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ABSOLUTE POWER MEASUREMENTS OF THE FORD NUCLEAR REACTOR

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I. Introduction

Measuring the absolute reactor power level is a problem common to many reactor operations groups. The most obvious need for an accurate determination of the reactor power level is that of satisfying the safety criteria established for a given system. Research reactors, however, are frequently involved with experiments requiring an accurate measure of the reactor power. Furthermore, the statistical significance of experimental measurements that are normalized to reactor power level cannot be meaningfully stated unless the statistical variation of the reactor power level measurement is known.

The more conventional (flow rate) \times (core Δt) method for determining reactor power was investigated with the existing instrumentation at The University of Michigan Ford Nuclear Reactor. The uncertainties in the flow meter calibration accuracy and the errors associated with measuring a 14 °F temperature difference prompted consideration of another technique for power determination. The method investigated is a calorimetric method in which the pool water system is treated as a calorimeter and measurements are made to determine the rate at which energy is being added to the system. The errors inherent in this method appear to be reasonably small and the method has been adopted for routine reactor power measurements by both experimenters and the operations group.

II. Description of Experiment

The Ford Nuclear Reactor (FNR) is a 2 megawatt pool-type reactor containing approximately 48,000 gallons of light water in the pool and primary cooling system. An isometric view of the reactor is shown in Figure 1. The reactor pool is approximately 26 feet deep by 10 feet wide by 20 feet long, one end being a semi-cylinder having

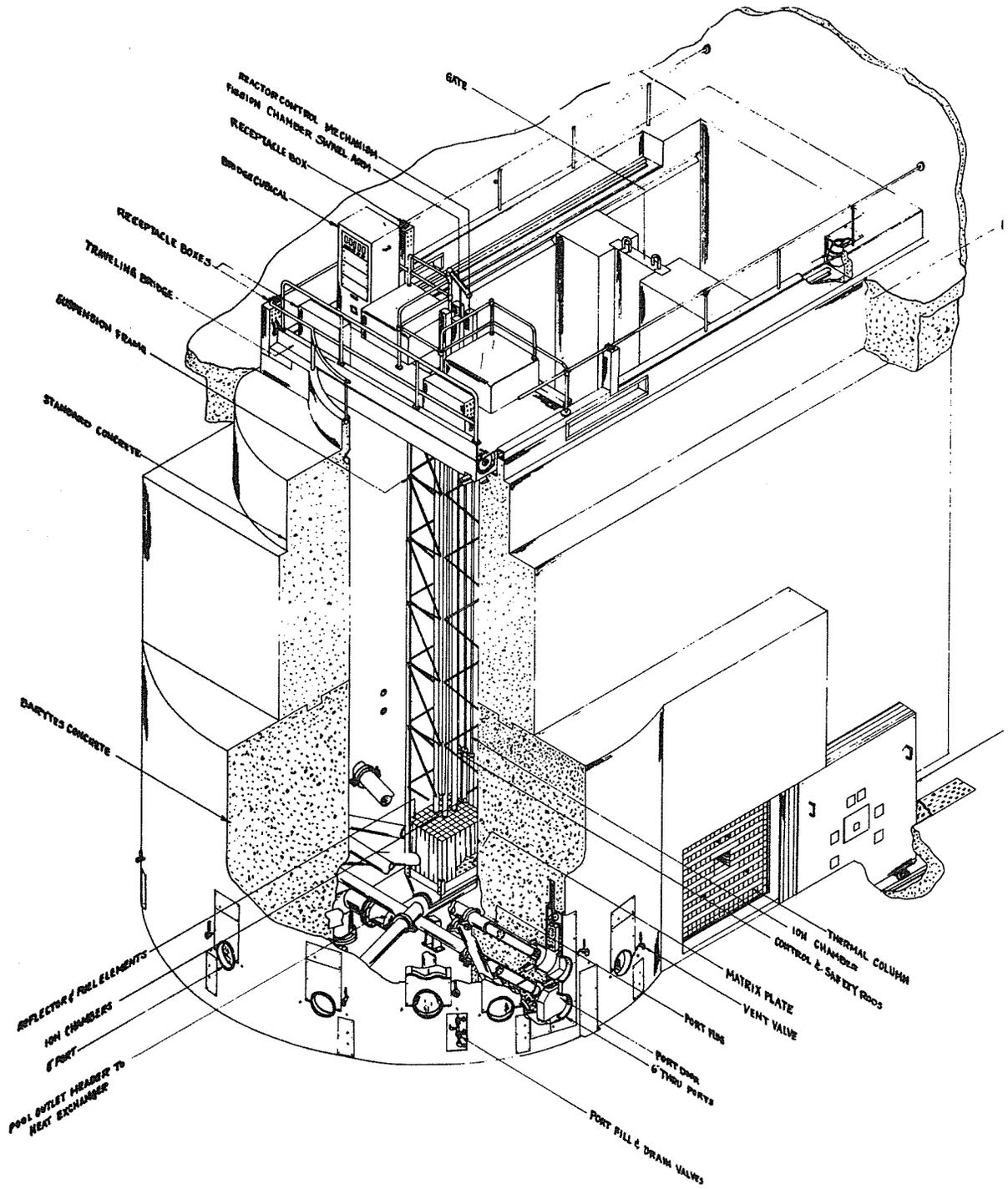


Figure 1 - Isometric View of the FNR

a 5 foot radius. The primary coolant water is pumped down through the core at approximately 1000 gallons per minute through the heat exchanger and back to the pool. The primary return is at the bottom of the pool where a deflector plate is used to spread the returned water over the pool floor.

The calorimeter experiment consists of randomly locating 12 thermocouples in the reactor pool and operating the reactor at full power without the use of the secondary cooling pump. In this mode of operation, it is observed that the return water to the pool is approximately 14 °F warmer than the bulk pool temperature. The combination of the deflector dispersion and the buoyant forces due to the 14 °F temperature difference result in a thorough mixing of the reactor pool water during the calorimeter experiment. This postulated mixing is confirmed by the observation that the thermocouples measure the same rate of increase of the pool temperature regardless of their location. The thermocouple data are subsequently analyzed with the aid of an IBM-7090 computer to determine the mean rate of increase of the bulk pool temperature and the statistical variation of the measurement.

For the case of a perfect calorimeter it may be recalled that the rate of energy input to the system is simply the product of the mass of the pool water, the specific heat of the water and the average rate at which the pool temperature increases. Two obvious bias errors which must be evaluated for the experiment are 1) heat losses from the system during the experiment, and 2) the accuracy of the pool water mass.

III. Bias Errors

Calculations for the heat losses from the reactor and primary system were made by using conservative heat transfer models which tend to overestimate the energy loss and thus to establish an upper limit estimate for the error in neglecting the losses. The loss factors considered were 1) conduction from the pool water to the ceramic tile lined reactor shield tank, 2) evaporation and radiation losses from the 246 ft.² pool surface, and 3) convection and radiation losses from the heat exchanger and primary piping. The details of the calculations are shown in Appendix A and a summary of the results is presented in Table I. It should be emphasized that all of these estimates are upper limit estimates and that the actual losses are expected to be lower than the 3.6% indicated by these calculations.

TABLE I

Summary of Heat Loss Calculations

<u>Loss Mechanism</u>	<u>Max. Energy Loss During Experiment</u>
Thermal radiation from pool surface	11.1×10^3 BTU
Thermal radiation from primary piping	17.6×10^3 BTU
Evaporation from pool surface	39.2×10^3 BTU
Convection from primary piping components	12.2×10^3 BTU
Conduction to pool walls	167.0×10^3 BTU
Total Losses	247.1×10^3

To determine the possible error in the pool water mass, accurate measurements were taken of the pool dimensions. These measurements indicate that the pool volume is known to within $\pm 1\%$. Corrections are made for the primary coolant system and any large objects in the pool at the time of the experiment.

IV. Data Analysis

An essential part of the data analysis procedure was in determining the copper-constantan thermocouple calibration constants. The entire temperature measuring system, including the thermocouple switch box and potentiometer readout device, was calibrated by making repeated thermocouple measurements in a water filled Dewar flask. The Dewar temperature was determined with a mercury thermometer which was graduated in 0.1 degrees centigrade and read to the nearest 0.05 °C. The calibration experiment consisted of taking measurements at various temperatures with the potentiometer readout dial being changed and readjusted for each measurement. Approximately 100 points were taken on each thermocouple and the data was reduced by a least squares analysis to determine the 95% confidence interval and the mean value of the calibration constant over the temperature range of interest.

Recall that the object of the calorimeter experiment is to accurately determine the mean rate of increase of the pool water temperature. This determination is made by fitting each set of thermocouple data to a straight line by the least squares method. The details of the statistical method used are given in Appendix B. From this analysis the value of the slope and its standard deviation are determined. The results of several experiments are plotted in Figure 2 along with the thermocouple calibration data. The error bar shown for each thermocouple represents the 95% confidence interval for the

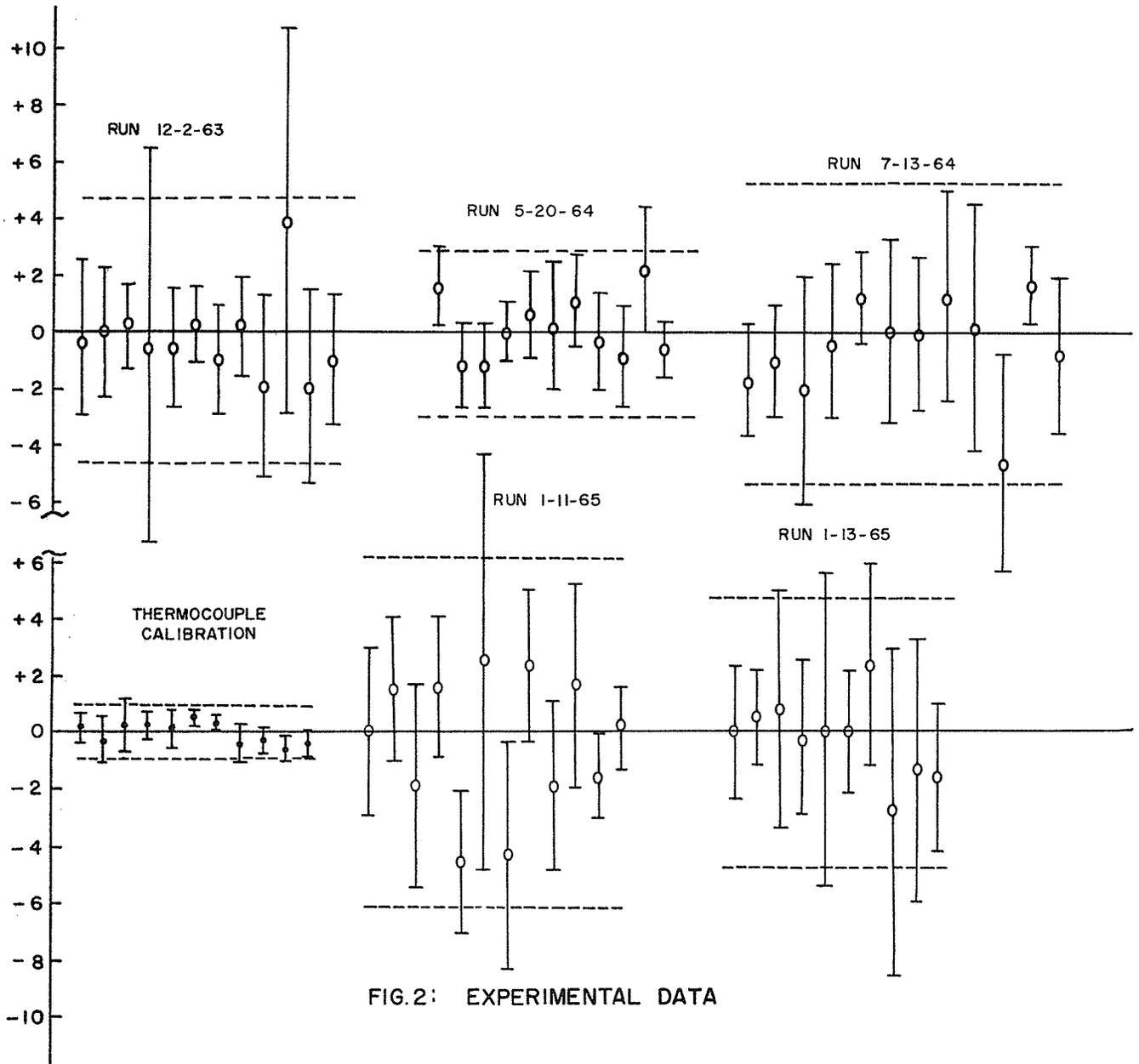


FIG. 2: EXPERIMENTAL DATA

Figure 2 - Experimental Data

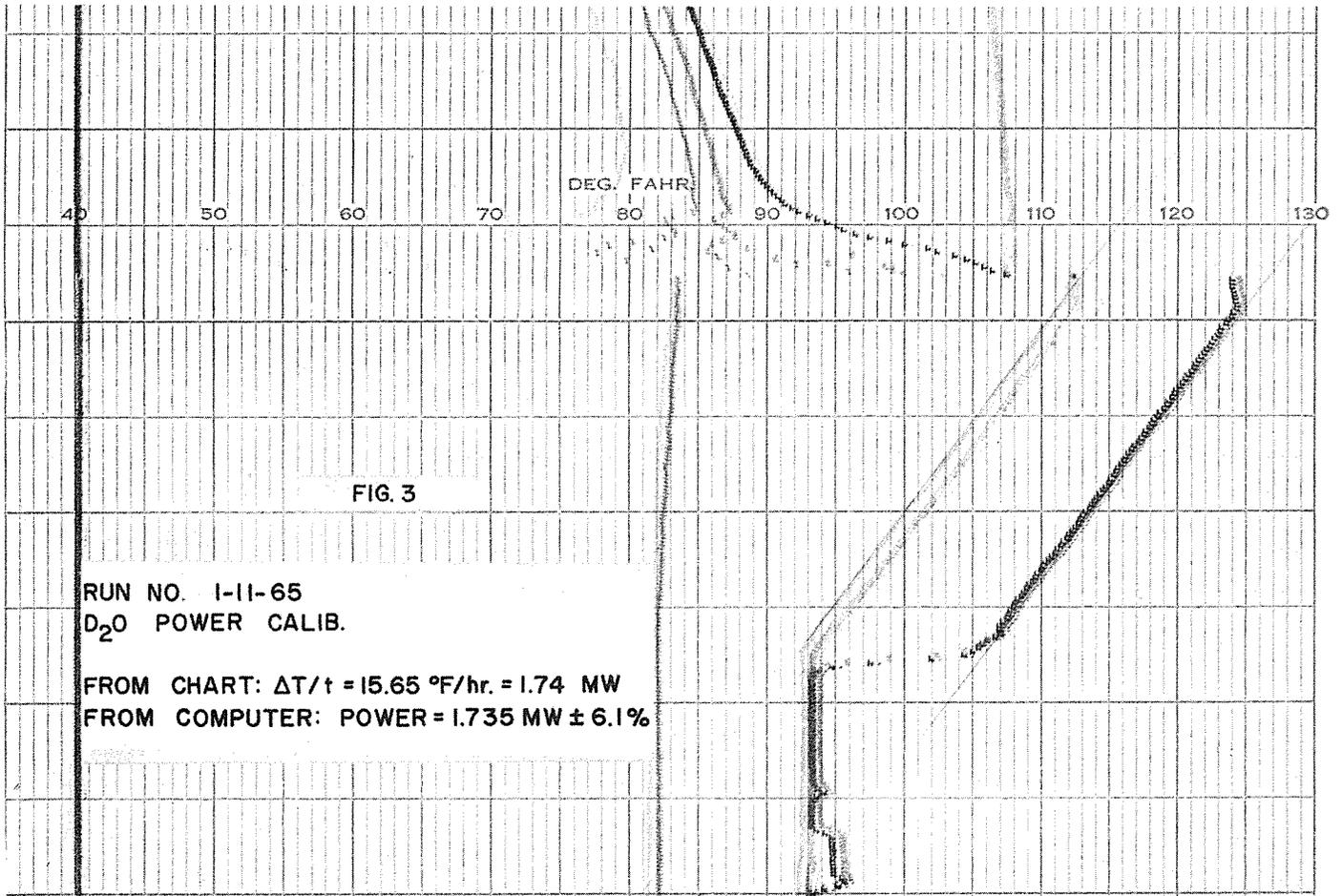
slope as determined from each set of raw thermocouple data. After determining the average value of the slope from each thermocouple, a mean value for the average of all thermocouple slopes is determined and is taken to be the mean rate of the pool temperature increase. The t distribution is used to calculate the 95% confidence interval for this average. The "dashed" line shown in Figure 2 represents the 95% confidence interval for each of the calorimeter experiments.

The thermocouples having a large variation were located at positions in the pool where the flow conditions caused a continuous movement of the T. C. during the experiment. The removal of these data from the calculations would result in a marked reduction of the confidence intervals.

During the routine calorimeter experiment data is also collected on the reactor control system temperature chart. By visually fitting a straight line to the slope on the temperature chart, it is also possible to get an estimate of the rate of increase of the pool temperature. Analysis of the temperature charts for several calorimeter experiments clearly indicates that the mean reactor power level can be determined from the strip chart recorder with reasonable accuracy. A typical trace is shown on Figure 3. The strip chart data technique is now frequently used for experiments and reactor operations requiring a quick reference to the absolute power.

V. Conclusions

The calorimetric power determination technique can be used to determine the reactor power level for systems having low heat losses, to within a few per cent. The method can be used to calibrate relative power measuring devices and to determine the confidence level for reference power meters.



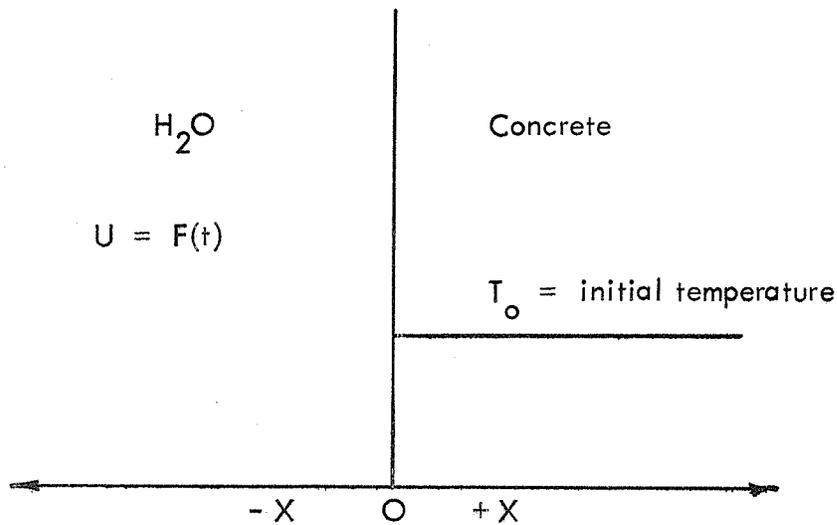
VI. Acknowledgements

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APPENDIX A

I. Conduction Losses from Pool to the Shield

Assume the walls of the pool to be an infinite slab extending from $X = 0$ to $X = +\infty$, and the pool water as slab extending from 0 to $-\infty$. Assume an infinite heat transfer coefficient between pool water and pool walls (i.e. no film drop). Since the temperature of the pool increases with time, the heat losses from the pool will be a function of time.



Using the notation and method of Churchill⁽¹⁾, the heat diffusion equation is

written:

$$(1) \quad U_t(x, t) = K U_{xx}(x, t) \quad (x > 0, t > 0)$$

with boundary conditions:

$$(a) \quad U(x, 0) = T_0 \quad (x > 0)$$

$$(b) \quad U(0, t) = gt \quad (t > 0)$$

$$(c) \quad \lim_{x \rightarrow +\infty} U(x, t) = T_0 \quad (t > 0)$$

$$x \rightarrow +\infty$$

Transforming equation (1) and applying B. C. (a):

$$(2) \quad -T_o + s u(x, s) = K u_{xx}(x, s) \quad (x > 0)$$

$$\text{and B. C. (b) becomes } u(0, s) = \frac{g}{s^2}.$$

The real solution of (2) is:

$$(3) \quad u(x, s) = A e^{-x \sqrt{\frac{s}{k}}} + \left(\frac{T_o}{s}\right).$$

$$\text{Using B. C. (b): } A = \frac{g}{s^2} - \frac{T_o}{s}.$$

$$(4) \quad u(x, s) = \left(\frac{g}{s^2} - \frac{T_o}{s}\right) e^{-x \sqrt{\frac{s}{k}}} + \left(\frac{T_o}{s}\right)$$

The heat flux per unit area is:

$$\frac{\phi(t)}{A} = K U_x(0, t),$$

thus from (4) and after inverting:

$$(5) \quad \frac{\phi(t)}{A_w} = \frac{K}{\sqrt{k\pi}} \left[2g \sqrt{t} + \frac{(F_o - T_o)}{\sqrt{t}} \right]$$

where $F_o = U(x, 0) \quad (x < 0)$

or, $F_o = F(0, t)$.

To estimate the total heat lost during operating time T , (5) is integrated as follows:

$$(6) \quad Q_T = \frac{A_w K}{\sqrt{k\pi}} \left[\frac{4}{3} g T^{3/2} + 2(F_o - T_o) T^{1/2} \right]$$

The thermal properties for barytes concrete are given by Rockwell⁽²⁾ as:

$$K = .884 \text{ BTU/hr. ft.}^2 \text{ } ^\circ\text{F}$$

$$k = .0250 \text{ ft.}^2/\text{hr.}$$

The total area of concrete in contact with pool water is:

$$A_w = 2270 \text{ ft.}^2$$

From a calibration experiment at 2 MW, g was found to be approximately constant and equal to $18.0 \text{ } ^\circ\text{F/hr.}$

Whenever the initial wall temperature is the same as the initial pool temperature,

$F_o = T_o$, and equation (6) becomes:

$$(7) \quad Q_T = \frac{4A_w K g T^{3/2}}{3\sqrt{k\pi}}$$

During the calibration experiment the pool temperature increases for one hour.

Therefore, the maximum possible heat loss to the shield is :

$$Q_T = \frac{4 \times 2270 \times .884 \times 18.0}{3 \times \sqrt{.0250 \pi}} = 1.67 \times 10^5 \text{ BTU}$$

II. Radiation Heat Losses

The conventional equation⁽³⁾ for heat losses by radiation from a surface of constant temperature T_s to an environment at temperature T_a is

$$q = A_s \xi \sigma \left[\left(\frac{T_s}{100} \right)^4 - \left(\frac{T_a}{100} \right)^4 \right] ,$$

it may be seen that the time dependent case can be written as:

$$q_{(t)} = A_s \xi \sigma \left[\left(\frac{T_{s(t)}}{100} \right)^4 - \left(\frac{T_a}{100} \right)^4 \right] .$$

The total heat loss by radiation during an experiment in which T_s increases linearly at g °F/hr. from T_o to T_{max} in time t is obtained by integrating $q_{(t)}$:

$$Q_T = A_s \xi \sigma \left\{ \frac{20}{g} \left[\left(\frac{gt + T_o}{100} \right)^5 - \left(\frac{T_o}{100} \right)^5 \right] - \left(\frac{T_a}{100} \right)^4 t \right\} .$$

During a standard calorimeter experiment at 2 MW, the pool temperature increases at ~ 18 °F/hr. to a maximum of 116 °F. The initial temperatures are $T_o = 98$ °F and $T_a = 80$ °F. The use of these constants in the above equation with $\xi = 1.0$ gives the maximum total heat loss from the pool surface as:

$$Q_T = 1.11 \times 10^4 \text{ BTU} .$$

The same equation is used to estimate the maximum losses by radiation from the 88 feet of 12 inch primary pipe and heat exchange. For this case however, T_{\max} is 130°F and T_o is 112°F . The calculation yields:

$$Q_T = 1.76 \times 10^4 \text{ BTU .}$$

III. Convection Losses from Horizontal Piping

A simplified equation for the convection coefficient from the horizontal primary piping at constant temperature is given on page 177 of reference 3 as:

$$h_c = .27 \left(\frac{\Delta t}{D_o} \right)^{0.25}$$

This equation can be written for the time dependent temperature case as:

$$h_{c(t)} = .27 \left(\frac{T_{p(t)} - T_{\text{air}}}{D_o} \right)^{1/4}$$

or, in terms of the heat loss as a function of time:

$$Q_{(t)} = h_{c(t)} (T_{p(t)} - T_{\text{air}}) \pi D_o L .$$

After substituting for $h_{c(t)}$, the time dependent heat loss relation is:

$$Q_{(t)} = \frac{.27 \pi D_o L}{D_o^{1/4}} (T_{p(t)} - T_{\text{air}})^{5/4} .$$

The total heat loss in operating time t is obtained by integrating, thusly:

$$Q_T = .27 \pi D_o^{3/4} L \int_0^t (T_{p(t)} - T_{air})^{5/4} dt,$$

and, since $T_{p(t)} = T_o + gt$

$$Q_T = .27 \pi D_o^{3/4} L \frac{4}{9g} \left| (gt + T_o - T_{air})^{9/4} \right|_0^t$$

For the standard one hour experiment $(T_o - T_{air}) = 32^\circ\text{F}$ and $gt \sim 18^\circ\text{F}$, therefore, the convection power loss from the 88 feet of 12 inch primary piping can be calculated to be:

$$Q_T = 1.22 \times 10^4 \text{ BTU}.$$

IV. Evaporation Losses

The water evaporation rate is calculated by using the equation from Brown⁽⁴⁾:

$$W = 240 + 3.7 T (P^* - P).$$

where:

$$W = \text{H}_2\text{O evaporated in grains/hr.} - \text{ft.}^2.$$

$$T = \text{pool water temperature} - ^\circ\text{F}.$$

$$P^* = \text{Vapor pressure of H}_2\text{O at } T - \text{in. Hg.}$$

$$P = \text{Partial pressure of H}_2\text{O vapor in air} - \text{in. Hg.}$$

The equation is written for the variable temperature case as:

$$w(t) = 240 + 3.7 T(t) (P^*(T) - P).$$

A simplification which results in a maximum estimate for the evaporation rate is obtained by assuming:

$$P^*(T) = \alpha + \beta (T_{(t)} - T_o),$$

where, $\alpha = 1.82$ and $\beta = .0702$.

The equation for the evaporation rate as a function of time is therefore:

$$w(t) = 240 + 3.7 T_{(t)} \left[\alpha + \beta (T_{(t)} - T_o) - P \right].$$

For the case $T_{(t)} = gt + T_o$, the equation is written:

$$w(t) = 240 + 3.7 (gt + T_o) (\alpha + \beta gt - P).$$

Integrating from $t = 0$ to $t = 1$ hr. gives:

$$W = 240 + 3.7\beta \frac{g^2}{3} + \left[(T_o + \frac{\alpha - P}{\beta}) \frac{g}{2} + T_o \frac{(\alpha - P)}{\beta} \right].$$

This equation has been evaluated for the maximum conditions of a 20% relative humidity in 70 °F building air and for T_{\max} of the pool = 116 °F.

The equation predicts a maximum of 40.5 lbs. of pool water will evaporate during the experiment. The total energy lost due to the heat of vaporization of the pool water is, therefore:

$$Q_T = 3.92 \times 10^4 \text{ BTU.}$$

APPENDIX B

I. Statistical Methods

The thermocouple data is recorded with the aid of a stopwatch so that time errors or variations may be neglected in the data analysis. Imposing this condition, the data approximates a straight line so that deviations in y can be written:

$$\delta y_i = y_i - (a + b x_i)$$

To minimize the deviations, the least squares method imposes:

$$\frac{\partial \left[\sum_i (\delta y_i)^2 \right]}{\partial a} = 0$$

and,

$$\frac{\partial \left[\sum_i (\delta y_i)^2 \right]}{\partial b} = 0$$

The solution of the equations which result from the application of these conditions can be written in terms of the mean slope as:

$$\bar{b} = \frac{n \sum x_i y_i - \sum y_i \sum x_i}{n \sum x_i^2 - (\sum x_i)^2}$$

The variance for \bar{b} has been derived⁽⁵⁾ as:

$$\sigma_b^2 = \frac{N}{N-2} \frac{\sum y_i^2 - 2a \sum y_i - 2b \sum x_i y_i + Na^2 + 2ab \sum x_i + b^2 \sum x_i^2}{N \sum x_i^2 - (\sum x_i)^2}$$

The mean of all slopes is calculated by:

$$b^* = \frac{\sum_k (\bar{b}_k / \sigma_k^2)}{\sum_k 1 / \sigma_k^2} .$$

The variance for b^* is calculated by the variance of sums theorem:

$$\sigma_{b^*}^2 = \frac{1}{k} \sum_{i=1}^k \left[\sigma_i^2 + (\bar{b}_i - b^*)^2 \right] .$$

References

1. Churchill, R. V., Operational Mathematics, 2nd Ed., McGraw-Hill Co., Inc., p 132, 1958.
2. Rockwell III, T., Reactor Shielding Manual, 1st Ed., D. Van Nostrand Co., Inc., p 186-187, 1956.
3. McAdams, W. H., Heat Transmission, 3rd Ed. , McGraw-Hill Co., Inc. Eqn. 4-9, 1954.
4. Brown, G. G., Unit Operation, John Wiley and Sons, p 557, 1954.
5. Parrat, L. G., Probability and Experimental Errors in Science, John Wiley and Sons, p 131, 1961.