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SOME STEADY-STATE THERMAL CHARACTERISTICS OF A
THREE-LOOP REACTOR POWER SYSTEM

by

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ABSTRACT

The "three-loop" power system which is to be used with Experimental Breeder Reactor No. II (EBR-II) has been analyzed to determine: (1) coolant flow rate requirements at various power levels; (2) coolant temperatures at various power levels; (3) effects of heat exchanger sizes (system optimization); and (4) effects of control errors.

An intermediate heat exchanger, preheater, evaporator, and superheater are included in the EBR-II power system. Constant thermal resistances and physical properties, and perfect insulation were assumed in the analysis.

Among other things, the study showed that (1) at low power levels, excessive thermal stresses are produced at the cold end of the intermediate heat exchanger unless a high sink temperature is used; (2) a short cut may be used to determine approximate system conditions at all power levels; (3) system optimization requires compromises; (4) system flow rate control is possible through high-low measurements of two coolant temperatures in the primary system.

PREFACE

Most of the material given in Sections I-IV was presented at the First Winter Meeting, American Nuclear Society, December 10-12, 1956. Additional work in the three succeeding years may be summarized as follows:

(1) According to latest available information, at rated power the EBR-II power system will operate with the conditions listed in Table 1. There have been included, for comparison purposes, values suggested as a result of calculations in Sections III and IV. The present values of the products UA listed in the table were calculated from construction drawings of the heat exchange equipment (U is the overall heat transfer coefficient and A the area.) Those values marked "present values" are substantially higher than any previously considered, because the equipment designers

tried to be conservative. As the table indicates, large values of UA are beneficial in that they permit lower reactor coolant (and fuel) temperatures, with no sacrifice in steam temperature.

Table 1

EBR-II POWER SYSTEM OPERATING CONDITIONS
AT RATED POWER

Condition	Present Values	Suggested Values	Section III Values
Rated power, Mw (thermal)	62.5	62.5	60.0
$(UA)_{1,2} [\text{Btu}/(\text{hr})(\text{F})] \times 10^{-6}$	5.0	2.8	3.3
$(UA)_{E2,3} [\text{Btu}/(\text{hr})(\text{F})] \times 10^{-6}$	2.9	2.0	1.2
$(UA)_{S2,3} [\text{Btu}/(\text{hr})(\text{F})] \times 10^{-6}$	0.58	0.53	0.41
$TH_1, ^\circ\text{F}$	890	900	900
$TH_2, ^\circ\text{F}$	881	870	880
$TH_3, ^\circ\text{F}$	850	850	850
$TC_1, ^\circ\text{F}$	700	750	720
$TC_2, ^\circ\text{F}$	582	594	580
$TC_3, ^\circ\text{F}$	550	450	380
$TE_2, ^\circ\text{F}$	801	810	817
$TE_3, ^\circ\text{F}$	578	576	572
$M_1, [\text{lb}_m/\text{hr}] \times 10^{-6}$	3.7	4.7	3.7
$M_2, [\text{lb}_m/\text{hr}] \times 10^{-6}$	2.3	2.5	2.2
$M_3, [\text{lb}_m/\text{hr}] \times 10^{-6}$	0.25	0.22	0.20

(2) As should be expected, when changes in values of UA with coolant flow rates are taken into account, eq. (16) gives values which are too high, since UA invariably decreases when %P decreases. For example, it turns out that the temperature difference across one end of the EBR-II superheater (the hot end) does not drop to less than 1°F until the per cent of rated power is almost zero, when changing UA is considered. (The temperature differences across one end of the heat exchanger and of the evaporator drop to less than 1°F at about 50% of rated power, even when changing values of UA are considered, because those temperature differences are only 9 and 4°F , respectively, at rated power.)

(3) Thermal stresses in the tubes at the hot end of the evaporator have been held to an allowable value by installing thermal baffles around the tubes in the vicinity of the hot end.

(4) Iterative solution of the simultaneous transcendental equations which are encountered in this type of work is greatly facilitated by making use of a crossplot between q/UA , ΔT_1 , and ΔT_2 , where ΔT_1 and ΔT_2 are the temperature differences across each end of a heat exchanger, and q is the quantity of heat transferred. Such a plot speeds the solution of eqs. (3), (8), (9), (10), (18), (19), or (20) when q/UA and one ΔT are known.

I. INTRODUCTION

The "three-loop" reactor power system, of which a typical example is shown schematically in Fig. 1, has become associated with sodium-cooled power reactors for several reasons. First, it is desirable to confine the radioactive reactor coolant to as small a space as possible. Second, it is inadvisable to introduce radioactive sodium into a steam generator, particularly at the present state of the art. A third reason is that the use of an intermediate, or secondary, system reduces both transient and steady-state thermal stresses in the steam-generating equipment (at the expense of heat exchanger surface).

Fig. 1 "Three-loop" Reactor Power System

For these reasons, a three-loop system was adopted for the EBR-II during its conceptual stage. Since that time, the EBR-II system has been analyzed to determine such things as coolant flow rate requirements at various power levels, coolant temperature at various power levels, effects of heat exchanger sizes (system optimization), and effects of control errors. The analyses consisted primarily of writing the steady-state heat balance and heat transfer equations for each heat exchanger in the system, and then solving the equations simultaneously for the unknown variables. The nomenclature employed is as follows:

Nomenclature

A	Surface area, ft^2
c	Specific heat, $\text{Btu}/(\text{lb}_m)(\text{F})$
H_{fg}	Latent heat of vaporization, Btu/lb_m
M	Coolant flow rate, lb_m/hr
P	Reactor power, Btu/hr
T	Temperature, $^{\circ}\text{F}$
U	Overall heat transfer coefficient, $\text{Btu}/(\text{hr})(\text{ft})^2(\text{F})$

Subscripts

C	Coldest
E	Evaporator
H	Hottest
P	Preheater
S	Superheater
T	Primary tank
1	Primary system
2	Secondary system
3	Tertiary (water-steam) system
100	100% reactor power

II. ASSUMPTIONS

The following assumptions were used in the analysis:

1. Overall heat transfer coefficients, U , remain constant regardless of coolant flow rates.
2. All equipment is perfectly insulated thermally.
3. The specific heats of the coolants remain constant.

III. COOLANT FLOW RATE REQUIREMENTS AND TEMPERATURES AT VARIOUS POWER LEVELSA. Heat Exchanger Equations

The equations which apply to the heat exchanger which connects the primary and secondary systems, both of which employ the single-phase coolant sodium, are:

$$T_{H1} - T_{C1} = (T_{H1} - T_{C1})_{100} (\%P)/(\%M_1) \quad (1)$$

$$T_{H2} - T_{C2} = (T_{H2} - T_{C2})_{100} (\%P)/(\%M_2) \quad (2)$$

$$P_{100}(\%P) = 100 (UA)_{1,2} \left[\frac{T_{C1} - T_{C2} - T_{H1} + T_{H2}}{\ln \frac{T_{C1} - T_{C2}}{T_{H1} - T_{H2}}} \right], \quad (3)$$

where P is the reactor power and M the flow rate. Figure 1 indicates the locations of all temperatures T used in the analysis. Equations (1) and (2) are heat balances which are readily obtained from the well-known equation $q = Mc\Delta T$, where c is the specific heat. Equation (3) is the well-known heat transfer equation which describes the behavior of simplified heat exchangers.

One simultaneous solution of eqs. (1), (2), and (3) is as follows:

$$T_{C2} = \frac{T_{C1} + [B(\%P) - T_{C1}] \exp [100 (UA)_{1,2} B/P_{100}]}{1 - \exp [100 (UA)_{1,2} B/P_{100}]}, \quad (4)$$

where

$$B = [(T_{H2} - T_{C2})_{100}/(\%M_2)] - [T_{H1} - T_{C1})_{100}/(\%M_1)]$$

As is apparent, if T_{C1} , $\%P$, $\%M_1$, and $\%M_2$ are given, T_{C2} can be found from eq. (4). Possession of all this information also makes it possible to obtain T_{H1} from eq. (1) and T_{H2} from eq. (2).

B. Equations for the Steam Generator

The boiler originally intended for the EBR-II power system was of the nonrecirculation type; it was baffled so that the entering feedwater came directly in contact with the surfaces containing secondary system sodium. In other words, the boiler contained a preheating section in which the feedwater was heated to the saturation temperature, not by mixing with saturated water, but by heat transfer directly from the secondary system sodium. Therefore, in the analysis it was assumed that the total surface area for preheating and evaporation in the boiler remained constant, due to water level control, but that the preheating area could increase at the expense of the evaporation area, and vice versa.

The equations, then, which apply to the steam-generator equipment which connects the secondary system to the tertiary (water-steam) system are as follows:

$$M_{2,100} c_{P2} (T_{P2} - T_{C2})(\%M_2) = M_{3,100} c_{P3} (T_{E3} - T_{C3})(\%M_3) \quad (5)$$

$$M_{2,100} c_{E2} (T_{E2} - T_{P2})(\%M_2) = M_{3,100} H_{fg} (\%M_3) \quad (6)$$

$$M_{2,100} c_{S2} (T_{H2} - T_{E2})(\%M_2) = M_{3,100} c_{S3} (T_{H3} - T_{E3})(\%M_3) \quad (7)$$

$$M_{3,100} c_{P3} (T_{E3} - T_{C3})(\%M_3) = 100 U_{PA} P \left[\frac{T_{C2} - T_{C3} - T_{P2} + T_{E3}}{\ln \frac{T_{C2} - T_{C3}}{T_{P2} - T_{E3}}} \right] \quad (8)$$

$$M_{3,100} H_{fg} (\%M_3) = 100 U_{EA} E \left[\frac{T_{E2} - T_{E3} - T_{P2} + T_{E3}}{\ln \frac{T_{E2} - T_{E3}}{T_{P2} - T_{E3}}} \right] \quad (9)$$

$$M_{3,100} c_{S3} (T_{H3} - T_{E3})(\%M_3) = 100 (U_A)_S \left[\frac{T_{E2} - T_{E3} - T_{H2} + T_{H3}}{\ln \frac{T_{E2} - T_{E3}}{T_{H2} - T_{H3}}} \right] \quad (10)$$

$$A_P + A_E = (A_P + A_E)_{100} \quad (11)$$

$$P_{100}(\%P) = M_{3,100} [c_{P3}(T_{E3} - T_{C3}) + H_{fg} + c_{S3}(T_{H3} - T_{E3})](\%M_3) \quad (12)$$

Equations (5), (6), (7), and (12) are heat balances and eqs. (8), (9), and (10) are heat transfer equations.

Equations (5) through (11) can be reduced to two simultaneous equations:

$$T_{C2} - T_{C3} = (T_{H2} - T_{E3} - M - N) \exp \frac{100 U_P}{M_{3,100} c_{P3} (\%M_3)} \left[\frac{(A_P + A_E)_{100} - \frac{M_{3,100} H_{fg} (\%M_3)}{100 U_E N} \ln \frac{T_{H2} - T_{E3} - M}{T_{H2} - T_{E3} - M - N}}{\frac{T_{C2} - T_{H2} + M + N}{T_{E3} - T_{C3}} + 1} \right] \quad (13)$$

$$T_{H2} - T_{E3} - M = (T_{H2} - T_{H3}) \exp \frac{100(U_A)_S}{M_{3,100} c_{S3} (\%M_3)} \left[1 - \frac{M}{T_{H3} - T_{E3}} \right], \quad (14)$$

where

$$M = \frac{(T_{H3} - T_{E3})(T_{H2} - T_{C2}) c_{S3}/c_{S2}}{[(T_{E3} - T_{C3}) c_{P3}/c_{P2}] + [(T_{H3} - T_{E3}) c_{S3}/c_{S2}] + H_{fg}/c_{E2}}$$

and

$$N = \frac{(T_{H2} - T_{C2}) H_{fg}/c_{E2}}{[(T_{E3} - T_{C3}) c_{P3}/c_{P2}] + [(T_{H3} - T_{E2}) c_{S3}/c_{S2}] + H_{fg}/c_{E2}}$$

During the process of obtaining eqs. (13) and (14), a third equation, which is convenient for other purposes, was derived from eqs. (5), (6), and (7):

$$\frac{\%M_3}{\%M_2} = \frac{T_{H2} - T_{C2}}{\frac{c_{P3} M_{3,100}}{c_{P2} M_{2,100}} (T_{E3} - T_{C3}) + \frac{c_{S3} M_{3,100}}{c_{S2} M_{2,100}} (T_{H3} - T_{E3}) + \frac{H_{fg} M_{3,100}}{c_{E2} M_{2,100}}} \quad (15)$$

C. Solution of the Equations

In the eight independent eqs. (5) through (12) there are eleven unknowns (%P is always known). Consequently, it is necessary to assign values to three of the unknowns if solutions to the equations are to be obtained. If it is planned to operate with constant feedwater temperature and constant boiler pressure, as in the EBR-II system, then T_{C3} and T_{E3} may be fixed. When this is done, T_{H3} becomes a function of only one other unknown, $\%M_3$, in eq. (12), and it is therefore convenient to fix $\%M_3$. The eight remaining unknowns then are T_{C2} , T_{P2} , T_{E2} , T_{H2} , T_{H3} , $\%M_2$, A_P , and A_E .

The following procedure was used to solve the equations: For given values of $\%P$ and $\%M_3$, the value of T_{H3} followed from eq. (12). The quantity T_{H2} was estimated to be somewhat higher than T_{H3} and eq. (13) was solved by trial and error to find T_{C2} . Then the estimated value for T_{H2} and its corresponding value of T_{C2} were checked in Eq. (14). This entire process, starting with re-estimation of T_{H2} , was repeated if necessary. Then $\%M_2$ came from eq. (15) and $\%M_1$ came, after specifying T_{C1} , from eq. (4), by trial and error. (It is planned to operate EBR-II with a constant reactor inlet temperature.) The value of T_{H1} was found from eq. (1).

Following the calculations, all of the variable system temperatures found, plus the parameters $(\%P)/(\%M_3)$ and $(\%P)/(\%M_1)$, were plotted against $(\%P)/(\%M_2)$ with $\%P$ as a parameter. From this plot it was then possible to determine any temperature or coolant flow rate in the system if $\%P$ and any other system variable not previously fixed were given.

D. Results

As has been mentioned above, in the EBR-II system it is planned to hold the reactor inlet temperature, the boiler feedwater temperature, and the boiler pressure all constant regardless of reactor power level. It has also been pointed out that one more variable may be fixed. (In performing the calculations, it was convenient to fix $\%M_3$.) Of the several possible methods of system control which are therefore available, it seems logical to consider only two, namely, the maintenance either of constant reactor outlet temperature or of constant superheated steam temperature.

By using the plot mentioned in the last paragraph of the preceding section, the coolant flow rates required to maintain a constant reactor outlet temperature at all powers were determined and are plotted in Fig. 2, together with the system temperatures which occur. In Fig. 3 the same variables are plotted likewise for the constant superheated steam temperature method of control. Figures 2 and 3 stress the point that if four system variables are held constant, i.e., T_{C1} , T_{C3} , T_{E3} , and either T_{H1} or T_{H3} , then the primary and secondary system coolant flow rates each must be held at one unique value at each power level, if steady-state conditions are to be obtained. The tertiary system flow rate will be established automatically due to the action of a steam bypass valve which maintains constant boiler pressure (and saturation temperature); Figs. 2 and 3 show the variation of tertiary system flow with power for the cases specified.

Fig. 2

Fig. 3

It should be noted that the actual UA products of the heat exchangers in the system will probably be different from those used in any analysis. Also, the UA products will vary with system power level, since the coolant temperatures and flow rates change with power level. Accordingly, the exact shapes of the curves in Figs. 2 and 3 must, eventually, be determined experimentally.

In order to appreciate several other important features of Figs. 2 and 3, it is desirable to realize that the temperature difference ΔT across one end of each heat exchanger in the system approaches zero at low power levels. This is true because at low powers the heat exchangers, which are built to transfer 100 per cent reactor power, must transfer only a small fraction of full power if steady state is to be maintained (or, to be more specific, if it is desired to keep the primary tank temperature from falling). Since the UA products of the heat exchangers remain comparatively constant, the only way to decrease the power transferred is to decrease the log mean ΔT across each exchanger. To accomplish this in a three-loop system with the fixed temperatures listed in either Figs. 2 or 3, the temperature difference across one end of each heat exchanger must approach a small value at low powers.

Fig. 4

possible to see that the ΔT across one end of each heat exchanger in the system drops below 1°F at less than 20 per cent reactor power.

Figure 4 was constructed to make it possible to determine readily the per cent power, transferred by any heat exchanger, at which the ΔT across one end of the exchanger decreases to an arbitrary low value, namely, 1°F . The values plotted in Fig. 4 were evaluated by means of the following equation:

$$\begin{aligned} \%P &= \frac{(100)(UA) [(\Delta T)_2 - 1] / \ln [(\Delta T)_2 / 1]}{[UA \Delta T_m]_{100}} \\ &= \frac{100 [(\Delta T)_2 - 1]}{\Delta T_{m,100} \ln (\Delta T)_2}, \end{aligned} \quad (16)$$

where $(\Delta T)_2$ is the temperature difference across the other end of the heat exchanger. In the EBR-II system, the $(\Delta T)_2 / \Delta T_{m,100}$ ratio is at least 1.0 for every heat exchanger, and $\Delta T_{m,100}$ is never over 150°F . By using this information, together with Fig. 4, it is pos-

Because of this behavior, it is possible to determine the low-power characteristics of the system with very few calculations. How this may be done is illustrated in Fig. 5, where the 100 per cent power temperatures in the system are plotted against the per cent of reactor power transferred in each heat exchanger. The low-power temperatures may be found by drawing straight lines (characteristic of this temperature-heat transfer type of plot) such that each heat exchanger in the system has a small ΔT across one end. There is only one way in which this may be done for the conditions of Fig. 2, and that is shown by the dotted lines in Fig. 5. Since, as has been noted, the approach ΔT 's are all under 1°F at powers below 20 per cent, it is safe to say that the dotted lines are good for all powers below 20 per cent. The agreement between Figs. 2 and 5 is excellent: both show T_{C2} dropping to 490°F , and T_{H2} and T_{H3} increasing to 900°F at low powers, and all temperatures remain essentially constant at powers below 20 per cent. Since this temperature constancy exists, all flow rates vary linearly with power at powers below 20 per cent (Figs. 2 and 3), and the entire curves of Figs. 2 and 3 may be roughed in with very few calculations.

Fig. 5

Probably the most important result from this analysis is that the coolant inlet temperature on the secondary side of the heat exchanger (T_{C2}) is found to drop considerably at low powers when the boiler contains a preheating section heated directly by secondary system sodium. As indicated in Fig. 5, at 100 per cent power there is a 140°F difference between primary and secondary system coolant temperatures at the cold end of the heat exchanger. This results in a thermal stress in the heat exchanger tubes which is close to the yield point of the tube material. At low powers, the temperature difference increases to 230°F , stressing the tubes above their yield point.

To alleviate this undesirable situation, it was decided to adopt a recirculation boiler and add another steam-heated preheater in the tertiary system to raise the boiler inlet temperature. With this new equipment,

T_{C2} can never drop below the boiler saturation temperature. The maximum fluid-to-fluid temperature difference in the system then always occurs at the hot end of the boiler and cold end of the superheater. For this reason it is advisable to operate with constant superheated steam temperature instead of constant reactor outlet temperature, since with the former mode of operation, the maximum ΔT and associated thermal stresses decrease at low powers instead of increasing. Another reason for adhering to the former mode of operation is that the reactor fuel temperatures are lower during low power operation.

If it is ever established definitely that thermal stresses at the hot end of the boiler and cold end of the superheater are responsible for equipment failures at those locations, several methods, which employ mixers or the like, are available to decrease those stresses. However, there is no justification for using these expensive procedures as long as original leaks in the equipment seem to account for most failures.

IV. EFFECTS OF HEAT EXCHANGER SIZES (SYSTEM OPTIMIZATION)

A. Equations

In the EBR-II power system it is desirable to use (1) a small heat exchanger, because of space limitations within the primary tank; (2) a low secondary system coolant flow rate, to reduce pumping power, pipe size, and/or pump size; (3) a low coolant temperature at the secondary side discharge of the superheater (T_{E2}), to reduce thermal stresses at the hot end of the boiler and cold end of the superheater; and (4) a small boiler and superheater, to reduce cost of equipment.

In order to design a system which best satisfies all these requirements it is necessary to determine the effect of each system parameter upon the others. These effects may be ascertained through the solution of the following simultaneous equations, which describe the system behavior at 100 per cent power:

$$M_{2,100} c_2 (T_{H2} - T_{C2}) = P_{100} \quad (17)$$

$$P_{100} = (UA)_{1,2} \left[\frac{T_{C1} - T_{C2} - T_{H1} + T_{H2}}{\ln \frac{T_{C1} - T_{C2}}{T_{H1} - T_{H2}}} \right] \quad (18)$$

$$M_{3,100} c_{S3} (T_{H3} - T_{E3}) = (UA)_{S2,3} \left[\frac{T_{E2} - T_{E3} - T_{H2} + T_{H3}}{\ln \frac{T_{E2} - T_{E3}}{T_{H2} - T_{H3}}} \right] \quad (19)$$

$$M_{3,100} [c_{P3} (T_{E3} - T_{C3}) + H_{fg}] = (UA)_{E2,3} \left[\frac{T_{E2} - T_{E3} - T_{C2} + T_{E3}}{\ln \frac{T_{E2} - T_{E3}}{T_{C2} - T_{E3}}} \right] \quad (20)$$

$$M_{2,100} c_{S2} (T_{H2} - T_{E2}) = M_{3,100} c_{S3} (T_{H3} - T_{E3}) \quad (21)$$

$$M_{3,100} [c_{P3} (T_{E3} - T_{C3}) + H_{fg} + c_{S3} (T_{H3} - T_{E3})] = P_{100} \quad (22)$$

B. Solution of the Equations

In the six independent eqs. (17) through (22), there are 13 unknowns. In order to obtain solutions to the equations it is necessary to assign values to seven of the unknowns. To comply with the "ground-rule" operating conditions established for the system, T_{C1} , T_{H1} , T_{H3} , T_{E3} , and T_{C3} were fixed during the analysis. (The setting of T_{C1} and T_{H1} automatically eliminated any need for an equation involving $M_{1,100}$.) In addition, arbitrary values were assigned both to $(UA)_{1,2}$ and to T_{H2} . The values of $(UA)_{1,2}$ which were used were compatible with the space limitations of the primary tank, and the values used for T_{H2} ranged from T_{H1} to T_{H3} .

By using the fixed values, $M_{3,100}$ followed immediately from eq. (22). For given values of T_{H2} and $(UA)_{1,2}$, corresponding values of T_{C2} came, by trial and error, from eq. (18). The quantities $M_{2,100}$ and T_{E2} followed from eqs. (17) and (21), respectively, and $(UA)_{S2,3}$ and $(UA)_{E2,3}$ then came from eqs. (19) and (20).

C. Results

The results found for two sizes of the heat exchanger $[(UA)_{1,2}]$ are plotted in Fig. 6. An inspection of the figure indicates that it is impossible to satisfy all of the desirable features listed in Section IV.A. above. For example, reduction of the heat exchanger size is beneficial not only per se, but also because T_{E2} is reduced. However, such a reduction will require a higher secondary system flow rate for any given boiler size. For the conditions shown in Fig. 6, a reasonable compromise seems to be to use a heat exchanger with a UA of about 2.8×10^6 Btu/(hr)(F) and a T_{H2} of 870°F [$M_2 \approx 2.5 \times 10^6$ lb_m/hr; $(UA)_{E2,3} \approx 2 \times 10^6$ Btu/(hr)(F)].

Fig. 6

V. EFFECTS OF CONTROL ERRORS

It was noted in Section III.D that, if the reactor inlet temperature, boiler feedwater temperature, boiler pressure, and either the reactor outlet or superheated steam temperature are held constant, then the primary and secondary system coolant flow rates must each be held at one unique value at each power level, if steady-state conditions are to be established.

The outcomes of a failure to meet these requirements may be studied with considerable ease when only low-power operation of the system is considered. This is true because the temperature difference across one end of each heat exchanger in the system must approach zero at low powers, as explained in Section III.D. For this reason, at low powers $TH_1 \approx TH_2 \approx TH_3$ and $TC_2 \approx TE_3$ (with a recirculating boiler). Accordingly, the heat transfer equations which describe the characteristics of the system no longer contribute any information and only the heat balance equations need be used in an analysis.

These equations are:

$$P = M_1 c_1 (TH_1 - T_T) \quad (23)$$

$$M_1 c_1 (TH_1 - TC_1) = M_2 c_2 (TH_2 - TC_2) \quad (24)$$

In order to understand these equations completely, it is necessary to realize that in the EBR-II system the coolant which leaves the primary side of the heat exchanger dumps into a large "primary tank." The primary system coolant pumps discharge coolant from the tank into pipes leading to the reactor. In eqs. (23) and (24) a distinction is made between

the reactor inlet temperature or primary tank temperature, T_T , and the primary system heat exchanger outlet temperature, T_{C1} . These equations are correct only for steady-state conditions, and when T_{C1} is different from T_T true steady state does not exist. However, the primary tank has such a large heat capacity that small differences between T_{C1} and T_T will not result in significant changes in T_T until long times have elapsed; consequently, eqs. (23) and (24) are accurate enough for this type of analysis.

By combining eqs. (23) and (24) and assuming that $T_{H2} = T_{H1}$ and $T_{C2} = T_{E3}$, as suggested on the previous page, the following expression may be obtained:

$$T_{C1} = X - Y(X + T_T - T_{E3}) + T_T \quad , \quad (25)$$

where

$$X = \frac{P}{M_1 c_1} = T_{H1} - T_T$$

and

$$Y = \frac{M_2 c_2}{M_1 c_1} = \frac{T_{H1} - T_{C1}}{T_{H2} - T_{C2}} \quad .$$

For the EBR-II system, the various terms in eq. (25) have the following values at powers below 20%, when no errors are present:

$$X_0 = 850 - 700 = 150^\circ\text{F}$$

$$Y_0 = \frac{850 - 700}{850 - 580} = 0.555$$

$$T_T - T_E = 700 - 580 = 120^\circ\text{F} \quad .$$

Equation (25) and the above values were used to determine T_{C1} for various quantities of the parameters X/X_0 and Y/Y_0 , where the zero subscript indicates the above "no-error" values. The results are plotted in Fig. 7. From eq. (23) it is apparent that

$$T_{H1} = X + T_T \quad , \quad (26)$$

so the $Y/Y_0 = 0$ line of Fig. 7 may be used to determine $T_{H1} \approx T_{H3}$, as noted. When there is an error in M_1 alone, both Y/Y_0 and X/X_0 change by the same percentage, and T_{C1} varies in the manner indicated by the dotted line in Fig. 7.

Fig. 7

As an illustration of the uses to which Fig. 7 may be put, consider the effect of having the power too high, when M_1 and M_2 are correct. In this case, X/X_0 is larger than unity and Y/Y_0 is equal to unity. Therefore, T_{C1} will be too high, according to the figure.

It should be noted that Fig. 7 should be used only for values of T_{C1} which are in the neighborhood of the control point. Otherwise, some of the assumptions on which eq. (25) is based become invalid. To illustrate, the $(Y/Y_0) = 2$ line in the figure is obviously wrong, since T_{C1} cannot fall below the sink temperature of 580°F. It should be noted also that more accurate calculations indicate that eq. (25) is also quite accurate at power levels above 20 per cent, provided that X_0 and Y_0 are assigned values compatible with the particular power level under consideration.

In order to devise a control scheme for an EBR-II-type power system, it is convenient to assume, first, that either P , M_1 , or M_2 is always correct, and then to determine how the remaining two variables must be altered in order to hold T_{H1} and T_{C1} at the desired values. A colleague of the writers, T. R. Spalding, has pointed out that it is advantageous to consider M_2 always correct, since it takes longer to make changes in M_2 than in either P or M_1 .

An inspection of Fig. 7 makes it apparent that, with M_2 always correct, errors in P or in M_1 cannot be well-defined merely by knowing that T_{H1} and T_{C1} are either high or low. However, it seems important to base the control scheme upon measurements of T_{H1} and T_{C1} , since these two temperatures are probably the most important in the system. Accordingly, a control scheme has been devised which is based on measurements of T_{H1} and T_{C1} , in spite of the weakness mentioned in the first sentence of this paragraph. This scheme is outlined in the Appendix. For comparison, a scheme, based on the assumption that P is always correct, is also presented.

APPENDIX

A proposed control scheme for a three-loop reactor power system is presented in Table 2.

Table 2

PROPOSED CONTROL SCHEME FOR EBR-II POWER SYSTEM*

Measured Variables			Corrective Action	
Case	Reactor Outlet Temperature, T_{H1}	Primary System Heat Exchanger Outlet Temperature, T_{C1}	Reactor Power, P	Primary System Flow Rate, M_1
1	Correct	High	Decrease	Decrease
2	Correct	Correct	None	None
3	Correct	Low	Increase	Increase
4	High	High	Decrease	None
5	High	Correct	None	Increase
6	High	Low	None	Increase
7	Low	High	None	Decrease
8	Low	Correct	None	Decrease
9	Low	Low	Increase	None

*Secondary flow rate is considered always correct.

This scheme requires measurements only of the reactor outlet temperature, T_{H1} , and of the primary system heat exchanger outlet temperature, T_{C1} ; the scheme assumes that the secondary system coolant flow rate is always correct. Listed in Table 2 are the nine possible combinations which the measurements may assume. The reasoning which lies behind the corrective action proposed for each combination, or case, is as follows:

Case 1: Since T_{H1} is correct, X/X_0 is unity (refer to Sect. V for nomenclature of Sect. V). Using this fact, together with Fig. 7, it is apparent that when, in addition, T_{C1} is high, then Y/Y_0 must be less than unity. Accordingly, M_1 is too high (remembering that M_2 is always considered correct). However, when M_1 is decreased, P must also be decreased, in order to keep X/X_0 at unity or T_{H1} correct.

Case 2: Self-explanatory

Case 3: The ratio X/X_0 again is unity, so that when, in addition, T_{C1} is low, Y/Y_0 is greater than unity. Accordingly, M_1 is too low, but when M_1 is increased P must also be increased to keep X/X_0 unity.

Case 4: Since T_{H1} is high, X/X_0 is greater than unity. When T_{C1} is also high, the figure does not show whether M_1 is high or low. Accordingly, the safe thing to do is decrease P to make X/X_0 unity. If T_{C1} remains high until X/X_0 becomes unity, Case 1 applies; if T_{C1} becomes correct before X/X_0 becomes unity, Case 5 applies; and if T_{C1} is correct when X/X_0 becomes unity, Case 2 applies.

Case 5: The ratio X/X_0 is again greater than unity. Figure 7 shows that when, in addition, T_{C1} is correct, Y/Y_0 is greater than unity and M_1 is low. Increasing M_1 will decrease X/X_0 , so no change in P is advisable unless another case develops.

Case 6: Similar to Case 5.

Case 7: Since T_{H1} is low, X/X_0 is less than unity. Figure 7 shows that when, in addition, T_{C1} is high, Y/Y_0 is less than unity and M_1 is high. Decreasing M_1 will increase X/X_0 , so no change in P is advisable unless another case develops.

Case 8: Similar to Case 7.

Case 9: The ratio X/X_0 is again less than unity. When T_{C1} is, in addition, low, Fig. 7 does not show whether M_1 is high or low. Therefore, it is logical to increase P in order to make X/X_0 unity, and not change M_1 unless another case develops.

In Table 3, a proposed control scheme, which assumes the reactor power P is always correct, is presented for comparison. The reasoning used to determine the proposed corrective measures of Table 3 is similar to that used for those of Table 2.

Table 3

PROPOSED CONTROL SCHEME FOR EBR-II POWER SYSTEM*

Case	Measured Variables		Corrective Action	
	Reactor Outlet Temperature, T_{H1}	Primary System Heat Exchanger Outlet Temperature, T_{C1}	Primary System Flow Rate, M_1	Secondary System Flow Rate, M_2
1	Correct	High	None	Increase
2	Correct	Correct	None	None
3	Correct	Low	None	Decrease
4	High	High	Increase	None
5	High	Correct	Increase	None
6	High	Low	Increase	None
7	Low	High	Decrease	None
8	Low	Correct	Decrease	None
9	Low	Low	Decrease	None

*Reactor power is considered always correct.

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