AIM

Association for Information and Image Management

1100 Wayne Avenue, Suite 1100
Silver Spring, Maryland 20910
301/587-8202

Centimeter

Inches

MANUFACTURED TO AIM STANDARDS
BY APPLIED IMAGE, INC.

1 of 1

(CLASSIFICATION)

DECLASSIFIED

This document classified by

E. R. Astley

This document consists of
17 pages, Copy 4 of
17 copies. Series 17

Classified by CG PR-2 and Changed To

DECLASSIFIED

By Authority of CG PR-2,
W. A. Snyder, 1-6-94,
By Jessie M. Allen, 1-10-94,
Verified By J. E. Savely 1-31-94

SHUTDOWN HEAT EXCHANGERS

July 30, 1959

D. L. Condotta

DISTRIBUTION

1. E. R. Astley	13. J. S. McMahon
2. J. R. Carrell	14. F. J. Mollerus, Jr.
3. A. B. Carson	15. W. J. Mundt
4. D. L. Condotta	16. G. J. Rogers
5. W. R. Conley	17-19. M. H. Russ
6. W. J. Gartin	20. R. E. Trumble
7. G. R. Hosack	21. F. W. VanWormer
8. H. G. Johnson	22. G. E. Wade
9. E. M. Kratz	23. D. E. Sebade
10. W. J. Love	24. 300 Area Files
11. W. A. Massena	25. Record Center
12. W. W. McIntosh	26. Burns & Roe, Inc.
	27-29. Extra

RESTRICTED DATA

This document contains restricted data as
defined in the Atomic Energy Act of 1954
transmittal of the disclosure of
content in any manner is unauthorized
persons prohibited

GPO

PRINTED FROM MATHEMATICS

DECLASSIFIED

DECLASSIFIED

HW-61285

SHUTDOWN HEAT EXCHANGERS

INTRODUCTION

Shutdown heat exchangers are required in the NPR primary loop to cool the primary coolant to a working temperature of about 90-120°F for maintenance and charge-discharge operations. Since the main heat exchangers are used to produce steam on the secondary side, they cannot be used for cooling to loop temperature below 212°F. It is, therefore, currently planned that shutdown coolers will be located on each coolant loop downstream from the primary pumps.

It is the purpose of this document to analyze the area requirements of the shutdown heat exchangers and to obtain typical transient coolant temperature curves.

SUMMARY

Typical transient temperature curves for the reactor outlet coolant have been obtained for the cooldown period. These curves are shown on Figures 1, 2, and 3. Additional curves showing the relationship of several variables on the required heat exchanger area were obtained and are shown on Figure 5. Conclusions of this study are:

- (1) Reactor bulk outlet temperatures of about 123°F can be obtained within ~3 hours following a reactor shutdown.
- (2) The reactor bulk outlet can be further reduced to the range of 90 to 100°F by 5 hours following a scram.
- (3) If only 4 loops (80 percent of installed capacity) are available, the 123°F temperature will be reached in about 3-1/2 hours; however, the 5-hour cooldown temperature is 7 or 8°F higher than with 5 loops.
- (4) A heat exchanger area of about 5 to 7000 ft²/loop, depending upon design and river water coolant flow rate, is satisfactory to achieve the above cooldown curves.
- (5) Use of the injection system to introduce a once-through coolant flow of up to 2000 gpm through the reactor helps to reduce the rear face temperatures although not significantly.

Requirements of the Shutdown Heat Exchangers

Two requirements of the shutdown heat exchangers have been specified.

- (1) They must cool the reactor outlet temperature to 123°F within 3 hours after a scram to permit tube discharge operations.⁽¹⁾

(1) Letter M. H. Russ to Burns & Roe, Inc., "After-heat Removal", dated June 26, 1959.

DECLASSIFIED

HW-61285

- (2) They should cool the reactor outlet temperature to about 100°F by 7 hours following a scram to permit extended personnel contact on the rear face for maintenance purposes.(2)

Neither of these two requirements are completely rigid; for example, 123°F in 3.3 hours may be as satisfactory as in 3 hours. Also, numerous variables exist in the conditions that will determine cooldown rate. The reactor after-heat will vary with power level, exposure and graphite period. Because of river water temperature changes, the minimum loop temperature may be 60°F in February and 90°F in August.

Therefore, the calculations shown are general in nature but do show what performance may be expected for various afterheat heat removal systems.

Results

It was assumed that the main heat exchangers will be used to cool the primary loop down to ~220°F and that this temperature could be reached in about 100 minutes following a scram. This time period is governed primarily by the thermal transient restriction of 200°F/hour cooldown rate from a maximum rear face temperature of about 550°F.

When the shutdown heat exchangers are first started, their action is defined by the following transient equation:

$$T_h = T_{R_1} + (T_{h_0} - T_{R_1}) e^{-P\theta} + \left(\frac{K_1}{K_2} \cdot \frac{1}{P} + \frac{m}{K_2 P^2} \right) \left(1 - e^{-P\theta} \right) - \frac{m\theta}{K_2 P} \quad (13)$$

where T_H = reactor outlet temperature

T_{R_1} = river temperature

The term P is a pseudo inverse time constant and is defined as follows:

$$P = \frac{C_P}{K_2} (M_X \mathcal{E} + M_b) \quad (9)$$

where M_X = coolant flow passing through the heat exchangers

M_b = injection - bleed flow.

A derivation of Equation (13) and a definition of all terms is provided in the Appendix.

The term, $\mathcal{E}$, is a heat exchanger effectiveness factor and is defined as follows:

$$\mathcal{E} = \frac{T_h - T_c}{T_h - T_{R_1}} \quad (5)$$

(2) From discussions with W. J. Gartin.

DECLASSIFIED

HW-61285

A plot of Equation (13) is shown on Figure 1 for river water temperatures of 60°F and 70°F. These curves were based on a value of $(M_X \epsilon) = 5 \times 10^6$ #/hr. Any combination of flow and heat exchanger effectiveness factor that gives this value will produce the same curves. Several combinations are presented in the following table:

$\frac{M_X}{\text{gpm}}$	ϵ	$\frac{M_X \epsilon}{\text{\#/hour}}$
20,000	.5	5×10^6
15,000	.667	5×10^6
12,000	.833	5×10^6

Figure 1 shows that with any of the above combinations, a reactor outlet temperature of ~123°F can be obtained three hours following a scram even with 70°F river water. This curve assumes the injection bleed flow is zero.

Figure 2 is a duplicate of Figure 1 except the value of $(M_X \epsilon)$ has been reduced to 4×10^6 or 80 percent of the value used in Figure 1. This curve may be used to interpret what the transient temperatures would be if only four out of five loops were operating and reactor flow was dropped to 80 percent of that with five loops (ϵ will remain constant in this case).

Figure 3 was obtained using a value for $M_X \epsilon$ of 4.5×10^6 , but including the cooling that would be obtained with an additional injection stream of 2000 gpm that passes through the reactor but does not pass through the heat exchanger. For a total reactor flow of 20,000 gpm, Figure 3 represents conditions identical to those used for Figure 1 except the effect of using an injection-bleed stream for cooling is considered. These curves show that lower loop temperature can be obtained by making maximum use of the injection bleed capacity although the change is not very large.

After about 3 hours of operation of the shutdown heat exchanger, the loop temperatures reach a nearly constant condition. When this occurs, the coolant temperature can be estimated by a simpler equation:

$$T_h = T_{R_1} + \frac{Q_R}{C_P} \left(\frac{1}{M_B C_P + \epsilon M_X C_P} \right) \quad (14)$$

where Q_R = heat output of the reactor - Btu/hour

A plot of Equation (14) is shown on Figure 1 for 60°F inlet water. This plot shows that Equation (14) will indicate the reactor outlet temperatures with sufficient accuracy about 5 hours after a reactor shutdown. Figure 4 was prepared using Equation (14) to show the effect of several variables on the rear face temperature at 5 hours after shutdown (or whenever the power level drops to 1 percent of the design power level). Some caution should be applied to using these curves since the heat exchanger efficiency factor, ϵ , is not a constant with changing heat exchanger flow unless the river side flow is changed accordingly.

DECLASSIFIED

HW-61285

Design of the Heat Exchangers

The heat exchanger effectiveness factor, ϵ , is a complex function of the heat exchanger area, heat transfer coefficients, design arrangement, and the ratio of the coolant flows on both sides of the unit. Fortunately, curves for various heat exchanger configurations have been printed in the heat transfer literature.⁽³⁾ Figure 5 has been prepared from this data and is for a typical 1-2 parallel-counter-flow U-tube type heat exchanger. This figure can be used to quickly estimate the afterheat heat exchanger characteristics necessary to achieve the cooldown capabilities shown on Figures 1 through 3. For example:

Assume reactor shutdown flow = 15,000 gpm or $\approx 7.5 \times 10^6$ #/hour. If no once-through injection cooling is assumed, all of this flow passes through the heat exchanger.

$$\therefore M_X \epsilon = 5 \times 10^6 \text{ \#/hour}$$

A typical U for a water to water heat exchanger is 300 Btu/hr-ft²-°F.

If a river coolant flow rate of 10×10^6 #/hour is used, $M_R/M_X = 1.33$. Therefore, from curve b on Figure 1, the required heat transfer area = 33,500 ft². If a U as high as 400 can be obtained, the area requirement can be reduced to 25,000 ft².

A general conclusion would be that a shutdown heat exchanger area in the range of 5 to 7000 ft² on each loop, depending on the heat exchanger design and river side flow rate, will provide sufficient afterheat cooling to meet the basic requirements. Such a system should provide transient curves similar to those shown on Figure 1 and 2 for 5 and 4 loop operation respectively.

Acknowledgement

The writer wishes to acknowledge the considerable assistance of H. Harden in performing the analysis and in doing most of the numerical evaluation of this problem.

A. L. Condotta
ERA

Reactor Design Analysis Unit
Process Design Sub-Section
NPR PROJECT SECTION

DL Condotta:bk

(3) For example, Principles of Engineering Heat Transfer, W. H. Giedt, reprinted from data provided by Kays and London, Stanford University.

DECLASSIFIED

HW-61285

APPENDIX I
DERIVATION OF EQUATIONS

The system of interest when the shutdown heat exchangers are in operation is shown in the following sketch:

A heat balance for the system is

$$Q_R = Q_S + Q_t + Q_B \quad (1)$$

where Q_R = heat generated in the reactor

Q_S = heat accumulated within the system

Q_t = heat transferred from the system through the shutdown heat exchangers

Q_B = heat removed through injection and removal of water from the primary loop

These terms are defined as follows:

Q_R = some function of time per Figure 6. For analytical purposes, Q_R will be defined as a straightline function of time. Therefore,

$$Q_R = K_1 - m \theta \quad (2)$$

DECLASSIFIED

HW-61285

If it is assumed that the temperature change of all components of the system is essentially equal to the change in T_H , then Q_S may be defined simply as

$$Q_S = K_2 \frac{d T_H}{d \theta} \quad (3)$$

where K_2 = a calculated heat capacity of the entire NPR primary thermal system

The third term of Equation (1) is

$$Q_t = M_X C_P [T_H - T_C] \quad (4)$$

However, since T_C is a second variable, the calculations are simplified if the typical heat exchanger efficiency term, $\mathcal{E}$, is introduced in Equation (4). This efficiency term is defined as

$$\mathcal{E} = \frac{T_H - T_C}{T_H - T_{R1}} \quad (5)$$

Curves of $\mathcal{E}$ as a function of $UA/M_h C_h$ and $M_h C_h/M_c C_c$ are available in the literature. By substituting in Equation (5), we obtain,

$$Q_t = M_X C_P \mathcal{E} (T_H - T_{R1}) \quad (6)$$

The fourth term of Equation (1) is defined as

$$Q_B = M_B C_P (T_H - T_{R1}) \quad (7)$$

since it is assumed the injection water is near the river temperature.

By combining Equations (1), (2), (3), (6) and (7), we obtain,

$$K_1 - m \theta = K_2 \frac{d T_H}{d \theta} + M_X C_P \mathcal{E} (T_H - T_{R1}) + M_B C_P (T_H - T_{R1})$$

$$\text{or } - \frac{d T_H}{d \theta} = \frac{C_P}{K_2} (M_X \mathcal{E} + M_B) (T_H - T_{R1}) + \frac{m \theta}{K_2} - \frac{K_1}{K_2} \quad (8)$$

$$\text{Letting } P = \frac{C_P}{K_2} (M_X \mathcal{E} + M_B) \quad (9)$$

DECLASSIFIED

HW-61285

$$\frac{dT_H}{d\theta} + P T_H = P T_{R1} + \frac{K_1}{K_2} - \frac{m}{K_2} \theta \quad (10)$$

Since Equation (10) is a linear equation, it can be integrated to obtain

$$T_H = T_{R1} + \frac{K_1}{K_2} \cdot \frac{1}{P} - \frac{m}{K_2 P^2} (P \theta - 1) + C e^{-P \theta} \quad (11)$$

If we define initial conditions as $T_H = T_{H_0}$ at $\theta = 0$

$$C = T_{H_0} - T_{R1} - \frac{K_1}{K_2} \cdot \frac{1}{P} - \frac{m}{K_2 P^2} \quad (12)$$

Therefore

$$T_H = T_{R1} + (T_{H_0} - T_{R1}) e^{-P \theta} + \left(\frac{K_1}{K_2} \cdot \frac{1}{P} + \frac{m}{K_2 P^2} \right) (1 - e^{-P \theta}) - \frac{m \theta}{K_2 P} \quad (13)$$

Equation (13) can therefore be used to solve for the temperature of the hot leg of the primary loop (T_H) at any time θ , as long as the various constants are defined.

Several hours following a shutdown, the primary loop temperature will be nearly constant. At this time, the term Q_S in Equation (1) can be neglected and a simpler relationship obtained by substituting Equations (6) and (7) in Equation (1).

$$Q_R = M_X C_P \mathcal{E} (T_H - T_{R1}) + M_B C_P (T_H - T_{R1})$$

$$\text{or } T_H = T_{R1} + \frac{Q_R}{C_P} \left(\frac{1}{M_B + M_X \mathcal{E}} \right) \quad (14)$$

This equation gives the reactor exit temperature available for maintenance operations at any time after about five hours following a shutdown.

DECLASSIFIED

HW-61285

APPENDIX II DEFINITIONS OF CONSTANTS

1. Heat Generation

The values of the two constants K_1 and m defining the afterheat generation within the reactor were obtained from Figure 6. This curve had been previously derived and is based on an average fuel exposure of 1000 MWD/T, a graphite period of 45 minutes, and a cooldown of the primary coolant to 220°F within 100 minutes following a shutdown by using the main heat exchangers. In the analytical solution, Figure 6 was approximated by straightline segments to give the following values of K_1 and m .

θ^* hours	K_1 Btu/hour	m Btu/hour ²
1-2/3 to 3	.021x13.652x10 ⁹	.00525x13.652x10 ⁹
3 to 5	.013x13.652x10 ⁹	.00150x13.652x10 ⁹
5 to 10	.010x13.652x10 ⁹	.00040x13.652x10 ⁹

2. Specific Heat

The constant, K_2 , defined as the specific heat of the NPR primary loop, has been estimated to be 2.8×10^6 Btu/°F in the neighborhood of 100°F. A value of 1 Btu/#-°F was used for C_p , the water specific heat in the temperature range of interest.

* During numerical solution, θ at the beginning of each interval is considered as 0.

DECLASSIFIED

HW-61285

APPENDIX III
NOMENCLATURE

A	Heat exchanger area, ft ²
C _p , C _h , C _c	Specific heat at constant pressure (subscripts referring to hot or cold sides), Btu/lb/°F
C	Constant of integration
ϵ	Heat exchanger effectiveness - dimensionless
e	Logarithmic base - 2.71828...
K ₁	Reactor heat rate intercept in plot of reactor heat generation versus time, Btu/hr.
K ₂	Calculated heat capacity of the entire NPR primary thermal system, Btu/°F
m	Slope of plot of reactor heat generation versus time, Btu/hr/hr
M _B	Bleed mass flow rate, lb/hr.
M _c , M _R	Mass flow through the cold side, the river side of the shutdown heat exchanger, lb/hr.
M _X , M _h	Mass flow through the hot side of the shutdown heat exchanger, lb/hr.
P	Inverse time constant, lb/hr.
Q _B	Heat rate due to bleed and raw injection of river water, Btu/hr.
Q _R	Heat generation rate of the reactor, Btu/hr.
Q _S	System storage heat rate, Btu/hr.
Q _t	Heat rate transferred by the shutdown heat exchanger, Btu/hr.
T _c	Temperature of the coolant at the reactor inlet, °F
T _H	Temperature of the coolant at the reactor outlet, °F
TR ₁	Temperature of the river into the secondary side of the heat exchanger, °F
U	Over-all coefficient of heat transfer between the two fluids in the heat exchanger, Btu/hr/ft ² /°F
θ	Time, hours

DECLASSIFIED

HW-61285

APPENDIX III (cont)

Subscripts

b	bleed
c	cold
h	hot
i	inlet
o	initial

DECLASSIFIED

HW-61285

HOT SIDE TEMPERATURE OF HEAT EXCHANGER
VS.
TIME AFTER SCRAM

FIGURE 1

DECLASSIFIED

HW-61285

HOT SIDE TEMPERATURE OF HEAT EXCHANGER
VS.
TIME AFTER SERAM

FIGURE 2.

DECLASSIFIED

HW-61285

HOT SIDE TEMPERATURE OF SHUTDOWN HEAT EXCHANGER
VS.
TIME AFTER SCRAM SIGNAL

FIGURE 3

DECLASSIFIED

HW-61285

REACTOR OUTLET TEMPERATURE 5 HOURS AFTER SCRAM
VS.
TOTAL REACTOR COOLANT FLOW

FIGURE 4.

DECLASSIFIED

HW-61285

COUNTER-FLOW HEAT EXCHANGER AREA VS. HEAT TRANSFER COEFFICIENT

FIGURE 5.

HEAT OUTPUT FROM THE SHUTDOWN REACTOR

For use in design of Shutdown Heat Exchangers; Curve assumes the coolant has been cooled to 220°F by 100 minutes following a scram using main heat exchangers.

Add 0.82 Mw Hrs. of heat for each °F coolant is reduced below 220°F to account for heat capacity of system.

DECLASSIFIED

RM-61285

DLC
7-9-59

DATE

FILMED

10/18/94

END