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Economic Evaluation of Recirculation as a
Method of Pile Cooling

AUTHOR

AB Carson/RH Purcell/LH McEwen

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Richland, Washington
April 7, 1954

R. B. Richards, Manager
Pile Technology Sub Section
ENGINEERING DEPARTMENT

This document consist of
60 pages, No. 1 of
10 copies, Series

Economic Evaluation of Recirculation as a Method of Pile Cooling.
POTENTIAL APPLICATION OF RECIRCULATING COOLING SYSTEMS

Your attention is directed to the attached report summarizing the applicability of recirculating cooling systems to Hanford type reactors. Estimates have been made of:

1. The probable limits placed on the rate of heat removal by single pass coolant operation,
2. the potential rates of heat removal by recirculating coolant operation, and
3. the relative costs of utilizing the full potential of the two systems.

On the basis of the information developed in this report, it is recommended that a detailed analysis be made of the conversion of the most promising of our present irradiation facilities, which would be a "K" Pile, to high temperature recirculation operation.

It should be noted that the estimates contained in this report are preliminary in nature, and are naturally subject to considerable refinement. The production rates which have been itemized for the various operating conditions do not represent predictions of future Hanford levels, but rather are estimates of potential heat removal rates, based on coolant considerations along, assuming

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HW-30907

Page 2

R. B. Richards

April 7, 1954

that other limits such as maximum slug power and graphite temperature do not apply. In arriving at the cost estimates included in the report, an effort has been made to include reasonable allowances for all factors affecting the relative costs of single pass versus recirculating coolant systems. These estimates thus should establish the order of magnitude of expenditures required to obtain certain operating conditions, rather than detailed cost for any specific equipment design. While the economic evaluation is adequate to demonstrate justification for high temperature, high pressure, recirculating coolant studies, the treatment has not been detailed enough to establish the feasibility of modifying the present piles under existing conditions. It is hoped that the required attention will be directed to this phase, and that technological development will proceed to the point where such pile modifications can be intelligently accomplished, should they appear economically justified.

AB Carson

Pile Technology Sub Section
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ENGINEERING DEPARTMENT

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Attachment

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Page 3

ECONOMIC EVALUATION OF RECIRCULATION
AS A METHOD OF PILE COOLING

April 5, 1954

By R. H. Purcell
Chemical Engineer
Technical Section
ENGINEERING DEPARTMENT

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I. INTRODUCTION

Reductions in irradiation costs and increases in production rate have provided a continuing incentive for more efficient operation of the Hanford Piles. These improvements have been obtained by means of higher specific powers, greater water flow rates, and better water utilization. However, the extent of the improvements which can be made in this manner may be limited by such factors as tube and slug corrosion, slug stability, and graphite damage rates at higher operating temperatures. Water purification and pumping costs are also factors to be considered. New slug designs are being developed which may be capable of much higher specific power operation. Higher graphite temperatures may also prove feasible, but the water plant performance limitations for the present single pass cooling systems may prove much more expensive to relieve. The use of recirculating cooling water as a means of attaining higher temperature, higher power operation has received preliminary study.

There are a number of potential advantages to the use of recirculating systems. Higher water purity can be maintained than is economically justified for a single pass system. Such high purity water should greatly reduce the problems of corrosion and film formation encountered at higher operating temperature. Also, the addition of radioactive waste water to the river could be avoided. Should recovery of useful power from the pile coolant appear desirable, a recirculating system would allow increases in pile inlet water temperature to a point where reasonable recovery efficiency could be attained.

The ultimate economic feasibility of employing this method of pile cooling depends on the maximum tolerable operating temperatures for single pass cooling, the maximum specific power attainable with new fuel element designs, and the relative cost of single pass and recirculating systems for the operating conditions under consideration.

A preliminary economic evaluation of an operating area equipped for recirculation versus single pass cooling is needed to better determine the relative merits of the two cooling methods. This report presents the results of such an evaluation and discusses the direction of future development work in the field of pile cooling.

II. SUMMARY

Recirculation system requirements and operating characteristics are described. Estimates are given of the costs of construction and operation of such systems for a range of flow rates and temperatures. Details of these cost estimates are presented in Appendix A.

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The operating costs of recirculating cooling systems are generally lower than single pass systems for comparable flow rates. However, due to the considerable higher construction costs per unit of flow capacity, such installations do not appear economically justified at present outlet water temperatures. When the higher potential water temperatures for the recirculation case are considered, it is evident that the investment costs per unit of irradiation capacity may become competitive with single pass systems. A number of representative cases are compared in the recapitulation table on the following page. It has been assumed in these computations that production levels are limited only by maximum attainable rates of heat removal. A detailed description of the method of analysis and of the assumptions made is given in Appendix B, "Technical Note on Pressurization of Hanford Piles", by L. H. McEwen. More complete comparison for a wider range of conditions is presented in Tables 6 through 9.

The preliminary recirculation studies which have been accomplished to date have shown that such cooling systems are technically feasible at present cooling water temperatures. In view of the potential economic application of recirculating coolant systems to the higher temperature, higher power pile operation, it is concluded that future work in the recirculation program should be directed toward such operating conditions.

III. DESCRIPTION OF A RECIRCULATION AREA

A. General

The basic recirculation area would consist of the pile and the cooling facilities to remove the heat picked up by the water passing through the piles. Also required are a small water treatment plant to treat water to be used as make-up water to the recirculation loop, fire and sanitary water, boiler feed water, and filtered water to the pile during shutdowns; disposal facilities; and the necessary pumps, piping, and valves to route the water wherever needed.

During pile operation, water will be recirculated through the recirculation loop consisting of the pile, cooling facilities, and the main pumps. The water used in the recirculation loop may be either deionized water or filtered water. The choice of the type of water will depend on the materials of construction and on pile operating conditions, especially temperature.

To lower the exposure of operating personnel to radioactivity during pile shutdowns and to prevent the contamination of the recirculation water if oil is used in charging and discharging, it is probably necessary that the water passing through the pile during the shutdown be used on a "one-pass" basis. This water would be routed to the disposal facilities.

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RECAPITULATION TABLE

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Page 6

PILE	STATUS	CAPITAL COSTS	OPERATING CONDITIONS	OPERATING COSTS \$/YR.	PRODUCTION RATE	PAY-OFF PERIOD
B, D, DR, F, & H	Single Pass After CG-558 Present tubes Minor Press.	\$700,000 for rear face work and some water plant changes	72,000 gpm flow 105°C bulk outlet 450 psi tube inlet No power recovery.	Pump. \$ 420,000 Treat. 220,000 Misc. 3,855,000 Total \$4,501,000	1760 MW, for product value \$7,920,000 per year	Base
	Recirculation Pressurized to limit of the present tubes	\$22,000,000 for rear face work and water plant changes	83,000 gpm flow 146°C bulk outlet 600 psi tube inlet Recovery possible	Pump. 607,000 Treat. 67,000 Misc. 4,235,000 Total \$4,909,000	2710 MW, for product value \$12,195,000 per year	\$23,150/MW 5.7 year pay-off
	Recirculation Pressurized to limit for new process tubes	\$31,700,000 for rear & front face work, new tubes, and water plant.	94,000 gpm flow 250°C bulk outlet 1700 psi tube inlet Recovery possible	Pump. 827,000 Treat. 75,000 Misc. 4,820,000 Total \$5,722,000	4180 MW, for product value \$18,810,000 per year	\$13,099/MW 3.3 year pay-off
C	Single pass After CG-558 Present tubes Minor Press.	\$770,000 for rear face work and some water plant changes	91,000 gpm flow 105°C bulk outlet 370 psi tube inlet No power recovery.	Pump. 457,000 Treat. 280,000 Misc. 4,041,000 Total \$4,778,000	2230 MW, for product value \$10,035,000 per year	Base
	Recirculation Pressurized to limit of the present tubes	\$24,900,000 for rear face work and major water plant changes	111,000 gpm flow 144°C bulk outlet 600 psi tube inlet Recovery possible.	Pump. 813,000 Treat. 86,000 Misc. 4,572,000 Total \$5,471,000	3560 MW, for product value \$16,020,000 per year	\$18,700/MW 4.7 year pay-off
	Recirculation Pressurized to limit for new process tubes.	\$42,800,000 for rear & front face work, new tubes, and water plant.	124,000 gpm flow 250°C bulk outlet 1700 psi tube inlet Recovery possible	Pump. 1,088,000 Treat. 96,000 Misc. 5,372,000 Total \$6,556,000	5550 MW, for product value \$24,075,000 per year	\$12,900/MW 3.5 year pay-off
K	Single pass Present tubes Minor Press.	\$900,000 for rear face work and some water plant equipment.	140,000 gpm flow 105°C bulk outlet 195 psi tube inlet No power recovery	Pump. 434,000 Treat. 480,000 Misc. 4,352,000 Total \$5,266,000	3430 MW, for product value \$15,435,000 per year	Base
	Recirculation Pressurized to limit of the present tubes	\$36,500,000 for rear face work and major water plant changes	258,000 gpm flow 141°C bulk outlet 600 psi tube inlet Recovery possible	Pump. 1,905,000 Treat. 200,000 Misc. 6,200,000 Total \$8,305,000	8100 MW, for product value \$36,450,000 per year	\$ 7,815/MW 2.0 year
	Recirculation Pressurized to limit for new	\$67,400,000 for rear & front face work, new tubes,	290,000 gpm flow 250°C bulk outlet 1700 psi tube inlet	Pump. 2,538,000 Treat. 220,000 Misc. 8,830,000 Total \$11,588,000	13,000 MW, for product value \$58,500,000	\$ 7,042/MW 1.8 year

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It is possible to construct two types of recirculation loops depending upon the temperature of the water when it leaves the pile. A non-pressurized system would be used if the outlet temperature is in the vicinity of 100 C. The loop would be pressurized at least through the cooling facilities, if higher outlet temperatures are desirable.

B. Types of Water

The facilities installed for additional treatment of the recirculation water beyond the treatment in a standard filter plant will depend on the final water quality desired. Two choices of the final water quality are filtered water and deionized water. Inexpensive treatment facilities would be required if filtered water was used. However, deionizers are needed for deionized water.

The use of deionized water would require the following equipment:

1. Make-up deionizers to deionize the make-up water to the recirculation loop. The flow rate through these deionizers is determined by the system losses and pump-seal leaks and is estimated to be from one-half to one percent of the flow around the loop.
2. Loop deionizers installed in a bypass line in the recirculation loop. These units would be used to remove the impurities picked up by the water recirculating in the recirculation loop. The flow rate through the deionizers is estimated to be up to one percent of the loop flow in a zirconium-stainless steel system. The flow rate through the deionizers would be increased if aluminum is present in the recirculation loop.

C. Overall View of the Area

A block diagram of a recirculation area using deionized water is presented in Figure 1.

IV. PRELIMINARY COST ESTIMATES OF CONSTRUCTING A RECIRCULATION AREA

A. Operating at Present Outlet Temperature Limits

To establish the feasibility of recirculation, the costs of constructing a recirculation area must be compared to the costs of a "one pass" area. The basis of comparison that will be used is the replacement cost of the water plant per design gpm. The method of calculating the estimated costs and the detailed estimated costs are presented in Appendix A.

The estimated construction cost of a 40,000 gpm recirculation area using deionized water is \$743/Design gpm. Figure 2 presents a comparison with the equivalent costs of the present areas.⁽¹⁾ From the estimated cost of

(1) Conversation with N. O. Strand

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RECIRCULATION AREA

RECIRCULATION AREA USING DEIONIZED WATER

FIGURE 1

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the recirculation area, it may be seen that recirculation is not economically feasible for the construction of a new area if it is possible to build a "one pass" system to operate under similar outlet temperature conditions.

B. Operating at Higher Temperature Limits

1. General

It is quite evident from the estimated construction costs that recirculation areas operating at present pile outlet temperatures cannot compete with 100 K Area. The way that recirculation areas may become economical is by the use of higher outlet temperatures permitted by increased water purity and reduced corrosion rates. It would, of course, be necessary to pressurize the system from the rear face through the heat exchangers or perhaps the entire loop.

2. Cost of a High Temperature Recirculation System

For the purpose of this discussion, it will be assumed that the recirculation area will operate at a " Δt " of 150 C. To compare the costs of the recirculation area with 100 K Area, the basis of comparison will be the water plant replacement cost per megawatt of power level. A reactor in 100 K Area with a flow of 140,000 gpm, with a " Δt " of 75 C is capable of reaching a power level of about 2,770 MW. The estimated cost of the water plant is \$49,000,000. The cost per megawatt is therefore, \$17,700.

It is possible to estimate the additional costs of pressurizing the necessary parts of the recirculation loop and expanding the cooling facilities for high temperature operation. The additional cost for expanding the cooling facilities is \$1,320,000. The pressurizing costs are approximately \$2,000,000.

Total costs for pressurized recirculation areas (40,000 to 140,000 gpm) operating at a " Δt " of 150 C are shown in Table II in Appendix A. This table is based on the estimated construction cost of a recirculation area using deionized water corrected for the increased flow rates. The correction factor was obtained by averaging data for nine different types of equipment.⁽²⁾

It will be observed that the cost per design gpm (\$502 to \$825) of a recirculation area is greater than the predicted \$350/Design gpm of 100 K Area. However, the cost per megawatt (\$12,700 to \$16,800) for recirculation areas of 70,000 gpm or more is less than the \$17,700/megawatt cost for 100 K Area. It is evident from this table that recirculation is economical when higher pile outlet temperatures can be obtained. For a pile designed for power recovery, the thermodynamic considerations

(2) Chilton, C.H., "Cost Data Correlated", Chemical Engineering 56, No. 6, Page 97 (1949)

ALEX. OR. HIGHLAND, WASH.

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tend toward much higher outlet temperatures than are available at the present piles.

Comparisons of water plant capital costs between recirculation areas using deionized water and "single pass" areas are presented in Table III in Appendix A. Power levels of 2770 MW and 5530 MW were chosen for the comparisons.⁽³⁾ These comparisons reveal that a 2770 MW, the water plant capital cost of the recirculation area is \$2,800,000 cheaper and at 5530 MW, it is \$4,200,000 cheaper.

V. OPERATING COSTS OF NEW RECIRCULATION AREAS

A. Operating at Present Outlet Temperature Limits

As a basis for determining operating costs, a comparison has been made between the number of operators estimated to be necessary for the operation of the recirculation system and the number of operators necessary for 100 H Area. In addition, a comparison has been made between the estimated cost of chemicals concerned in the recirculation area and the chemical costs for 100 H Area.

The detailed study is presented in Appendix A. The results indicated that the operating savings of a 40,000 gpm recirculation area using deionized water were \$93,000 per year when compared to the existing costs for 100 H Area.

B. Operating at Higher Outlet Temperature Limits

The estimated costs of operating the recirculation area at high temperatures will be approximately the same as the operating costs for the same area at low temperatures with the exception that the pumping costs, if the loop is only partially pressurized, and the maintenance costs will be somewhat higher. No attempt has been made to estimate the magnitude of these two increases. It is believed that these two increases will not be major factors in the overall cost picture.

Table III presents comparisons of operating costs between "single pass" systems and recirculating systems using deionized water operating at power levels of 2770 MW and 5530 MW.⁽³⁾ The yearly gains for the recirculating systems are \$334,700 at 2770 MW and \$669,500 at 5530 MW.

The consolidated gains of the recirculation areas using deionized water over a period of 15 years are also presented in Table III. The gain at 2770 MW including the capital gain is \$7,810,000 while the gain at 5530 MW is \$14,250,000.

(3) Personal Communication from L. H. McEwen

VI. ESTIMATED COSTS OF CONVERTING AN EXISTING AREA TO A RECIRCULATION AREAA. Operating at Present Outlet Temperature Limits1. General

Although not probable, it is possible that it will become necessary to limit the radioactivity added to the Columbia River with spent pile cooling water, to the extent that serious limitations to production levels could occur. In this event, a possible method to overcome such a limitation would be the conversion of one or more of the present areas to recirculation. The major modifications would be the construction of suitable cooling facilities plus various modifications to the area piping.

2. Estimated Costs of Converting a 50,000 GPM Area

The estimated costs of converting an existing 50,000 gpm area to a recirculation area are as follows:

<u>Facility</u>	<u>Estimated Cost</u>
Heat Exchanger	\$ 6,300,000
River Pump House	2,190,000
Make-up Deionizers	220,000
Loop Deionizers	680,000
Piping Revisions	<u>3,000,000</u>
	<u>\$ 12,390,000</u>

It can be easily seen that it is very expensive to convert an area and would only be done under extreme conditions if the operation of the recirculation loop is limited to present pile outlet temperatures.

B. Operating at Higher Outlet Temperatures

A complete study of the economics of converting any of the present pile areas to recirculation is presented in Appendix B as "Technical Note on Pressurization of Hanford Piles", by L. H. McEwen.

VII. OPERATING COSTS OF A CONVERTED AREAA. Operating at Present Outlet Temperature Limits

The operating costs of a converted area would be approximately the same as for a new recirculation area. For a converted area with a flow rate of 40,000 gpm, the savings would be approximately \$93,000 per year. Higher maintenance costs due to the larger amount of contaminated equipment may decrease the savings by a small amount.

Using the conversion costs of a 50,000 gpm area of \$12,390,000, estimated operating savings of \$116,000 per year, a pay-off period of 105 years is obtained. This long pay-off period is another reason why recirculation at present pile outlet temperatures is not economical.

B. Operating at Higher Outlet Temperature Limits

The actual operating costs will depend on the new flow and temperature conditions of the area after the conversion. Pumping costs will be increased if the area is being operated for maximum plutonium production. If the area is being operated at a power level approximately the same as the power level before conversion, then the pumping costs decrease due to the lower flow rate. Maintenance costs of the converted area should increase due to the larger amount of contaminated equipment.

Operating costs of the converted area are presented in Appendix B for each of the conditions of temperature, pressure and flow.

VIII. JUSTIFICATION OF HIGH TEMPERATURE WORK AND NEED FOR ADDITIONAL EXPERIMENTAL FACILITIES

Preliminary recirculation studies at the present pile operating conditions are now being made both in and out-of-pile to determine the technical feasibility of recirculation and the possibility of the use of recirculating water cooling systems in place of the "once through" or "single pass" cooling systems in the Hanford Reactors. These studies have shown that recirculation is technically feasible, but as discussed in this document recirculation is not economical at present pile operating conditions. However, recirculation is economical at high temperatures.

The feasibility of operation of recirculating loops at high temperatures is based on new fuel elements now being developed. These new fuel elements show promise of withstanding much more stringent operating conditions than those presently in use, especially with the high purity water which may be used economically in the recirculation loops.

Higher specific powers and thus low unit cost of product may be achieved by full utilization of such capabilities. These cooling conditions also make feasible the recovery of useful quantities of power which are wasted at present. A complete investigation of attainable operating conditions will permit an intelligent approach to pile cooling developments for the present piles as well as for new designs to replace or supplement the present installations.

To take advantage of the recent developments by the Technical Section to permit a higher pile outlet temperature, the use of higher pressures and temperatures for recirculating systems is being considered. At the present time,

some of the out-of-pile loops are being operated at temperatures in the vicinity of 175 C. The in-pile loop at 100 H Area is being modified for operation at outlet temperatures of 200 C. In addition, the recently authorized Water Studies Semi-Works, Building 1706 KE, has been scoped to contain space provisions for later installation of specialized equipment for high purity cooling water recirculation studies.

To obtain a complete investigation of the attainable operating conditions will require new facilities capable of operating at temperatures in the vicinity of 300 C. The current recirculation facilities cannot operate at these temperatures due to the high pressures necessary to suppress boiling.

Pumps are now on order to operate at 300 C for the out-of-pile loops. However, the problems of the in-pile loop cannot be solved as easily. The maximum outlet temperature is limited at a value less than 300 C by the design of the in-pile recirculating system itself.

The most economical means of obtaining a new in-pile facility would be to take advantage of the space provided in the 1706 KE Building to install one or more in-pile loops before the start-up of the 105 KE Reactor.

IX. CONCLUSIONS

From the estimated costs, it may be concluded that:

1. An area built for recirculation using present outlet temperatures limits will cost more per design gpm than the corresponding costs of 100 K Area, 105 C, 105 DR, and 100 H Area.
2. Recirculation areas operating with a pile " Δt " double the existing " Δt " and with flows of 70,000 gpm or greater cost less per megawatt of pile power than the corresponding costs of any of the present pile areas including 100 K Area.
3. The operating costs of a 40,000 gpm recirculation area operating with the existing pile outlet temperatures are \$93,000 per year less than the corresponding costs of 100 H Area.
4. The operating costs of a 40,000 gpm recirculation area operating with a pile " Δt " double the existing " Δt " are approximately the same as the costs of a "one pass" area such as 100 H Area.
5. Recirculation areas may be built and operated for less money than a "one pass" area operating at the same power level.
6. It would not be economical to convert any of the existing areas to recirculation if the existing pile outlet temperatures must be maintained.

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7. The economics of converting an area to recirculation and operating at high temperatures are most favorable at the "K" Piles, next most favorable at "C" Pile and least favorable at the older piles.
8. Small operational savings of approximately \$100,000 per year are obtained through the use of smaller amounts of water treatment chemicals when an existing area is converted to recirculation for operation at present outlet temperatures.
9. Operating costs of an area converted to recirculation for operation at high outlet temperatures will depend on the new operating temperatures and pressures.
10. Experimental work on high temperatures recirculation is justified and the recirculation program should be in this direction.

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APPENDIX AA. PRELIMINARY COST ESTIMATES OF CONSTRUCTION OF A 40,000 GPM RECIRCULATION AREA TO OPERATE AT PRESENT PILE OUTLET TEMPERATURES

Preliminary cost estimates for a recirculation area using steam condensate as the recirculating water are available from Document No. INDC-3149⁽⁴⁾. This estimate is based on assumed unit costs which might differ widely from the unit costs at the Hanford Project. Fortunately the costs of the 100 H Area water plant are presented for comparison using the same unit costs. It is then possible to compare the estimate 100 H Area costs with the actual construction costs of that area. This comparison will allow the computation of the recirculation costs on an actual basis.

It is possible to modify the estimates of the recirculation area using steam condensate to arrive at an estimated cost for a recirculation area using deionized water. This estimate may be related to actual costs through the use of the 100 H Area estimated and actual costs.

The cost data are listed in Table I. The values obtained were as follows:

<u>Estimated Recirculation</u>	<u>100 H Area</u>	
	<u>Estimated</u>	<u>Actual</u>
\$19,980,000	\$23,666,000	\$23,083,000

Corrections to Estimated Costs

In order to place the estimated cost of the recirculation areas on the same basis as the actual cost of 100 H Area, the costs of the recirculation areas must be lowered by the percentage that the estimated costs of 100 H Area exceed the actual costs.

The results are:

<u>Recirculation</u>	<u>100 H Area</u>	
	<u>Estimated</u>	<u>Actual</u>
\$19,490,000	\$23,083,000	\$23,083,000

(4) Giffles, R.F., "Water Study Report for GED-13, Process Water Recirculation". INDC-3149, May 16, 1949.

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HW-30907
Page 17

The water plant at 100 H Area is capitalized at \$29,075,000. The increase over the actual costs shown in the table is due to design costs, other indirect costs and overhead. The percentage increase is 26 percent. The capitalized value of the recirculation area would therefore be approximately 26 percent greater than the estimated costs for a capitalized value of \$24,560,000 for the deionization area.

To compare the costs of the recirculation areas and the present pile areas, the Water Plant Replacement Cost/Design gpm may be used as a basis. The correction due to inflation since 1949 is 21 percent. The replacement costs of the recirculation areas would be 21 percent greater than the capitalized value or a total replacement cost of \$29,710,000 for deionization. Based on a design gpm of 40,000, the replacement cost of the recirculation areas is \$743/Design gpm. Corresponding values for the present areas are 100 D - \$1,140, 100 B - \$1,000, 100 F - \$985, 100 H - \$734, 105 DR - \$640, 105 C - \$486, and 100 K - \$350⁽¹⁾.

(1) N. O. Strand, op. cit.

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TABLE I

ESTIMATED CONSTRUCTION COSTS OF A RECIRCULATION
AREA - DEIONIZED WATER

<u>FACILITY</u>	<u>ESTIMATED COSTS - ASSUMED UNIT COSTS⁽⁴⁾</u>		<u>ACTUAL COSTS⁽⁵⁾</u>
	<u>RECIRCULATION</u>	<u>100 H AREA</u>	<u>100 H AREA</u>
a. River Pump House			
Construction	\$ 497,000	\$ 811,000	
Mechanical	710,000	429,000	
Electrical	130,000	186,000	
TOTAL	<u>\$ 1,337,000</u>	<u>\$1,426,000</u>	<u>\$1,198,000</u>
b. Heat Exchangers			
Construction	\$ 414,000	Not Present	Not Present
Mechanical	2,849,000		
Electrical	30,000		
TOTAL	<u>\$ 3,293,000</u>		
c. Filter Plant			
Construction	\$ 462,000	\$2,456,000	
Mechanical	331,000	2,258,000	
Electrical	24,000	360,000	
TOTAL	<u>\$ 817,000</u>	<u>\$5,074,000</u>	<u>\$5,188,000</u>
d. Process Pump House			
Construction	\$ 314,000	\$1,047,000	
Mechanical	1,913,000	2,240,000	
Electrical	224,000	730,000	
TOTAL	<u>\$ 2,471,000</u>	<u>\$4,017,000</u>	<u>\$4,424,000</u>
e. Power House			
Construction	\$ 699,000	\$ 699,000	
Mechanical	2,715,000	2,715,000	
Electrical	159,000	159,000	
TOTAL	<u>\$ 3,573,000</u>	<u>\$3,573,000</u>	<u>\$3,006,000</u>

(4) R. F. Giffles, op. cit.

(5) Design and Construction History, Project C-165 A Pile Area H, HW-24800-2, June, 1952.

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TABLE I (Continued)

<u>FACILITY</u>	<u>ESTIMATED COSTS - ASSUMED UNIT COSTS</u>		<u>ACTUAL COSTS</u>
	<u>RECIRCULATION</u>	<u>100 H AREA</u>	<u>100 H AREA</u>
f. Make-up Deionizers			
Construction	\$ 30,000	Not Present	Not Present
Mechanical	80,000		
Electrical	<u>3,000</u>		
TOTAL	<u>\$ 113,000</u>		
g. Loop Deionizer			
Construction	\$ 60,000	Not Present	Not Present
Mechanical	291,000		
Electrical	<u>125,000*</u>		
TOTAL	<u>\$ 476,000</u>		
*Primarily complex instrumentation and control.			
h. Primary Substation			
Construction	\$ 53,000	\$ 53,000	
Mechanical	8,000	8,000	
Electrical	<u>473,000</u>	<u>470,000</u>	
TOTAL	<u>\$ 534,000</u>	<u>\$ 531,000</u>	<u>\$1,203,000</u>
i. 1500 Area Lighting			
	\$ 1,440,000	\$1,440,000	\$1,104,000
Transmission lines, fire alarms, telephones, etc.			
j. 1600 Area - General Facility			
	\$ 608,000*	\$1,250,000	\$ 933,000
Ties, road, fences, railroads, etc.			
*Corrected for addition of septic tanks and process waste lift station.			
k. 1700 Area Administrative & Service Building			
	\$ 1,425,000	\$1,425,000	\$1,321,000

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DECLASSIFIEDTABLE I (Continued)

<u>FACILITY</u>	<u>ESTIMATED COSTS -</u> <u>RECIRCULATION</u>	<u>ASSUMED UNIT COSTS</u> <u>100 H AREA</u>	<u>ACTUAL COSTS</u> <u>100 H AREA</u>
l. 1800 Area - Outside Pipe Lines and Condensate Return Lines	\$ 246,000	\$ 401,000	\$ 328,000
m. 1900 Area - Outside Under- ground Pipe Lines	\$ 2,921,000*	\$2,919,000	\$2,440,000
*Corrected for emergency lift station and fire and sanitary elevated storage tanks.			
n. 182 Reservoir and Pump House	Not Present	\$1,610,000	\$1,938,000
o. Disposal Basin	\$ 726,000	Not Present	Not Present
	<u>\$19,980,000</u>	<u>\$23,666,000</u>	<u>\$23,083,000</u>

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B. OPERATING COST OF RECIRCULATION AREAS AT PRESENT OUTLET TEMPERATURES1. Operating Personnel

The estimated number of operating personnel for the recirculating water plants is as follows: (4).

<u>Building or Facility</u>	<u>Operators</u>
River Pump House and Heat Transfer Building	6
Filtration Building	10
Power House	22
Deionizers	10
Process Pump House	<u>14</u>
Sub Total	62
Supervision and Clerical	<u>15</u>
TOTAL	<u>77</u>

There are now 77 people in the Power and Water Facilities at 100 H Area. (6)
They are divided as follows:

<u>Shift Workers</u>	
181 River Pump House	4
182 Reservoir and Pump House	4
183 Filter Plant	18
184 Power House	12
190 Process Pump House	15
Supervisors	<u>4</u>
Total Shift Personnel	<u>57</u>
<u>Day Workers</u>	
Operators	15
Supervisors and Clerical	<u>5</u>
Total Day Personnel	<u>20</u>
TOTAL PERSONNEL	<u>77</u>

(4) R. F. Giffles, op. cit.

(6) Conversation with C. E. Harkins

The number of operators in the recirculation area is smaller than the number in 100 H Area, but the number of supervisors is larger. It is entirely possible that the number of supervisors might be reduced. However, this reduction might result in an increase in the number of operators through the addition of Chief Operators. It will suffice to say that the number of personnel needed to operate either a recirculation area or a "one pass" area is almost the same.

2. Chemical Costs

The average monthly chemical costs in 100 H Area (based on the year 1952) and the estimated monthly chemical costs for recirculation areas using deionized water are:

<u>Chemical</u>	<u>100 H Area (7)</u>	<u>Recirculation Area*</u>
Chlorine	\$ 726	\$ 726
Ferrifloc	4,640	183
Line	717	26
Sodium Chloride	240	313
Sodium Phosphate	28	28
Sodium Dichromate	3,630**	0
Solids (Pile Purging)	50	0
Solids (Boiler Purging)	94	94
Sulfuric Acid	0	345
Resin	200***	1,170***
	<u>\$10,325</u>	<u>\$2,585</u>

*Estimates modified from condensate estimates presented in Document INDC-3149.

**Average monthly cost for period that sodium dichromate was used.

***Based on 5 percent replacement per year.

The monthly savings of a recirculation area using deionized water are \$7,740 or a yearly savings of \$93,000.

3. Additional Operating Costs

The cost of maintenance work in a recirculating loop will be higher than on a "one pass" system due to the larger amount of contaminated equipment. The actual increase is not known nor can it be reasonably estimated.

(7) Conversation with G. W. Wells

DECLASSIFIEDTABLE IIESTIMATED COST OF A RECIRCULATION AREA USING DEIONIZED
WATER OPERATING AT A PILE " Δt " OF 150 C

<u>FLOW RATE</u> <u>GPM</u>	<u>COST EXPANSION</u> <u>FACTOR</u>	<u>WATER PLANT</u> <u>COST</u>	<u>COST/DESIGN GPM</u>	<u>POWER LEVEL</u> <u>MW</u>	<u>COST/MW</u>
40,000	1	\$33,000,000	\$ 825	1580	\$ 20,900
50,000	1.14	37,600,000	752	1980	19,000
60,000	1.28	42,200,000	703	2370	17,800
70,000	1.40	46,200,000	660	2770	16,700
80,000	1.52	50,200,000	628	3160	15,900
90,000	1.63	53,800,000	598	3560	15,100
100,000	1.74	57,400,000	574	3950	14,500
110,000	1.84	60,700,000	552	4350	14,000
120,000	1.94	64,000,000	533	4740	13,500
130,000	2.04	67,300,000	518	5140	13,100
140,000	2.13	70,300,000	502	5530	12,700

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DECLASSIFIEDTABLE III(3)COMPARISON OF CAPITAL AND OPERATING COSTS FOR ONE PASS AND RECIRCULATION WATER PLANTSGeneral Data

Power Level in MW	2,770	2,770	5,530	5,530
Flow in gpm	140,000	70,000	280,000	140,000
Pile in °C.	75	150	75	150

Capital Cost Data

Capital Cost of Water Plant	\$49,000,000	\$46,200,000	\$74,500,000	\$70,300,000
Gain in Capital Cost		\$ 2,800,000		\$ 4,200,000

Operating Costs

Labor	Same	Same	Same	Same
Pumping	Same	Same	Same	Same
Maintenance	Small	Large	Small	Large
Chemical/year	\$389,800	\$55,100	\$779,600	\$110,200
Yearly Gain		\$334,700		\$669,400

Consolidated Gains

15 Years of Operating Costs	\$5,010,000	\$10,050,000
Capital Cost Gain	<u>2,800,000</u>	<u>4,200,000</u>
TOTAL GAIN	\$7,810,000	\$14,250,000

(3) L. H. McEwen, op. cit.

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DECLASSIFIEDAPPENDIX BTECHNICAL NOTE ON PRESSURIZATION OF HANFORD PILES**I. INTRODUCTION**

At the present time, all existing or scheduled Hanford Piles operate with the bulk effluent temperatures below 100°C and discharge effluent water at atmospheric pressure. This is a necessary condition for operation of these piles, but only because of the nature of the structures for handling the effluent stream. By changing these structures, higher temperature effluent water can be accommodated. This report deals with aspects of pressuring the effluent system and operating Hanford Piles with process tube exit temperatures above 100° C.

II. SUMMARY AND CONCLUSIONS

Existing data concerning hydraulic characteristics of existing slug and tube geometries are fairly firm. Existing data concerning high temperature creep strength limitations of present process tubes are much less firm. Combination of these two sorts of data permits calculation of maximum possible water flow and outlet temperature for existing slug and tube systems. Calculations of this sort were made, taking a rather optimistic view of the high temperature tube strength data, and from these the power level and power recovery potential for pressurizing the existing piles are secured.

Because these potentials have been computed without reference to other potential limits to power level, such as slug service, tube corrosion, graphite effects, shielding wear and distortion, and thermal expansion problems, the potentials as computed cannot be attained without prior solution to the other potential limiting problems. This fact must be borne in mind when reviewing the results of this study.

Using rather approximate methods, the capital costs necessary for application of pressurization techniques to the piles were estimated. These costs, together with pile operating expenses and power level and power recovery values, act to determine the economic gains assignable to pressurization.

The computed economic gains are summarized in Tables Nos. 7, 8, and 9. As can be seen, cases have been computed for pressurization with: (1) one-pass and recirculatory water flow, (2) the three different sorts of piles at Hanford, (3) existing process tubes and process tubes of higher pressure rating, and (4) with and without power recovery. From a study of the table, the following general conclusions can be drawn:

1. Pressurization and power recovery schemes require substantial capital investment. (Up to \$150,000,000)
2. Pressurization techniques make possible the achievement of high power levels otherwise unattainable. (3500 MW to 13,00 MW at "K" Pile for example)

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3. High temperature pressurization with recirculated water is the most likely means of attaining extremely high power levels.
4. Pressurization without concurrent power level increase or power recovery is not particularly attractive.
5. Pressurization with concurrent power level increase is competitive with new construction, of existing types, as a means of increasing production.
6. Within the limits of present ability to estimate the cost of low pressure power recovery equipment, power recovery is economically feasible from the pressurized systems examined.
7. Economics of pressurization are most favorable at the "K" Piles, (about 3 year pay-off), next most favorable at "C" Pile, (about 4 year pay-off), and least favorable at the older piles. (about 5 year pay-off).

III. DETAILS AND DISCUSSION

A. Basic Principles of Pressurization

It is postulated that the slugs, tubes, shielding, and graphite can hold up under any conditions of heat generation, then the limit to pile power level becomes simply the limit at which heat can be removed from the pile. Utilizing liquid water as a coolant, such a limit depends only on the pile cooling water flow rate, and the temperature rise during its passage through the pile.

Ignoring pre-cooling, the inlet water temperature can be anywhere between river water temperature and the maximum allowable front shield temperature. The outlet water temperature, for liquid phase flow, must be lower than the boiling point at the pressure existing in the effluent piping system. For any given tube and slug geometry, the maximum obtainable flow rate depends on the maximum allowable tube inlet pressure and the pressure in the rear header. With the pile inlet temperature fixed for some particular reasons, it can be seen that the attainment of a large temperature rise in the pile is at the expense of the attainable flow rate since increases in permissible effluent temperature require increases in rear header pressure and lower pressure drops in the process tubes. It turns out, however, that the allowable exist temperature is increased markedly by modestly increased effluent pressures, whereas the attainable flow rate is decreased only slightly by modest decreases in tube pressure drop. On net balance, therefore, pressurization of the effluent system will increase the capability of removing heat from the pile.

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HW-30907
Page 27

B. Main Advantages of Pressurization

By increasing the capability of the cooling system to remove heat, three main advantages result. The first advantage is that pressurization permits increases in power level up to the hydraulic limit of the pile structure, providing the slugs, tubes, graphite and shielding are or can be made suited to these power levels. This type of operation acts to minimize the costs of irradiation in any particular facility, to increase total production, or to permit retirement from service of less efficient units.

The second advantage of pressurization is that for any particular power level, which may be limited by slugs, tubes, graphite or shielding, there will be a lower gallonage flow rate, and this may lower pumping costs or water treatment costs. Whether or not these cost advantages will actually result depends considerably on the details of the particular case in question.

The third advantage of pressurization is that by increasing the effluent temperature, the feasibility of the economical utilization of waste heat for electric power production is considerably enhanced.

C. Main Disadvantages of Pressurization

Aside from the cost of making any pile into a pressurized pile, there are three main disadvantages to pressurized operation. The first and most important disadvantage is that the high coolant temperatures require some successful combination of slugs, tubes, and coolant. From information now at hand, there exists serious doubts as to the ability of the present slug-tube-coolant combination to guarantee satisfactory performance at high effluent temperatures. With present slugs and tubes, it is quite likely that very pure water will be required for high effluent temperatures. Since very pure water is costly, the use of this sort of water almost inevitably calls for re-use of the pure water by post-pile cooling and subsequent recirculation. This method requires expensive heat exchangers and deionizers. Unfortunately, information now at hand does not clearly indicate the upper temperature limit for one-pass water, and this makes difficult any determination of the conditions under which recirculation is mandatory and single pass flow not applicable. The situation is even less clear when considering new slugs, tubes, or both. About the best that can be said is that for any slug and tube situation which can or may exist, recirculated high-purity water will permit higher effluent temperatures than will one-pass low-purity water. In this report, and for purposes of comparison only, it is assumed that recirculated water is required for operation at bulk pile outlet temperatures greater than 120° C.

The second main disadvantage of pressurization is that it creates a new effluent water disposal problem. Existing and planned facilities call for

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atmospheric discharge, retention, and disposal of effluent. With effluent temperatures above the atmospheric boiling point, disposal of one-pass effluent to the river will require cooling of effluent to less than 100° C, or else the questionable practice of releasing vast quantities of steam to the atmosphere near the production areas. If the one-pass effluent must be cooled to below 100° C, by dilution or other heat exchange method, it becomes apparent that the total gallonage of thru-the-pile flow plus effluent coolant will be the same, at any power level, for a pressurized pile as for a non-pressurized pile. The pressurized pile maintains an advantage, however, since its effluent coolant or dilution stream need only be raw water. In the non-pressurized pile, the entire flow probably would have to be of treated water.

Different circumstances arise when recirculated water is used. The effluent must be cooled in heat exchangers, rather than by dilution. Such heat exchangers must be large because they must cool the effluent to some satisfactory pile inlet temperature, rather than merely to some temperature just below 100° C for easy disposal. For such piles, the raw water effluent cooling flow must be as great as the pile throughput flow rate for a non-pressurized system of the same power level. The cost of the heat exchangers and raw water pumps and piping for such a cooling system will not be insignificant, but to offset this somewhat, the raw water treating costs will be small and the raw water pressure drop will be much lower than for the same gallonage flow through the process tubes.

The third main disadvantage of pressurization lies in its increase of mid-pile cooling water temperature. Effluent outlet temperature is probably of most significance when corrosion is considered, but mid-pile coolant temperature is important when uranium core temperatures are considered. For any particular slug and tube system, at any particular power generation rate, the pressurized pile will have a higher uranium core temperature than the non-pressurized pile. Thus, if uranium core temperature is a true limit to power level, the pressurized pile is at a disadvantage.

D. Pressure Considerations

Present and proposed operation of existing or scheduled piles considers flow rates lower than those limited by the hydraulic characteristics of the process tubes and standard slug loading⁽¹⁾. For new or hypo-

(1) Throughout this report it is assumed that in existing and scheduled piles, the diameter and length of the slug train will be the same as that now in use or scheduled. There is possibly a small amount of latitude in slug diameters for existing or scheduled process tubes, and a greater latitude in slug train length. These two possibilities have been ignored in this report, but only to make the calculations easy. Adjustments of slug diameter and charge length are possible and will certainly act to alter the hydraulic characteristics of the slug-tube systems.

DECLASSIFIED

ROUGH DRAFT

HW-30907
Page 29

thetical arrays of slugs and tubes, the hydraulic characteristics are under the control of the designer. For the existing piles, however, with the shield entry holes in place, the designer does not have an entirely free hand. New tubes can probably be made that can handle high pressure and temperature. Unfortunately, the tube strength increases as the tube thickness increases, and reactivity decreases as slug diameter decreases. With the tube O. D. fixed by the shield entry holes, it thus would appear difficult to create a re-tubed pile with better pressure drop versus flow characteristics than in the existing piles. The possibility of securing better pressure drop-flow characteristics by using smaller, enriched uranium slugs, is probably feasible, but is ignored. Any re-tubing program discussed in this report is considered to alter the pressure versus temperature characteristics of the present system, but not the pressure versus flow characteristics.

There are four pressure characteristics of particular importance in the application of pressurization to existing slug and tube systems. These are: (1) pressure drop between van stone flanges versus tube flow, (2) pressure drop from rear van stone flange to rear header versus tube flow, (3) allowable tube pressures, and (4) pressures required at rear header entry point to suppress boiling in the process tubes. These are discussed separately below.

Approximate van stone to van stone pressure drops versus flow rate for the three Hanford annuli are shown in Figure No. 3. These curves make no allowance for temperature effects on water density or viscosity and are approximations only.

For pressurization it is advantageous to minimize the pressure drop between rear van stone and rear header. Since all pressurization schemes discussed in this report will require revision of rear face piping components of existing piles, the assumption has been made that any pressurization scheme will use rear pigtails substantially equivalent to those to be supplied for the "K" Piles. Approximate pressure drop-flow relationship for this type of pigtail is indicated in Figure 4.

The allowable tube pressure, based on creep strength, is temperature sensitive and can possibly be pushed as high as 600 psig for temperatures as high as 80° C. Data for the higher temperature regions are shown in Figure No. 5. These data are not held to be extremely precise, and Figure No. 5 should not be taken to be much more than a rough estimate. Reliable data for temperatures between 60° C and 120° C are not available. In the calculations in this report it is assumed that if the tube inlet pressure is at the allowable limit and the tube outlet pressure at the allowable limit, all other portions of the tube are within the allowable limit. This is not necessarily so, and the lack of better information pertinent to this situation weakens considerably the calculations based on allowable tube pressure. This weakness should be well understood.

DECLASSIFIED

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30

HW-30907

The curve for K Ale is in error. the error does not affect the general conclusions of this report. A separate report considering the application of pressurization to K Ale is now in process of preparation

FIGURE 3
PRESSURE DROP - FLOW RELATIONSHIPS
PROCESS TUBES

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31

HW-30907

FIGURE NO. 4
PRESSURE DROP - FLOW RELATIONSHIPS REAR PIGTAILS

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32

HW-30907

FIGURE NO. 5
ALLOWABLE PROCESS TUBE PRESSURES
B, C, D, DR, F, H, & K TUBES

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The last pressure effect of interest is the quench pressure required to suppress process tube boiling. The designer has some freedom in the selection of this pressure, and in this report, the following rules are used.

1. The temperature rise in the process tube of highest outlet temperature will be 10/9 of the bulk pile temperature rise. This corresponds to a 90 percent water utilization efficiency.
2. Sufficient pressure must be available at the outlet of the rear pigtail to prevent boiling in the process tube of maximum outlet temperature, even when the flow in that tube drops 10 percent.

As can be seen, the quench pressure requirements is stipulated for the end of the rear pigtail and for a temperature rise of 123.5 percent of the average for the pile. The allowable tube pressure, on the other hand, is stipulated for the rear van stone and for a temperature rise for the pile as a whole. Thus, these pressures pertain to two different points and two different temperatures. The relationships between these are a little complicated, but act to determine the allowable outlet temperature for any pressurization scheme. Knowing the allowable rear van stone pressure as a function of average effluent temperature, the comparable allowable pressure at the end of the rear pigtail will be lower by the pigtail pressure drop and will thus depend on flow rate. The required quench pressure, on the other hand, depends on inlet temperature for any particular bulk outlet temperature. These relationships are shown on Figure No. 6. Maximum allowable bulk pile outlet temperatures are indicated by intersections of curves of allowable pressure and required pressure. It is seen that the maximum allowable bulk pile outlet temperature with existing tubes depends somewhat on tube flow rate and inlet water temperature, but is typically between 140° C and 150° C.

E. Inlet Temperature Effects

River temperature determines the lower limit to pile inlet temperature. Front shield wear determines the upper limit of inlet temperature. On existing piles, the masonite-steel or concrete front shielding cannot stand continuous temperatures much in excess of 80° C without serious deterioration. How much deterioration can be tolerated is a moot point, and much could be written about 90° C, for example, as opposed to 80° C as a maximum inlet temperature. Nevertheless, 80° C is used in this report as the maximum allowable inlet water temperature for existing piles. For piles yet to be built, it seems reasonable to count on design adequate to cope with any inlet temperature.

Achievable inlet water temperatures depend on whether the flow system is one-pass or recirculatory. For one-pass systems, river water temperature is achievable. For recirculatory systems, river water is used

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HW-30907

34

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FIGURE NO. 6
ALLOWABLE AND REQUIRED DOWNSTREAM
PRESSURES

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to cool the recirculated stream, and the recirculated water cannot, in a practical sense, be brought closer than 10°C to the river water temperature.

Whether the inlet water temperature should be maintained as low as possible or as high as possible depends on whether power recovery is sought. Maintaining high inlet temperatures maximizes the amount of electric power recoverable per unit of heat generated in the pile. On the other hand, this is done at the expense of lowering considerably the amount of heat which can be removed from the pile at any particular flow rate and effluent temperature. Such considerations are most important for piles not yet built where permissible inlet temperatures can be varied between, say, 12°C or 22°C to perhaps 250°C . For existing piles, where the variation is only between 12°C or 22°C and 80°C , inlet temperature exerts a modest effect on power recovery potential, but a large effect on maximum power level.

F. Scope of Modifications to Existing Piles

The nature of the modifications to existing piles for application of pressurization depends on the factors enumerated below:

- a. One-pass or recirculated water.
- b. Effluent cooling by dilution or by heat exchange.
- c. Power recovery from or complete throw-away of heat.
- d. Existing slugs and tubes or new slugs and tubes.

Pressurization schemes have in common the general re-working of pile components which handle effluent streams. In most cases, the rear pig-tails, headers, risers, crossovers, downcomers, and effluent disposal piping to some out-of-pile use point must be made suitable and strong enough for the necessary pressures and should be sized for minimum pressure drop. The exception to the above arises from the possibility that a small degree of pressurization can be effected by field-expedient techniques. As an example of this, consider (1) the installation of throttles at each end of each rear header, (2) removing charges from the extreme near and far columns of fringe tubes, (3) retubing these columns with corrosion resistant pipes, and (4) supplying such pipes with river water for cooling the rear header flows to 95°C . Such a system would act to increase rear header pressures and would add effluent dilution water upstream of the throttles. Providing the pigtails and headers can stand the pressure and the risers, crossovers, and downcomers can stand the flows, no other modifications are required. This sort of technique can be applied in many different ways, and the case described above is only an example of what can be done at modest cost. Field expedient techniques have limits, and for more extensive pressurization, it is considered that the effluent piping out to some out-of-pile use point must be under pressure. Figures Nos. 7 through 12 indicate the nature of the flow arrangements necessary for more extensive pressurization, with and without recirculation, with and without new process tubes, and with and without power recovery. Table No. IV, based on

Existing Tubes
One Pass Flow
Heat Throw-Away
Field Expedient Pressurization

Pressure Code:
Near Atmospheric —
About 50 psi —X—
About 150 psi —Δ—
About 700 psi —O—

36

FIGURE 7
PROCESS ARRANGEMENT
SCHEME A

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HW-30907

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Existing Tubes
One Pass Flow
Heat Throw-Away
Pressurization to Tube
Strength Limit

Pressure Code:

Near Atmospheric ———
About 50 psi —X—
About 150 psi —Δ—
About 700 psi —O—

FIGURE 8

PROCESS ARRANGEMENT
SCHEME B

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37

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HW-30907

FIGURE 9
PROCESS ARRANGEMENT
SCHEME C

Pressure Code:

Near Atmospheric

About 50 psi

About 150 psi

About 700 psi

Existing Tubes

One Pass Flow

Power Recovery

Pressurization to

Tube Strength Limit

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38

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HW-30907

Existing Tubes
Recirculation
Heat Throw-Away
Pressurization to Tube
Strength Limit

Pressure Code:
Near Atmospheric —
About 50 psi —X—
About 150 psi —Δ—
About 700 psi —O—

FIGURE 10
PROCESS ARRANGEMENT
SCHEME D

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39

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HW-30907

FIGURE 11

PROCESS ARRANGEMENT
SCHEME E

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New Tubes
Recirculation
Power Recovery
Pressurization to Tube
Strength Limit

Pressure Code:

Near Atmospheric

About 50 psi

About 150 psi

About 700 psi

Between 1100 & 1700 psi

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41

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HW-30907

FIGURE 12

PROCESS ARRANGEMENT
SCHEME F

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TABLE NO. IV

SCHEDULE OF REQUIRED MODIFICATIONSPRESSURIZATION DESIGNATION

CHIEF FEATURES

LOCATION OF FLOW ARRANGEMENT SKETCH

LOCATION OF COST ANALYSIS

REQUIRED MODIFICATIONSPILE AND PILE PIPINGPIPING, PUMPS TO FRONT RISES

Existing, 700 psi nominal
New, 1700 psi nominal

FRONT RISES, HEADERS, NOZZLES, PICTAILS

Existing, 700 psi nominal
New, 1700 psi nominal

PROCESS TUBES

Existing, 600 psi nominal at 20°C
New, 1700 psi nominal at 250°C

REAR PICTAILS AND NOZZLES

Existing, small
New, large, 150 psi nominal
New, large, 1100 psi nominal

REAR HEADERS

Quench admission gear
Throttles
Existing, 50 psi nominal
New, 150 psi nominal
New, 1100 psi nominal

REAR RISES, CROSSOVER, DOWNCOMER, ETC.

Existing, atmos. nominal
New, 150 psi nominal
New, 1100 psi nominal

HIGH HEAD PROCESS PUMPS

Existing, 600 psi nominal
New, 700 psi nominal
New, 1800 psi nominal

WATER TREATMENT EQUIPMENT

Existing facilities
Additions, but of existing type
Make-up pump
Storage
De-ionizing facilities

POWER RECOVERY APPARATUS

Turbines
Generators
Feed water pump

HEAT EXCHANGE EQUIPMENT

Rear face quench addition gear
Out-of-pile quench addition gear
Vapor generator, 150 psi nominal
Vapor generator, 1100 psi nominal
Condenser, 1.5 inches mercury nominal
Primary effluent cooler, 150 psi
Secondary effluent cooler, 150 psi
Secondary effluent cooler, 1100 psi

RAW WATER SYSTEM

Additional pumps, 50 psi nominal
Additional pumps, 150 psi nominal
Transfer piping, pumphouse to use point
and return

HIGH PRESSURE PIPING

Use point to process pumps, 150 psi
Use point to process pumps, 1100 psi

<u>a</u>	<u>b</u>	<u>c</u>	<u>d</u>
Existing Tubes	Existing Tubes	Existing Tubes	Existing Tubes
One-Pass Flow	One-Pass Flow	One-Pass Flow	Recirculatory Flow
Heat Throw-away	Heat Throw-away	Power Recovery	Power Recovery
Field Expedient Pressurization	Pressurization to Tube Strength Limit	Pressurization to Tube Strength Limit	Pressurization to Tube Strength Limit
See Figure 7	See Figure 8	See Figure 9	See Figure 10
Case 1 Tables 7, 8, & 9	Case 2 Tables 7, 8, & 9	Case 2 Tables 7, 8, & 9	Cases 3 & 4 Tables 7, 8, & 9

Item No.	Required Items	Required Items	Required Items	Required Items
1	1	1	1	1
2				
3	3	3	3	3
4				
5	5	5	5	5
6				
7	7	8	8	8
8				
9				
10	10			
11	11			
12	12			
13		13	13	13
14				
15	15			
16		16	16	16
17				
18	18			
19		19	19	19
20				
21	21			
22		22	22	
23				23
24				24
25				25
26			26	
27			27	
28			28	
29	29	30	30	
30			31	
31				
32			33	
33				34
34				
35				
36				
37	37		37	37
38		38		
39		39	39	39
40				40
41				

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Existing Tubes	Respiratory Flow	Heat Throw-away	Pressurization to Tube Strength Limit	See Figure 11	Cases 3 & 4 Tables 7, 8, & 9	Required Items
Flow	Recovery	Power	Pressurization	See Figure 12	Cases 5, 6, & 7 Tables 7, 8, & 9	Required Items

1	2	3	5	8	13	16	19	23	25	26	27	28	31	33	35	36	37	39	40
---	---	---	---	---	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----

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Figures Nos. 7 through 12, details the scope of the modifications necessary for these same schemes of pressurization.

G. Cost of Modifications to Existing Piles

The cost of equipment modifications and additions perculiar to the re-circulation of the pile coolant have been estimated by others. These costs concern the necessary high pressure process pumps (Item 19 and 20, Table No. IV.), recirculation gear (Items 23, 24, and 25), effluent cooling heat exchangers (Items 34, 35, and 36), and high pressure recirculation piping (Items 1, 2, 40, and 41). Such costs also concern the portion of the raw water pumps and transfer lines (Items 37 and 39) which pertain to recirculation and not to power recovery.

The other costs of pile modifications have been estimated by the writer and are discussed in detail below:

1. Field Expedient Pressurization

This consists of added raw water pumps, rear face distribution facilities to feed raw water into each end of each rear header, and throttles on each end of each header. Use will be made of existing piping to connect raw water pumps with 105 Building distribution facilities. Estimated order-of-magnitude costs are as follows:

TABLE V.

COSTS OF FIELD EXPEDIENT PRESSURIZATION

<u>Pile</u>	<u>Quench Flow gpm</u>	<u>Throttles</u>	<u>Pumps & Fittings</u>	<u>Total</u>
B,D,DR,F, H.	9,000	\$100,000	\$600,000	\$700,000
C	11,000	100,000	670,000	770,000
K	17,000	150,000	750,000	900,000

2. Front & Rear Face Pressurization

Data for a projected case of installing new rear headers, pigtails, and nozzles at "H" Pile indicated that a total cost of \$1,500,000 would be incurred. Complete pressurization of a 2,000 tube pile would require this plus pressurized risers, crossover pipe, downcomers, effluent line to out-of-pile use point and a quench dilution facility. By order of magnitude, this is about equivalent to the pigtail-header-nozzle project, and should cost about the same, so the entire pressurization job should cost about \$3,000,000 if present tubes are retained.

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Comparable pressurization work on the front of a pile should cost about one-half as rear-face work. Naturally, extra costs will be incurred for higher degrees of pressure, and for larger piles.

These costs are summarized in Table No. VI.

3. Re-Tubing

Costs to re-tube a pile are hard to compute with precision. A very approximate calculation is given below:

<u>Work Description</u>	<u>Per Tube Required Time in Minutes</u>
Unbutton front nozzle and adjust flow	5 Minutes
Discharge metal	5 Minutes
Remove nozzles	10 Minutes
Push old tube and cut up	60 Minutes
Remove expansion keys	60 Minutes
Grind graphite channel	20 Minutes
Insert new tube	10 Minutes
Van stone rear	20 Minutes
Install nozzles	10 Minutes
Recharge new metal	5 Minutes
Cap up and set to normal	<u>5 Minutes</u>
TOTAL	210 Minutes
Allow for contingencies	<u>30 Minutes</u>
TOTAL	<u>240 Minutes</u>

Thus, approximately 4 hours are allowed for removal and replacement of one tube. Assuming four tubes being handled simultaneously, there will be 2,000 hours of down time, or 83 days. This down time, for piles rated at 1,400 MW and \$15 charged for each MW of lost production, will be worth \$1,740,000.

Assuming: (1) 2 Hour rear face time limit, (2) front face crews made from almost-burnt-out rear face crews, (3) rear face continuous crew of 12 men for 4 process tube work points, (4) 10 Man front work area service crew, and (5) four man continuous HI coverage, there will be 62 direct labor man days per shift. At \$5.00 per man hour, this amounts to \$620,000 for an 83 day operation.

Nozzles, tubes, and pigtails for "K" Pile cost \$167 per process tube. Assuming that high pressure replacements cost twice as much, or \$334, the cost for a 2,000 tube pile will be about \$670,000.

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TABLE VI

COST OF FRONT & REAR FACE PRESSURIZATION

<u>ITEM</u>	<u>2000 TUBE PILE</u>		<u>3200 TUBE PILE</u>	
	<u>700 Psi Front</u> <u>150 Psi Rear</u> <u>Nominal</u> <u>Pressure</u>	<u>1700 Psi Front</u> <u>1100 Psi Rear</u> <u>Nominal</u> <u>Pressure</u>	<u>700 Psi Front</u> <u>150 Psi Rear</u> <u>Nominal</u> <u>Pressure</u>	<u>1700 Psi Front</u> <u>1100 Psi Rear</u> <u>Nominal</u> <u>Pressure</u>
ear pigtails, headers, nozzles	\$ 1,500,000	\$ 1,500,000	Existing	\$ 1,500,000
Add for extra size			Equipment	500,000
Add for extra pressure		500,000	Suitable	500,000
TOTAL	<u>\$ 1,500,000</u>	<u>\$ 2,000,000</u>		<u>\$ 2,500,000</u>
ear risers, cross-over, downcomer	1,500,000	1,500,000	\$ 1,500,000	\$ 1,500,000
and effluent line to use point				500,000
Add for extra size		500,000	500,000	500,000
Add for extra pressure				
TOTAL	<u>\$ 1,500,000</u>	<u>\$ 2,000,000</u>	<u>\$ 2,000,000</u>	<u>\$ 2,500,000</u>
Front risers, headers, nozzles	Existing	\$ 1,500,000	Existing	\$ 1,500,000
and pigtails	Equipment		Equipment	
Add for extra size	Suitable	500,000	Suitable	500,000
Add for extra pressure				1,000,000
TOTAL		<u>\$ 2,000,000</u>		<u>\$ 3,000,000</u>
TOTAL FOR FULL PRESSURIZATION	<u>\$ 3,000,000</u>	<u>\$ 6,000,000</u>	<u>\$ 2,000,000</u>	<u>\$ 8,000,000</u>

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ROUGH DRAFT

HW-30907
Page 46

From these three basic cost elements, a rough total project cost can be computed as follows:

Down time	\$1,740,000
Labor	620,000
Material	670,000
Estimated Jigs & Fixtures	200,000
Laundry & Miscellaneous	100,000
Contingencies	160,000
Design	25,000
	<hr/>
TOTAL COST	<u>\$3,515,000</u>
ROUND OFF	\$4,000,000

This is a very rough estimate for the cost of retubing a 2,000 tube pile. Such a cost will be incurred to provide tubes which can handle 250° C bulk pile outlet temperature, but with pressure-flow characteristics assumed to be no better than for the existing slug and tube systems. A similar calculation, made for one "K" Pile, rated at 3000 MW and with 6 simultaneous work points gives \$7,000,000.

4. High Pressure Process Pumps and Water Treatment

For cases of one-pass water it has been necessary to estimate the cost of converting present high pressure process pumps to units of the same gallage capacity, but delivering sufficient pressure to supply 600 psig at the front of the process tubes. Such a change has been estimated at \$2,000,000 per pile, regardless of size, on the basis that, on order of magnitude, such conversion represents about 40 percent as much work as the \$5,000,000 per pile estimated for Project CG-558. This concerns items 19b and 19c in Table No. IV.

Water treatment facilities suited to one-pass systems are indicated as Item 22 in Table No. IV, and concern standard flocculators, filters, etc., as now in use at the "K" Piles. The "K" Pile water plant, including high-pressure process pumps, cost about \$350 per installed gpm. Consequently, any additional flow rate above pre-existing water plant capacity was estimated as costing \$350 per gpm. Estimated pre-pressurization water plant capacities are as follows: B, D, Dr, F, and H Piles, 72,000 gpm; C Pile, 100,000 gpm; K Piles, 140,000 gpm.

5. Power Recovery Equipment

The estimates given below are speculative to a certain extent because honest doubts exist as to the practicality of utilization of low pressure steam such as is contemplated herein. The estimates given below are based on extrapolations from other power recovery systems discussed in the literature.

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ROUGH DRAFT

HW-30907
Page 47

5a. Vapor Generator

Comparison of Figures Nos. 8 and 9 shows that a vapor generator is required for power recovery from one-pass flow, and that no equivalent heat exchange equipment exists for the heat throw-away case. This equipment is estimated as costing \$1,000,000 regardless of pile size or flow rate.

Comparison of Figures 10 and 11, on the other hand, indicate that power recovery from the recirculation system requires a vapor generator and secondary effluent cooler while heat throw-away from the recirculation system requires a primary effluent cooler, but no vapor generator or secondary cooler. Since the combined heat transfer capacity of these mutually exclusive units is identical, they have been considered to be of equal cost. Primary effluent cooler costs have been estimated by others as a portion of costs peculiar to pressurization.

5b. Turbo-Generators

A re-computation of turbogenerator cost for a recent document concerning in-pile boiling indicated an installed cost, including overhead, of \$42,79 per KW for a system operating with turbine feed of dry saturated steam at about 400 psig.

To account for special low pressure piping, turbogenerators have been estimated at \$75 per KW installed, including overhead, including necessary piping, controls, and housing.

5c. River Pump House

The same study mentioned above showed an installed cost of \$7,800,000 including overhead, for a river pump house of about 200,000 gpm capacity. Using flow as a size indicator, this figure was extrapolated on the basis that cost is proportional to the 0.6 power of the size. Such a relationship has been used by others for extrapolating costs of processing equipment. See Figure No. 13.

5d. Condensers

From the same study it appeared that a condenser transferring 1336 MW of heat, with temperature differences of 1°C on one end and 26°C on the other, cost \$9,100,000 installed including overhead. Using area as a size indicator, and the logarithmic mean temperature difference as a temperature driving force, the relative area of this condenser is $1336/7.7$ or 174 units. Condensers in this study use: (1) temperature differences of 11°C and 21°C on each end, for a logarithmic mean temperature driving force of 15.5°C , and (2) 10°C

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ROUGH DRAFT

48

HW-30907

FIGURE NO. 13
RIVER PUMPHOUSE COSTS

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temperature rise. Thus, these have a relative area of

$$\text{Area} = \frac{(\text{gpm}) (.2635) (10)}{(1000)} / 15.5 = 0.00017 \frac{\text{Units}}{\text{gpm}}$$

Using area to the 0.6 power as being proportional to cost, the relationship shown as Figure No. 14 was derived and used for estimating costs of condensers.

H. Power Recovery Implications

Power can be recovered from any pile effluent stream hotter than river water. Whether or not it is in order to recover the power from the effluent depends on economics only. A thorough analysis of power recovery is beyond the scope of this report, so approximate methods are used.

The bases for the method are: (1) such a power recovery system will probably work, (2) transfer ducts for steam at atmospheric pressure will not be exceedingly costly, and (3) doubts exist as to the practicability of using sub-atmospheric pressure steam as economical turbine feed due to the large size of the equipment required for handling steam of such a high specific volume.

The method is outlined in Figure No. 15. As can be seen, the effluent stream will be cooled to 100° C in a vapor generator by a working fluid stream which enters the vapor generator at 30° C as liquid water, from a condenser at 1.5" Hg pressure, and leaves the vapor generator at 100° C as "dry" saturated steam for turbine feed.

This system aims at using atmospheric pressure turbine feed but at a considerable expense in power recovery efficiency. The only portion of the pile heat which can be recovered is that available above 100° C. The thermodynamic potential of steam at this temperature is very low, and only 13.3 percent of the heat picked-up by the working fluid will turn up as generated power.

The system as shown on Figure No. 15 happens to lend itself to simple calculations, and for that reason was used in this report in preference to two other systems of higher thermodynamic potential operating on the same principle and within the same temperature boundaries. One such system would add a pre-heater heat exchanger whose function would be to heat the working fluid from 33° C to about 95° C prior to its entry to the vapor generator. The post-vapor-generator effluent stream would be used to do the heating since it must be cooled anyway before re-use or throw-away. This system is about 10 percent more efficient than the one shown in Figure No. 15. A system of similar efficiency and possibly lower cost would be one where the pile effluent is passed through a throttle and flashed to 100° C with the resulting vapor used directly as turbine feed.

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FIGURE 14
CONDENSER COSTS

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FIGURE 15

SCHEMATIC SKETCH OF STANDARD
POWER RECOVERY ARRANGEMENT

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The use of any of the above systems for pile effluent streams at 250° C is exceedingly harsh on the power recovery potential from these cases of operation. With an effluent stream at 250° C, common sense would indicate the wisdom of flashing at least once at some intermediate temperature before flashing at 100° C. The importance of this is shown in Figure No. 16 where the net delivered electric potential per MW of heat absorbed by working fluid is plotted as a function of flasher temperature. As can be computed from Figure No. 16, with a pile effluent stream at 250° C one vapor generator at 175° C delivering half the total heat available above 100° C, plus one vapor generator at 100° C delivering the other half, will give an electrical generation efficiency of 17.7 percent, or 33 percent more power than will a single vapor generator at 100° C. Time has prevented applying the multiple stage heat extraction principle to the high temperature effluent systems discussed elsewhere in this report. Consequently their power recovery potential has been considerably understated.

I. Review of Primary Process Assumptions

Much of the text up to this point has concerned process variables which affect the calculation of potential gains from pressurizing existing piles. A review of these assumptions is given below:

1. Slugs, shielding, graphite and thermal expansion effects will not limit power level after pressurization.
2. One-pass water, under present or future treatment, will not be suited for any slug or tube combinations above 120° C bulk pile outlet temperature.
3. Throw-away effluent must be at 95° C or lower.
4. Pressure-flow characteristics of process tubes in re-tubed piles will be the same as in existing piles and will be as in Figure 3.
5. Rear pigtails can have no hydraulic characteristics better than in Figure No. 4, and will be used for pressurization cases.
6. Allowable tube inlet pressures of 600 psig are possible with existing process tubes up to 80° C.
7. Allowable tube outlet pressures in existing tubes are as in Figure No. 5, and can be computed as applying to average tubes rather than to hottest tubes.
8. All portions of the process tube are within allowable pressure limits if the front and rear portions are within allowable limits.
9. New process tubes can be developed which permit operation at 1700 psi front tube pressure at 80° C and lower, and rear tube pressure at 1100 psi at 250° C.

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ROUGH DRAFT

53

HW-30907

FIGURE 16

POWER OUTPUT AS FUNCTION OF VAPOR GENERATOR TEMPERATURE

ROUGH DRAFT

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10. For all liquid flow, the rear header pressure must be the saturation pressure corresponding to a temperature equivalent to 123.4 percent of the bulk pile temperature rise.
11. One-pass inlet temperature will be 12° C.
12. Minimum recirculation inlet temperature will be 22° C.
13. Maximum allowable inlet temperature will be 80° C due to shield wear.
14. Power recovery from effluent streams above 100° C is feasible.
15. Net electrical power generated will be 79 percent of the theoretical work available from isentropic expansion of working steam.
16. Low-cost field expedient pressurization will suffice for bulk pile outlet temperatures up to but not beyond 105° C.

J. Calculation of Potential Gains From Pressurization

Within the framework of the assumptions previously enumerated, for any pile, a wide variety of cases of operation can be computed. For example, at any particular power level a case can be computed where power level is constant and the circulation technique applied. Or, a process flow rate can be held constant and the recirculation techniques applied as a means of increasing power level. Consequently, to show the sort of a potential which can be assigned to pressurization, a few special cases have been computed for each sort of pile.

These cases are summarized in Tables Nos. VII, VIII, and IX. For each case pertinent process variables and cost data have been presented.

Case No. 1 represents the approximate maximum potential following initial construction in case of "K" Pile, (3430 MW) and after "full scale" Project CG-558 modifications to the other piles. (1760 MW for old piles, 2230 MW for "C"). This case is used as a basis for comparison. Basically, when successful operation has been attained at the maximum possible post CG-558 level, the point will be reached where an additional series of pile modifications are in order. The remaining six cases, represent the sorts of alternatives available at such a time, providing the prior experimental work has indicated an adequate degree of confidence of successful operation under the more severe operating conditions.

Case No. 2 represents operation to the limit of one-pass water flow.

Case No. 3 represents operation to the limit of a recirculation system with present process tubes. As can be seen, Case No. 3 power levels (2710 MW for old piles, 3560 MW for "C" and 8100 MW for "K") are somewhat higher than for Case No. 2 (2560 MW, 3450 MW, and 7900 MW) and the electric power generation is markedly higher than for Case No. 2 (4.8% vs. 2.5%).

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Case No. 4 considered recirculation with existing tubes as a means of achieving power recovery without increasing plutonium production. Power level is held to Case No. 1 values, so the probability of successful attainment of goals is about comparable in both cases.

Case No. 5, on the other hand, represents quite an optimistic goal. It represents near the maximum power than can be produced with new tubes and very high temperature circulation. Satisfactory performance under these conditions is difficult to forecast. The reader should note that this type of operation calls for operation at power generation rates as high as 200 kw per foot of uranium.

Case No. 6 represents high temperature recirculation as a method of securing power recovery without increasing production. Comparison of Cases Nos. 4 and 6 shows the merits of a higher degree of pressurization for securing power recovery without increasing production.

Case No. 7 represents high temperature recirculation and power recovery with power level held at Case No. 2 levels.

The important thing to observe in Tables Nos. VII, VIII, and IX is that the relevant pay-off periods for pressurization schemes lie well within the typical amortization periods used for new pile depreciation. Consequently, if successful performance can be reasonably assured, these cases represent sound economics.

If slug power generation rates are considered to be indices of probability of successful operation, it is apparent that Cases Nos. 1, 4, and 6 are roughly comparable; Cases Nos. 2, 3, and 7 are more difficult to achieve, but are about equal in probability of attainment; Case No. 5 represents a target case which will be the most difficult to achieve.

For any particular degree of difficulty of achievement, therefore, the choice of alternates depends on the importance assigned to power recovery as a means to lower irradiation costs.

K. Application to the Piles

The power levels shown in Tables Nos. VII, VIII, and IX are much higher than those now envisioned. Successful achievement of these power levels will require satisfactory solution of difficult technical problems. Some of the problems are discussed briefly below:

ka. Process Tubes

Existing tubes are assumed to be workable under the process conditions assigned. These combinations of high pressure and temperature are much more severe than present practice, yet even at the present time downstream tube corrosion is troublesome. Little accurate data exists as to high temperature creep rates, and yet these determine allowable pressures.

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TABLE NO. VII

APPLICATION OF PRESSURIZATION TO B.D.DR.F. A

	Item No.	Units	B,L,DR,F, & H PILES	B,L,DR,F, & H PILES	B,L,DR,F, & H PILES	B,L,DR,F, & H PILES
			Field Expedient Pressurization	Pressurized to Tube Pressure Limit	Pressurized to Tube Pressure Limit	Pressurized to Tube Pressure Limit
			One-pass Flow	One-pass Flow	Recirculatory Flow	Recirculatory Flow
			Present Tubes	Present Tubes	Present Tubes	Present Tubes
			Inlet Temperature Set By River	Inlet Temperature Set By River	Inlet Temperature Set For Maximum Plutonium Production	Inlet Temperature Set For Maximum Power Generation
			Maximum Potential Post Proj. CG-558	Maximum Potential With One-pass Flow	Maximum Potential With Existing Tubes	Level Restricted To Case 1 Value For Comparison
GENERAL DATA						
Water Use Efficiency	1	%	90	90	90	90
Front Tube Pressure	2	Psig	450	600	600	600
Rear Header Pressure	3	Psig	20	30	110	100
Central Zone Tube Flow	4	gpm	40	50	46	47
Pile Flow Rate	5	gpm x 10 ³	72	90	83	84
Pile Bulk Outlet Temperature	6	°C	105	120	146	150
Pile Inlet Temperature	7	°C	12	12	22	70
PILE POWER LEVEL	8	MW	1760	2560	2710	1760
WITHOUT POWER RECOVERY						
PROCESS DATA						
Flow to cool effluent to 95C	9	gpm x 10 ³	9	27	--	--
Flow to cool effluent to inlet	10	gpm x 10 ³	--	--	124	81
OPERATING COST DATA						
Constant operating costs	11	\$/Yr x 10 ⁶	3.15	3.15	3.15	3.15
Pumping energy	12	\$/Yr x 10 ⁶	.426	.677	.607	.599
Enrichment	13	\$/Yr x 10 ⁶	.705	1.025	1.085	.705
Water Treatment	14	\$/Yr x 10 ⁶	.220	.280	.067	.068
CAPITAL COST DATA						
Rear Face	15	\$ x 10 ⁶	.100	3.0	3.0	3.0
Front Face	16	\$ x 10 ⁶	--	--	--	--
Tubes	17	\$ x 10 ⁶	--	--	--	--
Water Plant Equipment	18	\$ x 10 ⁶	.6	9.2	19.0	19.0
ECONOMIC COMPARISON DATA						
Irradiation Sales Income	19	\$ x 10 ⁶	7.92	11.52	12.195	7.92
Operating Expenses	20	\$ x 10 ⁶	4.501	5.132	4.909	4.522
Apparent Profit	21	\$ x 10 ⁶	3.419	6.388	7.286	3.398
Profit above Case No. 1	22	\$ x 10 ⁶	Base	2.969	3.867	loss
Capital Cost	23	\$ x 10 ⁶	.7	12.2	22.0	22.0
Extra Capacity Purchased	24	\$ x 10 ⁶	Base	800	950	--
PAY-OFF PERIOD	25	years	Base	4.1	5.7	--
PRICE OF EXTRA CAPACITY	26	\$/MW	Base	15,250	23,150	--
WITH POWER RECOVERY						
PROCESS DATA						
Proportion of Pile Heat made into Power	27	%	--	2.46	4.93	8.31
Marketable Power	28	MW	--	63	134	126
Condenser Flow	29	gpm x 10 ³	--	149	317	350
OPERATING COST DATA						
Pile Operating Cost	30	\$ x 10 ⁶	4.714	5.571	5.371	5.043
Power Recovery Operating Cost	31	\$ x 10 ⁶	--	.189	.402	.438
CAPITAL COST DATA						
Pile and Water System	32	\$ x 10 ⁶	.7	12.2	22.0	22.0
Vapor Generator	33	\$ x 10 ⁶	No	1.0	--	--
River Pump House	34	\$ x 10 ⁶	Power	6.5	10.0	11.0
Turbogenerators	35	\$ x 10 ⁶	Recovery	4.7	10.0	11.0
Condensers	36	\$ x 10 ⁶	Considered	2.8	4.5	4.7
ECONOMIC COMPARISON DATA						
Irradiation Sales Income	37	\$ x 10 ⁶	7.920	11.520	12.195	7.920
Power Sales Income	38	\$ x 10 ⁶	--	1.89	4.02	4.380
Total Sales	39	\$ x 10 ⁶	7.92	13.410	16.215	12.300
Total Expenses	40	\$ x 10 ⁶	4.714	5.760	5.773	5.481
Apparent Profit	41	\$ x 10 ⁶	3.206	7.650	10.442	6.819
Profit above Case No. 1	42	\$ x 10 ⁶	--	2.444	7.236	3.613
Capital Cost	43	\$ x 10 ⁶	.7	27.2	47.0	49.0
Extra Capacity Purchased	44	MW	Base	800	950	--
PAY-OFF PERIOD	45	years	Base	6.1	6.5	13.6
PRICE OF EXTRA CAPACITY	46	\$/MW	Base	34,000	49,470	--

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DR, F, & H PILES

DR, F, & H PILES

Pressurized to
Pressure Limit

Recirculatory Flow

New Tubes

Inlet Temperature
Set For Maximum
Power GenerationLevel Restricted
to Case 1 Value
For Comparison

B, D, DR, F, & H PILES

Pressurized to
Tube Pressure Limit

Recirculatory Flow

New Tubes

Inlet Temperature
Set For Maximum
Power GenerationLevel Restricted
to Case 1 Value
For Comparison

B, D, DR, F, & H PILES

Pressurized to
Tube Pressure Limit

Recirculatory Flow

New Tubes

Inlet Temperature
Set For Maximum
Power GenerationLevel Restricted
to Case 2 Value
For Comparison90
1700
1100
52
94
250
80
418090
1235
1100
22
39
250
80
176090
1360
1100
32
58
250
80
2560

191

81

119

3.15
.827
1.67
.0753.15
.149
.705
.0323.15
.298
1.024
.0474.0
2.0
4.0
21.74.0
2.0
4.0
15.74.0
2.0
4.0
15.718.81
5.722
13.088
9.669
31.7
2420
3.3
13,0997.92
4.036
3.884
.465
25.7
55.311.52
4.519
7.001
3.582
25.7
800
7.2
32,12011.73
490
1,17011.73
206
48611.73
300
7236.941
1.4704.445
.6185.165
.90031.7
22.0
37.0
9.825.7
13
15
5.825.7
16.5
22.0
7.418.81
14.70
33.510
8.411
25.099
21.893
100.7
2420
4.6
41,6007.92
6.18
12.10
5.063
9.037
5.831
58.7
10.011.52
9.00
20.52
6.065
14.455
11.249
71.7
800
6.4
89,620

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TABLE NO. VIII APPLICATION OF PRESSURIZATION

CASE DESIGNATION PILE

DESCRIPTION OF CASE

	Item No.	Units	1 C PILE Field Expedient Pressurization One-pass Flow Present Tubes Inlet Temperature Set By River Maximum Potential Post Proj. CG-558	2 C PILE Pressurized to Tube Pressure Limit One-pass Flow Present Tubes Inlet Temperature Set For River Maximum Potential With One-pass Flow	3 C PILE Pressurized to Tube Pressure Limit Recirculatory Flow Present Tubes Inlet Temperature Set For Maximum Plutonium Production Maximum Potential With Existing Tubes	4 C PILE Pressurized to Tube Pressure Limit Recirculatory Flow Present Tubes Inlet Temperature Set For Maximum Power Maximum Potential With Existing Tubes
GENERAL DATA						
Water use efficiency	1	%	90	90	90	
Front tube pressure	2	Psig.	370	600	630	
Rear header pressure	3	Psig.	20	30	105	
Central zone tube flow	4	gpm	50	67	61	
Pile flow rate	5	gpm x 10 ³	91	121	111	
Pile bulk outlet temp.	6	°C	105	120	122	
Pile inlet temp.	7	°C	12	12	22	
PILE POWER LEVEL	8	MW	2230	3450	3560	
WITHOUT POWER RECOVERY						
PROCESS DATA						
Flow to cool effluent to 95°C	9	gpm x 10 ³	11	36	—	
Flow to cool effluent to inlet	10	gpm x 10 ³	—	—	163	
OPERATING COST DATA						
Constant operating costs	11	\$/Yr x 10 ⁶	3.15	3.15	3.15	
Pumping energy	12	\$/Yr x 10 ⁶	.457	.905	.813	
Enrichment	13	\$/Yr x 10 ⁶	.891	1.38	1.222	
Water treatment	14	\$/Yr x 10 ⁶	.28	.37	.086	
CAPITAL COST DATA						
Rear Face	15	\$ x 10 ⁶	.1	3.0	3.0	
Front Face	16	\$ x 10 ⁶	—	—	—	
Tubes	17	\$ x 10 ⁶	—	—	—	
Water Plant Equipment	18	\$ x 10 ⁶	.67	10.2	21.9	
ECONOMIC COMPARISON DATA						
Irradiation Sales income	19	\$ x 10 ⁶	10.035	15.525	16.020	
Operating expenses	20	\$ x 10 ⁶	4.778	5.805	5.471	
Apparent profit	21	\$ x 10 ⁶	5.257	9.720	10.549	
Profit above Case No. 1	22	\$ x 10 ⁶	Base	4.463	5.292	
Capital Cost	23	\$ x 10 ⁶	.77	13.2	24.9	
Extra Capacity purchased	24	MW	Base	1220	1330	
PAY-OFF PERIOD	25	Years	Base	3.0	4.7	
PRICE OF EXTRA CAPACITY	26	\$/MW	Base	11,400	18,700	
WITH POWER RECOVERY						
PROCESS DATA						
Proportion of pile heat made into power	27	%	0	—	8.76	
Marketable power	28	MW	0	2.46	—	
Condenser flow	29	gpm x 10 ³	—	60	195	
				200	466	
OPERATING COST DATA						
Pile operating cost	30	\$ x 10 ⁶	5.006	6.392	6.378	
Power recovery operating cost	31	\$ x 10 ⁶	—	.180	.513	
CAPITAL COST DATA						
Pile and water system	32	\$ x 10 ⁶	.77	13.2	24.9	
Vapor generator	33	\$ x 10 ⁶	No	1.0	—	
River pump house	34	\$ x 10 ⁶	Power	7.8	12.0	
Turbogenerators	35	\$ x 10 ⁶	Recovery	4.5	12.8	
Condensers	36	\$ x 10 ⁶	Considered	3.4	5.2	
ECONOMIC COMPARISON DATA						
Irradiation sales income	37	\$ x 10 ⁶	10.035	15.525	16.020	
Power sales income	38	\$ x 10 ⁶	—	1.8	5.13	
Total Sales	39	\$ x 10 ⁶	10.035	17.325	21.15	
Total expenses	40	\$ x 10 ⁶	5.006	6.572	6.591	
Apparent profit	41	\$ x 10 ⁶	5.029	10.753	14.559	
Profit above Case No. 1	42	\$ x 10 ⁶	Base	5.724	9.530	
Capital Cost	43	\$ x 10 ⁶	.77	29.9	54.9	
Extra capacity purchased	44	MW	Base	1220	1330	
PAY-OFF PERIOD	45	Years	Base	5.2	5.8	
PRICE OF EXTRA CAPACITY	46	\$/MW	Base	24,500	41,300	

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O C PILE

4	5	6	7
LE	C PILE	C PILE	C PILE
Pressurized to Tube Pressure Limit	Pressurized to Tube Pressure Limit	Pressurized to Tube Pressure Limit	Pressurized to Tube Pressure Limit
Recirculatory Flow	Recirculatory Flow	Recirculatory Flow	Recirculatory Flow
New Tubes	New Tubes	New Tubes	New Tubes
Inlet Temperature Set For Maximum Power Generation	Inlet Temperature Set For Maximum Power Generation	Inlet Temperature Set For Maximum Power Generation	Inlet Temperature Set For Maximum Power Generation
Level Restricted To Case 1 Value For Comparison	Maximum Potential With New Tubes	Level Restricted To Case 1 Value For Comparison	Level Restricted To Case 2 Value For Comparison
90	90	90	90
500	1700	1230	1355
90	1100	1100*	1100
62	69	28	43
112	124	50	77
150	250	250	250
74	80	80	80
230	5550	2230	3450
—	—	—	—
102	254	102	158
3.15	3.15	3.15	3.15
.804	1.088	.186	.389
.891	2.222	.891	1.38
.087	.096	.039	.060
3.0	4.0	4.0	4.0
—	2.0	2.0	2.0
—	4.0	4.0	4.0
2.0	32.8	21.4	26.9
0.035	24.075	10.035	15.525
4.932	6.556	4.266	4.979
5.103	17.519	5.809	10.546
loss	12.262	.552	5.289
5.0	42.8	31.4	36.9
none	3320	none	1220
never	3.5	56.9	7.0
—	12,900	—	30,200
4.8	11.7	11.7	11.7
1	649	261	404
7	1,550	625	967
5.634	8.165	5.840	4.789
.585	1.947	1.212	.783
5.0	42.8	31.4	36.9
—	—	—	—
3.0	26.0	15.0	20.0
4.6	48.7	19.6	30.3
5.6	8.4	4.9	6.4
0.035	24.075	10.035	15.525
5.85	19.47	7.83	12.12
5.885	44.445	17.865	27.645
6.219	10.112	5.572	7.052
9.666	34.333	12.293	20.593
4.627	29.304	7.264	15.564
58.2	125.9	70.9	93.6
none	3320	none	1220
12.6	4.3	9.8	6.0
—	37,900	—	76,700

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TABLE NO. IX

APPLICATION OF PRESSURIZATION TO K P

			1	2	3	4
			"K" Piles	"K" Piles	"K" Piles	"K" Piles
			Field Expedient Pressurization	Pressurized to Tube Pressure Limit	Pressurized to Tube Pressure Limit	Pressurized to Tube Pressure Limit
			One-pass Flow	One-Pass Flow	Recirculatory Flow	Recirculatory Flow
			Present Tubes	Present Tubes	Present Tubes	Present Tubes
			Inlet Temperature Set by river	Inlet Temperature Set by River	Inlet Temperature Set for Maximum Plutonium Production	Inlet Temperature Set for Maximum Power Generation
			Maximum Potential Post Construction	Maximum Potential With One-pass Flow	Maximum Potential With Existing Tubes	Level Restricted To Case 1 Value For Comparison
	Item No.	Units				
GENERAL DATA						
Water Use Efficiency	1	%	90	90	90	90
Front Tube Pressure	2	Psig	195	600	600	370
Rear Header Pressure	3	Psig	20	30	95	90
Central Cone Tube Flow	4	gpm	48	96	89	64
Pile Flow Rate	5	gpm x 10 ³	1.00	278	258	186
Pile Bulk Outlet Temperature	6	°C	1.5	120	141	150
*Pile Inlet Temperature	7	°C	12	12	22	80
PILE POWER LEVEL	8	MW	3430	7900	8100	3430
WITHOUT POWER RECOVERY						
PROCESS DATA						
Flow to cool effluent to 95C	9	gpm x 10 ³	17	84	—	—
Flow to cool effluent to inlet	10	gpm x 10 ³	—	—	270	157
OPERATING COST DATA						
Constant Operating Costs	11	\$/Yr x 10 ⁶	2.98	2.98	2.98	2.98
Pumping Energy	12	\$/Yr x 10 ⁶	.434	2.378	1.905	.86
Enrichment	13	\$/Yr x 10 ⁶	1.372	3.160	3.220	1.372
Water Treatment	14	\$/Yr x 10 ⁶	.280	.950	.200	.145
CAPITAL COST DATA						
Rear Face	15	\$ x 10 ⁶	.150	2.0	2.0	2.0
Front Face	16	\$ x 10 ⁶	—	—	—	—
Tubes	17	\$ x 10 ⁶	—	—	—	—
Water Plant Equipment	18	\$ x 10 ⁶	.750	52.275	34.5	28.7
ECONOMIC COMPARISON DATA						
Irradiation Sales Income	19	\$ x 10 ⁶	15.435	35.55	36.45	15.435
Operating Expenses	20	\$ x 10 ⁶	5.266	9.168	8.305	5.357
Apparent Profit	21	\$ x 10 ⁶	10.169	26.382	28.145	10.078
Profit Above Case No. 1	22	\$ x 10 ⁶	Base	16.213	17.976	10.00
Capital Cost	23	\$ x 10 ⁶	.9	54.275	36.5	30.7
Extra Capacity Purchased	24	MW	Base	4470	4670	—
PAY-OFF PERIOD	25	Years	Base	3.3	2.0	—
PRICE OF EXTRA CAPACITY	26	\$/MW	Base	12,142	7,815	—
WITH POWER RECOVERY						
PROCESS DATA						
Proportion of Pile Heat Made into Power	27	%	—	2.46	4.58	9.51
Marketable Power	28	MW	—	194	371	326
Condenser Flow	29	gpm x 10 ³	—	462	880	774
OPERATING COST DATA						
Pile Operating Cost	30	\$ x 10 ⁶	5.482	10.517	9.678	6.294
Power Recovery Operating Cost	31	\$ x 10 ⁶	—	.582	1.113	.978
CAPITAL COST DATA						
Pile and Water System	32	\$ x 10 ⁶	.9	54.275	25.5	30.7
Vapor Generator	33	\$ x 10 ⁶	No	—	1.0	—
River-Pump House	34	\$ x 10 ⁶	Power	13.0	19.0	17.0
Turbogenerators	35	\$ x 10 ⁶	Recovery	14.6	27.8	24.4
Condensers	36	\$ x 10 ⁶	Considered	5.8	8.5	7.6
ECONOMIC COMPARISON DATA						
Irradiation Sales Income	37	\$ x 10 ⁶	15.435	35.55	36.45	15.435
Power Sales Income	38	\$ x 10 ⁶	—	5.82	11.13	9.78
Total Sales	39	\$ x 10 ⁶	15.435	41.37	47.58	25.215
Total Expenses	40	\$ x 10 ⁶	5.482	11.099	10.791	7.272
Apparent Profit	41	\$ x 10 ⁶	9.953	30.271	36.789	17.943
Profit above Case No. 1	42	\$ x 10 ⁶	Base	20.318	26.836	7.590
Capital Cost	43	\$ x 10 ⁶	.9	88.675	51.800	79.700
Extra Capacity Purchased	44	MW	Base	4470	4670	—
PAY-OFF PERIOD	45	Years	Base	4.4	3.4	10
PRICE OF EXTRA CAPACITY	46	\$/MW	Base	19,837	19,657	—

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5	6	7
"K" Piles	"K" Piles	"K" Piles
Pressurized to Tube Pressure Limit	Pressurized to Tube Pressure Limit	Pressurized to Tube Pressure Limit
Recirculatory Flow	Recirculatory Flow	Recirculatory Flow
New Tubes	New Tubes	New Tubes
Inlet Temperature Set for Maximum Power Generation	Inlet Temperature Set for Maximum Power Generation	Inlet Temperature Set for Maximum Power Generation
Maximum Potential With New Tubes	Level Restricted to Case 1 Value For Comparison	Level Restricted to Case 2 Value For Comparison
90 1700 1100 100 290 250 80 13000	90 1160 1100 26 76 250 80 3400	90 1360 1100 61 176 250 80 7900
595	157	362
2.98 2.538 5.850 .220	2.98 .226 1.372 .059	2.98 .892 3.160 .036
5.0 3.0 7.0 52.4	5.0 3.0 7.0 26.8	5.0 3.0 7.0 43.2
58.5 11.588 46.912 36.743 67.4 9570	15.435 4.637 10.798 .629 41.8 —	35.55 7.068 28.482 18.313 58.2 4470
1.8 7,002	66 —	3.2 13,020
11.7 1,521 3,620	11.7 401 955	11.7 924 2,200
15.343 4.563	5.404 1.203	9.024 2.772
67.4 — 43.0 114.1 19.2	41.8 — 20.0 30.1 8.9	58.2 — 32.0 69.3 14.3
58.5 5.63 104.13 19.906 84.224 74.271 243.700 9570	15.435 12.03 27.465 6.607 20.858 10.905 100.800 —	35.55 27.72 63.27 11.796 51.474 41.521 173.800 4470
3.2 25,460	9.1 —	4.1 38,880

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HW-30907
Page 59

For high temperature pressurization, what is required are high strength, low cross-section, corrosion resistant, and low cost tubes. Satisfactory achievement of a successful combination of these qualities will not be easy, but is required.

kb. Slugs

Process conditions stipulated call for successful operation at powers about double the present development goals. These powers will bring on temperature effects in order of magnitude above those considered heretofore. New problems of end cap and slug skin heat transfer will arise. Solution of these problems may be difficult.

kc. Graphite

Under the process conditions stipulated, and with graphite of present conductivity, extremely high graphite temperatures can be computed. High graphite temperature will act to anneal presently existing thermal conductivity damage, however. Consequently, graphite temperatures may not rise to extreme levels since the present graphite conductivity is about 1/10 that of virgin material. Improvement by a factor of 2 would not be unexpected. But regardless of this, the higher temperatures and radiation fields may bring on problems of a new sort which are not now troublesome.

kd. Shield Deterioration

The postulated conditions call for front, rear, top, and near and far side shield deterioration rates far in excess of those planned even for Project CG-558. This may call for field expedient techniques of a high degree of ingenuity.

ke. Thermal Expansion

These effects may be the most difficult of all to overcome, and particularly so with cases of high temperature recirculation. The entire pile structure; piping, tubes, stack, and shielding will undergo motions and stresses beyond original design values.

kf. Operating Efficiency

The process calculations on Tables Nos. VII, VIII, and IX have blandly assumed a constant 300 operating days per year. This will only be so if procedures are developed to improve charge-discharge techniques. For example, at 2500 KW per BDF length tube, 600 MWD

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