig iron produced is required for producing iron from an ore containing 50 or 60% iron, as compared with over 2000 kWhr/ton for direct electric smelting of the same ore. Pelletizing, hardening, and electric smelting of iron ore are proven operations. The steps not yet proven commercially are the production of partially reduced pellets on a traveling grate and the charging of hot pellets into the smelting furnace. It is claimed, however, that extensive pilot operations have demonstrated the feasibility of these operations.

³⁰J. M. Holmes, *Evaluation of DuPont Arc Process for Acetylene and Vinyl Chloride Monomer Production*, ORNL-TM-2725 (September 1969).

³¹T. E. Ban and D. C. Violetta, "D-LM New Commercial Iron Making Process," presented at AISE convention, Cleveland, Ohio, June 1968. McDowell-Wellman Engineering Co.

Fig. 18. Manufacturing Cost of Acetylene vs Cost of Power.

It may be possible to produce pig iron economically by this new process at rates as low as 500 or 600 tons/day, but it is doubtful that a blast furnace with a capacity much less than 2000 tons/day can produce iron economically. On the other hand, there are definite limitations on the size and, therefore, on the production rates of an electric smelting furnace. Presently, the maximum production from a single electric smelting furnace seems to be 1000 or 1200 tons/day even with a partially reduced burden. The cost of iron produced is, of course, dependent on the costs of ore, energy, and the reductant. The blast furnace must use high-grade coke for the major energy source and for the reductant. With prereduction and electric smelting, noncoking coal can be used as a reductant and partial source of energy, but relatively expensive electric power must be used for a portion of the energy input. A comparison of the economics of pig iron production,³² from the blast furnace and D-LM processes, presented in Fig. 20, shows that coke must be available for \$11.00 per ton to produce pig iron at the same production cost (\$38.00 per ton) which can be achieved in the electric smelting furnace with power at 6 mills/kWhr and coal at \$9.00

per ton. For power at 1¢/kWhr the break-even cost of coke is \$15.00 per ton.

Estimates of Process Steam Consumption by Manufacturing Industries in the United States for the Year 1980

In a recent report (ORNL-HUD-2)³³ estimates were made of the consumption of process steam by manufacturing industries in the United States for the year 1980 as part of a program for evaluating the advantages of urban nuclear energy centers. A Perazich-type assumption was made with respect to the use of steam by the selected industries. This type of assumption held that four United States industries (Chemical, Paper, Petroleum, and Food),³⁴ the significant steam users in

³²J. L. Gregg, J. M. Holmes, and H. E. Goeller, *Evaluation of a Power-Intensive Process for Iron and Steel Production at a Nuclear Energy Center*, ORNL-TM-2697 (October 1969).

³³F. W. Miles, *Urban Nuclear Energy Center Study: Estimates of Process Steam Consumption by Manufacturing Industries in the United States for the Year 1980*, ORNL-HUD-2 (November 1969).

³⁴These shortened industry names are used here and throughout this report for convenience. In the *Standard Industrial Classification Manual*, the names are listed in the same order as: (1) Chemical and Allied Products Industry, (2) Paper and Allied Products Industry, (3) Petroleum Refining and Related Products Industries, and (4) Food and Kindred Products Industry.

Fig. 19. Vinyl Chloride Manufacturing Costs as a Function of Power Costs.

the manufacturing segment of United States industry, use all of their purchased fuel to produce steam. Steam consumption in 1962 was estimated by several methods for the selected industries from fuel consumption data in the *Census of Manufactures*. The values were projected to 1980 by using energy consumption projections of the type made by the Texas Eastern Transmission Corporation. The estimates of steam consumption for 1980 given in Table 14 varied from 67.6×10^{14} to 95.4×10^{14} Btu, depending on the methods and assumptions employed. This estimated consumption of steam by manufacturing industries is approximately equal to the 92×10^{14} Btu of equivalent electrical energy estimated to be generated for electric utility usage in 1980. This indicated that a significant amount of thermal energy from an urban nuclear

energy center would be consumed by manufacturing industries if the area served by the center had a fraction of the country's steam-using industries equal to its fraction of the country's population.

"Confirmatory" Steam Consumption Estimates for the Principal Steam-Using Manufacturing Industries by Methods Different from Those Used in ORNL-HUD-2

Steam consumption estimates in selected manufacturing industries of the United States were made by methods different from those used in ORNL-HUD-2. These "confirmatory" estimates would presumably establish to a degree the validity of corresponding values reported in that report if pairs of values are of

Fig. 20. Pig Iron Production Costs vs Cost of Power.

the same order of magnitude. In such a case, one might say that the "confirmatory" value and its corresponding value in the report were in the same "ball park." This close a relationship of two steam estimates independently obtained would probably be as good as can be hoped for because of the nature of the estimates.

The "confirmatory" values obtained are given in Table 15 along with corresponding interpolated values from a table in ORNL-HUD-2. Note that no confirmatory estimate was made for the Food industry because no basis for doing so was found. Also note that for each of the three industries the confirmatory estimate is within an order of magnitude of the ORNL-HUD-2 estimate. Therefore the desired degree of validity was established in each case. However, the closeness of the pairs of values for the Paper and the Petroleum industries is believed to be strictly fortuitous.

Complete descriptions of the methods used to obtain these confirmatory estimates are given in ORNL-TM-2646 (to be published). Brief descriptions of the methods are as follows.

For the Chemical industry a summation was made of the quantities of steam required in 1965 and 1966 (i.e., some of the values were for 1965 and others for 1966)

to produce steam-intensive chemicals manufactured by this industry. The results of this method suffered from lack of complete steam-usage data for industrial chemicals and also possibly from no allowance being made for steam used for nonprocess purposes such as heating of buildings.

For the Paper industry the rate of steam usage required per unit of output in this industry was determined for 1966 from capacity expansion factors.³⁵ Then, this steam-usage rate of quantity of steam per unit of output was multiplied by the total number of units of output reported for 1966 to obtain the quantity of steam consumed in 1966.

For the Petroleum industry the confirmatory estimate was made by multiplying the rate of steam usage (i.e., pounds of steam used per barrel of petroleum processed) by the number of barrels of petroleum produced in 1966. This, of course, assumed that the annual petroleum production was approximately equal to the quantity processed in that year.

Estimates of Steam Pressures and Pressure Distribution for the Four Principal Steam-Using Manufacturing Industries

The estimates of steam pressures and pressure distributions for the four principal steam-using manufacturing industries are listed in Table 16. Two observations were made while obtaining this steam pressure information: (1) the trend of steam pressure usage with time is one of increasing steam pressure and (2) the trend of steam usage with time is one of decreasing steam usage. These two trends are not mutually exclusive — the net effect of the two in the case of a given manufacturing process is one of unit cost reduction.

Seasonal and Diurnal Variation in Production for the Four Principal Steam-Using Manufacturing Industries

In general, only one of the four steam-using manufacturing industries (Food) is subject to seasonal and diurnal variations in production. Because of low total quantity of steam used when compared with the total of the four industries, 14% in 1966, the variations should not be of major significance. Furthermore, the

Table 14. Estimates of Process Steam Consumption by Manufacturing Industries in the United States for 1980

Source of Heat Consumption Data	Estimate of Steam Consumption (Btu $\times 10^{14}$)	
	Purchased Fuel Only	Purchased Fuel and Fuel Produced and Consumed Internally
Texas Eastern ^a	74.4	95.4
Census of Manufactures	67.6	88.7

^aOriginal fuel purchase data source was the *Census of Manufactures*.

Table 15. "Confirmatory" Steam Consumption Estimates and Corresponding HUD-2 Values for 1966 for the Principal Steam-Using Manufacturing Industries of the United States

Manufacturing Industry	Steam Consumption Value (Btu $\times 10^{14}$)	
	Confirmatory Estimate	HUD-2 Estimate
Chemical	7.6	28.2
Paper	16.9	13.6
Petroleum	14.5	16.3

³⁵R. M. Waddell, P. M. Ritz, J. De Witt Norton, and M. K. Wood, *Capacity Expansion Planning Factors - Manufacturing Industries*, National Planning Association, Economic Programming Center, Washington, D.C. (April 1966).

Table 16. Estimates of Steam Pressures and Pressure Distributions for the Four Principal Steam-Using Manufacturing Industries

Type of Industry	Estimate of Steam Pressure Data		Quantity of Fuel Used to Produce Steam in 1966 ^{a, b} (Btu)
	Pressure Range (psig)	Distribution (%)	
			$\times 10^{14}$
Chemical	450-1000	28	0.67
	200-450	27	0.64
	100-200	2	0.06
	≤ 100	43	1.06
	Total	100	2.43 ^b
Paper	100-200	71	9.7
	≤ 100	29	3.9
	Total	100	13.6
Petroleum	150-600	20	3.3
	≤ 150	80	13.0
	Total	100	16.3
Food	50-100	10	0.9
	≤ 50	90	8.5
	Total	100	9.4

^aInterpolated from Table 2 in ref. 33.

^bThe sample represented only a part of the total chemical industry; therefore the amount of fuel used was much less than the 28.2×10^{14} Btu interpolations from Table 2 in ref. 33. However, the pressure ranges and distributions are believed to be representative of the overall chemical industry.

trend in the food industries is toward longer operating periods in order to reduce overhead costs.

For the other three manufacturing industries (Chemical, Paper, and Petroleum), continuous operation is the rule. One notable exception to the rule is the seasonal variation (heavy in summer) in carbon dioxide production.

Agriculture

As part of the on-going studies in the use of desalted water for agriculture, work has proceeded in the economic evaluation of a number of agricultural variables, including additional crops, livestock, and food processing. Some studies have been done in the area of alternative water storage and irrigation schemes, in the effect of rainfall, and in preliminary planning work for the establishment of an experimental farm to develop and demonstrate agricultural methods uniquely suited to the use of desalted water.

Additional Farm Enterprises. — Rice. — Although rice may be considered a relatively high-value crop (sale price about double that of wheat), it has been traditionally assumed to require a large quantity of water based on the flooded field cultivation practice used in most parts of the world. Recently, new irrigation methods have demonstrated³⁶ that with careful timing of the water applications the requirement may be reduced to that normally used for wheat cultivation, with yields essentially unchanged. The basic "building block" data for rice cultivation using this new technique are summarized in Table 17, and the economic implications are indicated in Fig. 21. This figure shows that the break-even water cost would be in the range of 30 to 50¢ per 1000 gal.

The effect of incorporating rice as a summer crop into the cropping pattern of an irrigated farm using desalted water is also indicated in Table 17. Here a simple modification to system 2 ("high value" as given in ref.

³⁶J. S. Kanwar, "From Protective to Productive Irrigation," *Economics and Political Weekly* 4, 13 (Mar. 29, 1969).

Fig. 21. Cost of Raising Rice and Wheat vs Cost of Water.

Table 17. Characteristics of Rice in Controlled-irrigation Agriculture

Cultivation cost (not including water), \$/acre	40.00
Water used, in.	16.7
Yield (milled rice), lb/acre	4200
Net income increase over dry beans (system 2, ORNL-4290) at 6¢/lb for rice, millions of dollars	12.4
Internal rate of return using water at 25¢ per 1000 gal (export price level), %	
System 2 (ORNL-4290)	12
System 2 with rice replacing dry beans, rice at 6¢/lb	15

28) whereby rice is substituted for dry beans indicates an appreciable increase in the economic return.

Livestock. – As an example of a livestock enterprise, data on the production of chicken meat and eggs have been developed. Using 22,400 acres of wheat as the primary feed grain, it is estimated that about 59×10^6 lb of live broilers and 15×10^6 dozen eggs can be produced per year. The costs of producing the wheat plus other supplemental feed, all the required labor, and all capital costs at 10% cost of money are shown in Fig. 22 as a function of the cost of water. Using an average price of 21¢/lb (19.5¢/lb for the broilers, 38¢/dozen for eggs) the break-even water cost becomes 45¢ per 1000 gal. The initial investment for this enterprise is about \$11 million, and the net effect on the economic return for system 2 (ref. 28) is an increase in the internal rate of return of 0.8. The incremental return on the added investment would be about 27%.

Aquaculture. – Some investigation has begun in the area of intensive fish farming, particularly in conjunction with a large power and/or water station. Here the large volumes of water being pumped for cooling purposes may be directed into constant-temperature raceways for raising fin or shellfish at a rate of perhaps two crops per year. One of the most profitable of such enterprises appears to be shrimp culture – a relatively new development but a successful operation in a few parts of the world. Not only does this enterprise appear to be highly profitable, but the product provides a source of much-needed protein for a nutritionally balanced diet.

Rainfall. – None of the examples in the earlier general studies included rainfall in the analysis of the agricultural segment. Of the locales previously considered, the Kutch region of India exhibits perhaps the most fortunate timing of the rain: that is, most rain occurs in the summer, when the crop water require-

ments are greatest. This location receives 9.2 in. of rain, over 80% of the annual rainfall, during the months of June, July, and August. Since about 80,000 acres of land are not utilized during this period in the system 2 “high value” example given in ref. 28, it is possible to increase dry bean acreage by this amount using the natural rainfall and assuming a utilization efficiency of less than 50%. If the same direct production costs (not including water) and crop yields are assumed, the added income from this crop would increase the direct return on investment for the entire farm by about 4.5 percentage points. Thus, a farm internal rate of return would be nearly 12% using water at 30¢ per 1000 gal.

Building Block Data for Agricultural Product Storage and Processing Operations

Development of investment and operating expenses for agricultural product storage and processing operations was started in recognition that incorporation of this type of enterprise would be necessary for the handling of certain crops either as a part of an agro-industrial complex or as part of the comple-

Fig. 22. Cost of Raising Chickens vs Cost of Water.

mentary infrastructures. In addition, it appeared that such enterprises might significantly improve the overall economic return of an agro-industrial complex, and therefore information was needed to evaluate this aspect.

Two factors strongly influenced the choice of initial enterprises for study. The first was the large sum of money estimated as necessary for grain and potato storage facilities in a typical complex. For the conditions specified in ORNL-4290, this ranged from \$62 million to \$83 million, depending on the crop acreages chosen. The question raised was whether or not processing plants could result in significant reductions in the necessary storage requirements. The second factor was the belief that from almost any viewpoint, that is, water consumption, yield, calories, etc., potatoes would be a very important agricultural product, and therefore processing to put them in a less perishable and more easily transportable form should be investigated. Other enterprises were chosen later for cost development primarily on the basis of need for the enterprise if the crop under consideration appeared to be a likely candidate as part of the crop makeup of the complex. To some extent the choices were also influenced by the availability of information, as, for example, the milling of wheat to produce flour and by-products; much information was readily available on the milling industry in terms of plant sizes, millers' margin of profit, etc., but little on the breakdown of investment and operating costs for new plants. Study of processes which fell in this latter category, with the exception of potato processing, was deferred on the basis that the work could be done more efficiently through subcontracts by an individual or firm specializing in this type of work.

The major part of this initial effort was devoted to development of investment and operating cost information on a few enterprises; however, as sufficient data were accumulated to allow analysis of the effects of size of the installations vs costs, a preliminary effort was made to determine the benefit to the complex which would result from incorporation of the enterprise. The problem of determining a sales price immediately assumed a prime role. The question of sales price can be estimated or obtained from statistical yearbooks for basic materials such as wheat or raw potatoes; however, in most developing countries there is no established demand or price for many of the processed items. It is clear that any meaningful assessment of profit from a given enterprise must be based on a careful analysis of the marketing aspects for a given product at a given location, including the costs of market development. It

was therefore decided to concentrate on the development of building block information which would provide data and a framework within which later studies of specific sites could fill in information on prices and marketing costs to arrive at financial returns.

The following presents summary data on some of the enterprises studied, along with comments on additional enterprises for which information has been collected only in part.

Potato Storage Facilities. – Table 18 presents current investment and operating cost data obtained from several companies in the Idaho-Oregon-Washington area. For storage warehouses large enough to be of interest to a complex, there does not appear to be any significant scaling factor; however, the costs assume a storage complex of at least ten warehouses, each of at least 50,000 cwt (hundredweight) capacity but probably no larger than 250,000 cwt. It is also assumed that these warehouses are operated in conjunction with a potato processing plant, and thus minor efficiencies are gained through better utilization of management and some specialized labor interchange.

The data in Table 18 are in generalized form; in order to arrive at a cost per hundredweight of potatoes stored it is necessary to assign cost rates for labor, utilities, interest on investment, etc. One typical case investigated yielded an average operating cost for storage of

Table 18. Potato Storage Facility Investment and Operating Cost Data

All figures per hundredweight of capacity

Land requirement, including provision for separation between buildings and for truck maneuvering and access, 0.5 ft² per cwt

Initial investment (lifetime)	
Building (25 years)	\$0.68
Air handling equipment and controls (10 years)	0.165
Mechanical refrigeration equipment (10 years)	0.25
Fluming equipment (25 years)	0.075
Potato piling equipment (10 years)	0.02
Subtotal	\$1.19
Contingency (15%)	0.18
Total	\$1.37 ^a
Operating cost data	
Maintenance, building, and equipment	\$0.02
Labor, man-hr	1.1×10^{-2}
Management and clerical, man-hr	5.8×10^{-4}
Sprout inhibitor	\$0.035
Electricity, kWhr	1.78
Water, gal	5.4
Supplies and miscellaneous expense	\$0.01

^aThis compares with the value used in ORNL-4290 of \$1.82 per cwt.

about \$0.25 per hundredweight for all the harvested potatoes on a single crop per year basis. The storage capacity required amounted to about 82% of the crop, with 18% being delivered to the fresh market and/or the processing plant during the assumed harvest period of two months.

Potato Dehydration Facilities (Granule). – Discussions with a number of firms actively engaged in the processing of potatoes in various forms led to the conclusion that the process which led to the most basic and versatile form was that of dehydration to the granule form. Potato granules, or dehydrated mashed potatoes, are precooked, dehydrated potatoes in the form of fine granules of about 70 mesh. They consist largely of separated, whole tissue cells. On reconstitution with hot water or hot milk, a product closely resembling freshly prepared mashed potatoes is formed. This form is easily reconstituted, being tolerant of considerable variation in temperature and mixing conditions on reconstitution. The granules may be used directly for preparing mashed potatoes or they may be combined, at the plant or later, into various formulations containing dry skim milk, vitamins and/or protein additives, etc. For good operating conditions 1 lb of granules requires about 6 lb of raw potatoes.

Table 19 summarizes the fixed capital investment required for three sizes of processing plants, the associated plant operating costs, and the finished product costs, including allowances for working capital, raw materials, and storage. The costs are based on mid-1969 estimates for construction, including architect-engineer fees, in the Idaho-Oregon-Washington area.

As noted previously, many assumptions had to be made regarding labor costs, interest charges, etc., in order to arrive at these costs; however, the assumptions can easily be modified to suit conditions which might prevail for a specified location. A more difficult problem is the question of whether or not such an enterprise would be profitable for a complex. In order to answer this, a detailed market study would have to be performed for the specified location in order to arrive at a price at which the product could be sold. The costs of market development and marketing costs for a product not presently in demand in developing countries would probably be significant.

Animal Feed from Potato Process Plant Wastes. – Five to ten percent of the original raw potato input to granule plants, as described above, is recovered in the plant primary waste treatment plant. This material is largely potato peels, trimmings, etc., removed by the waste stream settling and filter plant. This trim and

filter cake is usually stored in piles for periods of several weeks to allow chemical and biological action to neutralize the material before feeding it to the livestock. Essentially all processors have found that it is not economically justified to dry potato wastes for animal feed. In many cases the waste is not sold but is contracted to livestock raisers on the basis that they will haul it away. For a complex such as we are considering it appears that the waste would be of value to a livestock enterprise; however, it might be necessary to treat and dry the material, at least during the hot part of the year.

Potato Dehydration Facilities (Flake). – Information similar to that previously presented on granule production has been collected for the flake process. This information has not been analyzed since this product is not as versatile as the granules; however, it is planned to do so, since the plants can economically be built and operated for smaller capacities.

Potato Grading and Bagging Facilities. – Information has been collected on the investment and operating costs for potato grading and bagging facilities to be operated as part of a potato processing plant. The analysis of costs has not been completed, however, since they have been incorporated as part of the potato processing plant, and little additional investment is required.

Grain Storage Facilities. – The capital investment and operating costs were developed for four sizes of terminal elevators. Due to the concentrated production area the usual farm storage and subterminal handling can be bypassed with attendant economies. In addition, the probability that feed, flour, and other processing plants would also be located in the complex and adjacent to the grain storage facilities leads to the possibility of more efficient utilization during the course of the year. Of course, this latter consideration would be dependent on the detailed cropping and processing operations in a specific location.

The costs include the site, storage tanks (concrete), equipment, and buildings required to perform the functions of a terminal grain elevator. These functions are to receive, grade, clean, dry, blend, store, and deliver grain.

The capital investment required for the four model elevators is shown in Table 20. Although details of the operating costs have been developed, the table presents only an illustrative summary of 1969 costs based on a typical location.

Other Enterprises. – Information on investment and operating costs has also been developed for both standard and extra-long staple cotton ginning facilities and feed mills for making poultry and livestock feed.

In addition to the above facilities on which detailed information has been developed, a considerable body of information has been collected in the form of reports and studies on a wide variety of agricultural, dairy, and poultry processing facilities. Typical of the type of studies are the following:

Plant Requirements for Manufacture of Fruit and Vegetable Juices
Economies of Size in Soybean Processing Plants

An Economic Analysis of Model Plants for Pasteurizing and Bottling Milk
An Economic Analysis of Butter-Nonfat Dry Milk Plants
Plant Requirements to Set Up and Operate a Seafood Processing Plant
Plant Requirements for Manufacture of Milled Rice
Onion Dehydration Facilities
Freeze-Drying of Foods: Cost Projections
Broiler Processing Costs
Costs and Returns for Model Sweet Potato Canning Plants
Economic Studies on Vegetable Canning and Freezing Operations

Table 19. Costs for Potato Granule Plants

Raw product input, cwt/day	4000	8000	16,000
Finished product output, cwt/day	666.7	1333	2667
Investment costs, total ^a			
Buildings (30 years life)	\$380,000	\$600,000	\$1,011,500
Equipment (20 years life)	978,000	1,713,000	3,173,000
Installation	603,000	1,098,000	2,068,000
Spare parts and maintenance inventory	100,000	200,000	400,000
Total	\$2,061,000	\$3,612,000	\$6,652,500
Investment costs per hundredweight annual capacity of raw potatoes ^a	\$2.06	\$1.81	\$1.66
Investment costs per hundredweight annual capacity of finished product ^a	\$12.36	\$10.86	\$9.96
Operating costs per hundredweight of product			
Depreciation (straight line over life)	\$0.55	\$0.482	\$0.443
Interest on investment (10% on $\frac{1}{2}$ cost)	0.617	0.541	0.50
Salaries and labor (includes 25% overhead)	4.40 ^b	3.10 ^c	2.511 ^d
Packaging material	3.12	3.12	3.12
Utilities	0.8225	0.797	0.7835
Supplies	0.35	0.326	0.274
Miscellaneous plant expenses (4% of \$25.00 per hundredweight of product)	1.00	1.00	1.00
Miscellaneous overhead expenses (taxes, insurance, sales, accounting, purchasing, etc.)	1.56	1.522	1.499
Total ^e	\$12.42	\$10.89	\$10.13
Production costs per hundredweight of product			
Operating cost	\$12.42	\$10.89	\$10.13
Working capital cost	1.16	1.16	1.16
Raw material and storage costs ^f	13.14	13.14	13.14
Total	\$26.72	\$25.19	\$24.43

^aCost of the required land (2-4 acres) is not included.

^bTotal employees, 155.

^cTotal employees, 212.

^dTotal employees, 358.

^eExcludes raw material, storage costs, and working capital costs.

^fRaw potatoes purchased for \$2.00 per hundredweight.

Table 20. Costs for Terminal Grain Elevators

Capacity, cwt	300,000	600,000	1,200,000	3,000,000
Land required, acres	3.0	4.3	6.4	10.6
Capital investment, thousands of dollars				
Land	7.1	10.2	15.1	25.2
Equipment	295.6	352.3	521.2	1080.3
Office and sample building	8.9	12.1	16.1	27.2
Yards and outside (spur track, roads, drainage, etc.)	18.0	23.2	28.0	51.6
Buildings	385.0	636.1	1148.2	2376.1
Total capital investment	714.6	1033.9	1728.6	3560.4
Investment ^a per hundredweight storage capacity, dollars	2.38	1.72	1.44	1.19
Annual operating costs, thousands of dollars				
Direct labor cost	11.7	23.0	47.0	73.7
Plant overhead	36.1	49.5	84.4	164.6
Utilities	4.8	9.2	18.5	42.1
Insurance on grain ^b	0.7	1.4	2.8	7.0
Other material	12.0	22.6	41.5	97.7
Audits	3.2	4.9	8.9	18.1
Interest ^c	36.0	50.1	87.2	179.5
Total annual costs	104.5	160.7	290.5	582.7
Annual cost per hundredweight capacity, cents	34.8	26.7	24.2	19.4

^aThe value used in ORNL-4290 was \$1.43 per hundredweight for a capacity of about 1500×10^3 cwt.

^bProvisional inventory insurance at 0.292¢/cwt at 80% of capacity utilized.

^c5% rate of interest used on capital requirement.

Analysis of Complexes

The sensitivity analysis given in ORNL-4290 has been extended to help identify the most important parameters and/or assumptions used in the economic analysis of agro-industrial complexes. The sensitivity to startup costs or delays in reaching full project income levels is illustrated in Fig. 23. Also shown in the figure is an indication of the time required for a complex to duplicate its facilities from the profits realized. If the cost of money were 7% and a sinking fund were to earn 6%, a second complex of the type used in Fig. 23 could be started in the fifth year of operation and would begin operation itself in the tenth year.

In the earlier studies no credit was taken for the water recovered by the drainage system or from the tubewell water storage system. Most of the 20% water loss assumed (80% irrigation efficiency) should be recoverable, particularly since the initial water quality is so high.

The effect of a 10% decrease in water requirement for the farm was examined for a far-term agro-industrial

complex (complex No. 26, Table 7.11, ORNL-4290). The total water usage was kept constant, and thus the farm acreage, and hence the investment, was increased by 10% to use up the water. The effect of this "stretching" of the water output was to increase the internal rate of return by about 0.5%, that is, from 16.4 to 16.9%.

This same complex produces oxygen as a by-product of the electrolytic hydrogen process, slag and ferrophosphorus as by-products of the electric-furnace process for elemental phosphorus production, and chlorine as a by-product of the brine electrolysis process. (Since this is an agro-industrial complex it is assumed to be located in an underdeveloped country, and thus chlorine is in oversupply and is considered a by-product with very little value.) In the economic analysis of complexes for ORNL-4290 no credit was assumed for any of the by-products produced. If an oxygen credit of \$4.00 per ton, slag credit of \$1.00 per ton, ferrophosphorus credit of \$50.00 per ton, and a chlorine credit of \$10.00 per ton are assumed, the net income of the above complex is increased by \$12.8

Fig. 23. Cash Flow Diagram for an Agro-industrial Complex.

million, and the internal rate of return is increased from 16.4 to 17.1%.

In an attempt to obtain a better estimate of industrial off-site costs, particularly for smaller plants, a study of four industrial segments was made. The types of plants examined and the number in each category are given below.

Type of Plant	Number of Plants
Fertilizer (nitrogenous and phosphatic)	18
Metals (aluminum, magnesium, and steel)	5
Chlorine	5
Organic products	11
Total	39

It is recognized that the correlations of off-site data for these diverse types of plants can only be approximate, since the industries have different off-site requirements and a facility that one plant might consider an off site would be considered as a battery limits cost in another. Since the literature data did not give detailed lists of off-site components, it was impossible to develop a standard definition for off sites. Therefore

equations were developed using regression analysis for each type of plant in addition to an overall equation for all types of plants. Results are given in Table 21. The "all plants" equation gives greater off-site costs for small plants, particularly below \$10 million, but confirms the equation used for large installations as given in ORNL-4290.

Table 21. Equations for Computing Off-Site Capital Costs

Type of Plant	Range of Battery Limits Costs (millions of dollars)	Regression Equation ^a	Multiple Regression Coefficient
Fertilizer	1.0-45.7	$F = 96.9(\text{BLC}) - 0.303$	0.63
Metals	24.7-99.3	$F = 64.3(\text{BLC}) - 0.389$	0.65
Chlorine	5.2-29.0	$F = 77.1(\text{BLC}) - 0.446$	0.98
Organics	5.0-95.7	$F = 46.1(\text{BLC}) - 0.161$	0.51
All plants	1.0-95.7	$F = 93.1(\text{BLC}) - 0.391$	0.71

^aF is off-site costs as a percent of battery limits plant costs, and BLC is plant costs, millions of dollars.

3.7 APPLICATIONS OF AGRO-INDUSTRIAL COMPLEXES

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 has involved evaluations of national needs for power and water in five Middle East countries, evaluations of alternatives to nuclear energy and desalting in meeting those needs, and design studies and economic analyses of large water-producing energy centers for selected locations. Completion of the study is scheduled for mid-1970.

Puerto Rico

A study of the energy center concept for Puerto Rico is being conducted by Burns and Roe with a major subcontract with Dow Chemical Company and is being supported by various agencies of the United States and Puerto Rican governments. The ORNL responsibility in this study project has been as an advisor to the AEC and in providing specialized assistance to Burns and Roe, Dow, and the other study participants. This study is expected to be completed in mid-1970.

India

Technical assistance work with the IAEA agro-industrial complex study team has continued and included a United States team visit to India in April 1969. The purpose of this visit was to review the status of the Indian projects, to determine how United States technical assistance should be directed, and to suggest directions for future work. A general impression resulting from these discussions is that the IAEA agro-industrial study team is proceeding at a good pace with determination and competence. They have acquired expertise from other branches of the government and from the private sector. The nuclear-powered tubewell project for the Upper Indo-Gangetic Plain is receiving serious attention by the central government. Desalting applications in the Kutch-Saurashtra region appear more long term, but consideration is being given to a

pilot farm using either high-purity groundwater or desalted seawater.

Cash Flow Analysis for Indo-Gangetic Plain Project.

A cash flow analysis was prepared for the Indo-Gangetic Plain tubewell project. The project was modified to include an expenditure for the purchase and installation of 16 gas-turbine packaged power plants. These power plants would be installed during the second year of reactor construction and would provide 193 MW(e) to power the tubewells until the reactor comes on line four years later. An electrical grid distribution system was included in the expenditures. Fuel for the gas-turbine power plants was assumed to cost 50¢/MBtu, and this accounts for 7.7 mills/kWhr of the total electric power cost (heat rate 15,410 Btu/kWhr). Income from the power produced was based on a price of 8 mills/kWhr for pumping power and 10 mills/kWhr for domestic use.

In the cash flow analysis illustrated in Fig. 24 the small power plants were sold for 50% of their initial value after the reactor began to supply power. All capital and operating costs for the overall project were as reported in the Indian report, except for the investment in the aluminum plant, which was based on our costs increased for a non-United States location. During the first year of operation the salable output from the industrial plant was assumed to be only 50% of rated output; however, full operating costs were assessed. The internal rate of return was calculated to be 14.1% under the stated assumptions and not including any benefits from the added agricultural production achieved.

As a check on the cost for the electrical distribution system, the General Engineering Division prepared a cost estimate for a transmission and distribution network based upon the following model: (1) rectangular area 80 X 150 miles with nuclear power station in center, and (2) 36,300 connected tubewells, 5-kW loads at 240 V, with three wells per square mile. Assuming that all the necessary equipment could be obtained indigenously and that labor costs would be one-half of United States labor, an initial capital investment of \$60.1 million was estimated. This cost was compared with the estimates prepared by the National Rural Electric Cooperative Association for the installation of rural electrification projects in five states of India for the U.S. Agency for International Development. The studies included economic and engineering feasibility studies for areas in Gujarat State, Andhra Pradesh State, Maharashtra State, Mysore State, and Uttar Pradesh State. Table 22 lists the estimated number of connections, total cost, and the estimated cost per connection

to supply the anticipated fifth-year load for each of the five areas. The percentage of all connections made for domestic and irrigation pump sets is also listed. The ORNL estimate appears somewhat high, although an increasing cost trend with percentage of irrigation pump connections (thus a more dispersed grid) may be observed.

Pump Layout Studies for Indo-Gangetic Plain. Preliminary layout studies of pumps, irrigation piping, and associated roads and power lines were made for a

tubewell project in northwest Uttar Pradesh in the Indo-Gangetic Plain of northern India. The plain is known to have two aquifers, a shallow one and a deep one. The shallow aquifer is believed capable of providing 3.5 cusec (cubic feet per second) of irrigation water per square mile, and the layout that was developed for the study provided seven 0.5-cusec pumps of 5 hp rating for each square mile. The deep aquifer is believed sufficient to supply at least 4.5 cusec/sq mile, and possibly twice this amount. For pumping the deep

Fig. 24. Indo-Gangetic Plain Alternative 1. Internal rate of return, 14.1%; 50% production achieved during first year of operation.

Table 22. Estimates of Rural Electrification Pilot Project Costs in India

Area and State	Number of Connections ^a	System Cost (millions of dollars)	Cost per Connection (dollars)	Percentage of All Connections Made	
				Domestic	Irrigation
Kodinar, Gujarat	17,000	16.1	950	6	85
Karimnagar, Andhra Pradesh	23,765	3.9	163	50	43
Shrirampur and Pahuri Talukas, Maharashtra	16,716	2.1	127	42	47
Hukeri Taluk, Mysore	14,000	1.8	118	78	21
Lucknow, Uttar Pradesh	14,515	3.2	223	63	33

^aAfter five years.

aquifer at the 4.5-cusec rate, the layout included three 1.5-cusec pumps of 15 hp rating for each square mile; alternatively, pumps delivering 2.0, 2.5, and 3.0 cusec each were also considered.

A typical layout for 1 sq mile is shown in Fig. 25. The seven shallow well pumps each provide water for 120 acres. The drawing at the bottom of Fig. 25, which is an 8-sq-mile layout, shows how the 1-sq-mile pattern can

be repeated. Two types of road grids were provided, a primary grid on a 4- by 4-mile spacing for traffic and a service road grid on a 1- by $\frac{3}{4}$ -mile spacing. Parallel power lines are run every $\frac{3}{4}$ mile. Pumps are located along the service roads and power lines to minimize length of driveways and individual pump power lines. Enough work was done to indicate that alternative arrangements of roads, power lines, and irrigation

Fig. 25. Layout of Deep- and Shallow-Well Pumps for Ganges Plain Irrigation.

Fig. 26. Layout of Irrigation Farming Area Between the Ganges and Ramganga Rivers.

pipng for a fixed set of conditions all cost about the same (within ~20%). Further studies should be made to verify or contradict this conclusion.

A brief macro study was also made of a layout covering 2,000,000 acres between the Ganges and Ramganga Rivers northwest of Agra and Aligarh. This area was chosen because the Indian AEC has previously made studies for a nuclear power station at Norara on the south bank of the Ganges River. The layout is shown in Fig. 26. The overall area covers about 3300 sq miles and is subdivided into six subareas, each about 550 sq miles in area. Main power lines were run to a substation in each subarea and to towns with ≥ 5000 population. Feeder lines were run to the pumps and to smaller towns. The average power requirement of each subarea is about 100,000 hp [about 75,000 MW(e)]

3.8 NUCLEAR DESALINATION INFORMATION CENTER

Background

The Nuclear Desalination Information Center was initiated in 1966 with the objective of collecting technical information concerned with nuclear desalination, analyzing and compressing this information, and then providing the means whereby the scientist in the nuclear desalination field could readily identify and retrieve the information as he needed it. Current and recent publications and patents are scanned, and material pertinent to the desalination program is selected by the Center. The selected material is reviewed, an informative abstract is prepared, and

carefully chosen index terms are assigned by technical specialists who are members of the Nuclear Desalination Program staff. Retrieval of information by author, corporate author, and individual or combinations of index terms is possible through the use of a computerized storage and retrieval system.

Although the major portion of the Center's activity is concerned with the AEC's interests, support for some of the activity is provided by the OSW. Their interest lies particularly in the area of seawater distillation processes.

Publications

Two new indexed bibliographies^{37,38} (including abstracts) of nuclear desalination literature were issued during the year. These present the complete reference and an informative abstract for each of about 500 published articles and patents pertinent to the field of nuclear desalination. This brings the total number of references in the Center's storage and retrieval system to about 1000. Distribution of the bibliographies was made in accordance with a standard AEC category (UC-89) plus a selected list of organizations that have expressed a specific interest in nuclear desalination work. A number of industrial organizations and research groups at universities have requested to be

added to the distribution list since the first bibliography was issued.

A journal article describing the operation of the Center was prepared and has been submitted for publication in the open literature. A permuted title index of OSW research and development progress reports was prepared for the OSW, and a special listing of United States patents on distillation processes is being prepared for them.

Requests for Information

Interest in the Nuclear Desalination Information Center continues to increase. Whereas there were 10 requests during the first year of operation and 44 during the second year, there were 76 requests made during the past year. About two-thirds of these came from industrial and academic groups as shown below:

Industrial organizations	26
Academic institutions	24
Government agencies	14
Foreign groups	12
Total	<u>76</u>

In many cases a request for information would also include a request for the individual to be added to the distribution list for future lists of abstracts. It would appear that the individual scientist is willing to use the library for the original literature but would like to have a copy of the condensed material in the form of abstracts for his personal use.

³⁷K. O. Johnsson, *Indexed Bibliography of Nuclear Desalination Literature* - 3, ORNL-NDIC-5 (May 1969).

³⁸K. O. Johnsson, *Indexed Bibliography of Nuclear Desalination Literature* - 4, ORNL-NDIC-6 (November 1969).

4. Papers, Journal Articles, and Reports

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- J. W. Michel, "Agro-Industrial Complexes," presented at the Western Water Resources Institute Conference, St. John's College, Santa Fe, New Mexico, Apr. 9-10, 1969.
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