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Technical Activities Report

Heat Transfer Studies

January 1952

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TECHNICAL ACTIVITIES REPORT

COPY 1 OF 1, SERIES A

HEAT TRANSFER STUDIES

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In Charge, Heat Transfer Studies
Pile Technology Unit
Engineering Department

February 1, 1952

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HEAT STUDIES - M. W. Carbon

BOILING CONSIDERATION STUDIES - R. O. Vanderwater

A document recommending a revision of the tube power limits has been issued. It is titled, "Boiling Limits", HW-23251, January 22, 1952. Uncontrolled boiling of the water in a process tube would result in high slug, tube and graphite temperatures and probably cause serious damage to the pile. Therefore, it is desirable to operate the piles with sufficient header pressure to minimize the possibility of boiling as well as to sweep the vapor from the tube should boiling occur. The pressure required to provide this protection was determined experimentally. However, to allow for experimental errors, power measurement errors, and variations from tube to tube, the recommended header pressures were increased to 23% above the values determined from the experimental data.

The recommended limits, based on a 23% factor, will be, on the average, about 1% lower at the B, D, and F Piles and 3-4% higher at H and DR piles than the present tube power limits. The present limits are given in document HW-19637, "Allowable Temperature Rise in Process Tubes", J. T. Carleton, December 5, 1950. The power levels of B, D, and F Piles are limited by graphite temperatures at present. Hence, no immediate effect of the change in limits is anticipated at those piles. However, the H and DR Piles are being operated at the present boiling limit. Thus, the increase in the limit would permit an increase in power level at the latter piles.

The limits given in HW-23251 are on a basis of tube power level versus header pressure. To simplify the use of the limits, they have been converted to a permissible tube water Δt versus header pressure basis. The Δt limits are given in a second document: "Tube Temperature Rise Limits - Boiling Considerations", HW-23274, January 24, 1952. The Δt limits are also included in this report in the section "Pile Process Specifications - Boiling Consideration Limits".

The permissible tube power limit for a given header pressure and tube condition is the same at all the piles. However, the Δt limits are given as a function of both header pressure and Panellit pressure. For a given header pressure and Panellit indication, the flow through an inlet nozzle of the type used at the B, D, and F Piles is slightly different from that through a nozzle of the type used at the DR and H Piles. Thus, the permissible Δt 's for the B, D and F Piles differ slightly from those at the DR and H Piles.

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WATER FLOW AND POWER LEVELS AT INCREASED HEADER PRESSURES - W. D. Gilbert

An estimate has been made of the water flows, tube inlet pressures, and boiling limits which may be attained if the crossheader pressures were increased. These data were based on the following conditions: (a) standard tube loading, (b) 20°C inlet water temperature, (c) 10 psi film drop, and (d) tube in top row in pile. The boiling limits were obtained from Document H¹-23251, Boiling Limits, R. G. Vandewater, 1-22-52. Additional power corrections may be applied as given in Document H¹-23254, Tube Temperature Rise Limits - Boiling Considerations, R. G. Vandewater, 1-24-52.

The estimated values are given below.

<u>Header Pressure</u>	<u>Orifice Size</u>	<u>Inlet Tube Pressure</u>	<u>Tube Power-K¹ Based on Boiling Limits</u>	<u>Pile Power-MW Based on Boiling Limit</u>	<u>Water Flow-gpm</u>
400	0.240	220	400	540	22.0
450	0.240	245	455	615	23.4
500	0.240	270	505	630	24.8
550	0.240	295	555	750	26.1
400	0.285	230	410	555	24.4
450	0.285	315	465	630	25.9
500	0.285	350	515	695	27.4
550	0.285	380	565	765	28.9
400	None	350	415	560	23.0
450	None	390	470	635	30.0
500	None	435	520	700	31.8
550	None	490	570	780	33.5

Values for the pile power levels were based on 1350 effective power tubes per pile.

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TESTING OF TIME DELAY RELAY - PRODUCTION TEST 105-502-E - W. D. Gilbert

The Microflex mechanical time delay relay, set at a three-second delay time, has been in operation at the 100-B Pile for a total period of 39 days. During the initial portion of the period, the relay was used only to record Panollit data and not as an operating part of the scram circuit. Since January 14, 1952 the relay has been connected into the No. 2 Safety Circuit. The following test data, using the three-second delay, have been obtained:

	<u>No. 2 Safety Circuit</u>	<u>Total</u>
1. Number of days of operation on 3 second delay, including shutdowns	1	39
2. Panollit trips, total, including tests and routine checking	35	222
3. Panollit Trips other than tests and checking	0	0

To date, no scrams or unusual difficulties have been experienced using the automatic time delay in the No. 2 Safety Circuit. This may be due, in part, to the following:

1. More rigid inspection and maintenance of the Panollit gages.
2. Raising the upper trip limits on numerous Panollit gages to prevent Panollit Alarms due to film build-up.
3. Use of the by-pass switch to the No. 2 Safety Circuit when testing the Panollit row lights or rewiring the Panollit gages.

Work is being done to devise a suitable system to permit working on the Panollit gages without by-passing the Safety Circuit. Also, the necessity for by-passing the Safety Circuit when the row lights are being checked is being investigated.

The time delay relay at 100-B was "function-tested" during a shutdown for a ruptured slug on January 26, 1952. A Panollit was purposely tripped in order to actuate the time delay relay. After holding the Panollit circuit open for three seconds, the pile was successfully scrambled with the No. 2 Safety Circuit.

With suitable trip limit changes and Panollit gage maintenance, it appears that the Panollit System could be placed on an automatic instantaneous scram. This probably would not cause a great number of shutdowns, since it has been shown at B Pile that only one shutdown would have resulted from a Panollit trip in more than three months of operation.

Supplement A to the Production Test, Document HW-23085, has been issued. It authorizes the use of the time delay relay and the No. 1 Safety Circuit to scram the pile. The change from the No. 2 to the No. 1 Safety Circuit is expected to be made at the next shutdown, probably on February 5, 1952.

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An additional 10 Microflex time delay units have been purchased and have arrived on the plant. These will be installed, two per pile, as soon as the necessary electrical changes have been completed in the Safety Circuits. Two relays are to be used in parallel at each pile so that a failure of one will not result in an unnecessary scram.

A flux decay type of time delay relay has also been ordered. This type of timer is believed by Electrical Section to be more "fail safe" than the Microflex, because it contains no moving parts. As soon as received, this time delay relay will be tested at 100 B Pile.

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HR-2344B

SLUG TEMPERATURE CALCULATIONS - H. H. Greenfield

In support of the slug development program, equations giving slug jacket and axial temperatures for a large variety of operating conditions have been set up. The calculations will be done by the Computing Unit of the Mathematics Section.

The equations are based on the following conditions:

- (1) 1.440" diameter slug can
- (2) 1.360" diameter uranium slug
- (3) Thermal conductivity of unirradiated uranium based on Kuniansky's T&E #5 data.
- (4) Cosine flux distribution, front to rear.
- (5) Augmentation distance of 35 cm. for each end of the slug column.
- (6) "older an" into correlation of water film heat transfer coefficient.
- (7) Temperature drop across the scale based on data given in documents "10-58" and 3-2206.
- (8) 1350 effective power tubes
- (9) 2,000 tube pins.

The operating variables and the range of these values that will be used in calculating slug surface and axial temperatures are as follows:

- (1) Process tube annulus size - standard, C-Pilo and Z*-Pilo
- (2) Process tube length - 23.2 to 31.2 feet
- (3) Tube power - 50 to 1,000 KW
- (4) Inlet water temperature - 0-30°C
- (5) Tube water flow - Standard Annulus - 20 to 40 gpm
C-Annulus - 20 to 55 gpm
"Z" Annulus - 20 to 70 gpm
- (6) **Pressure drop scale - 0 to 40 lbs/sq in
- (7) Temperature drop through slug jacket and bonding material: 0 to 200°C
- (8) Ratio of assumed conductivity of irradiated uranium to that for unirradiated uranium: 1.0 to 0.1

It is anticipated that, due to the large number and range of variables, these calculations will conservatively take from six to eight weeks to complete.

**Z" Annulus is assumed to be 1.5 times the water flow area of the standard process tube annulus.

**Pressure drop scale referred to a 20.4 gpm flow through a standard process tube annulus with a standard active total length.

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DISCONTINUITY IN SLUG BONDING - D. E. Aros and K. G. Toyoda

The 3-inch slugs which are presently being examined in 300 Area have aluminum jackets approximately 10 mils thicker than those on 4" slugs. During the month it was found that the 3" canned slugs were being rejected at a high rate from pile use by the "frost" test. Since the ultimate cause of rejection was unknown, an immediate investigation was begun to determine whether the thicker jacket would permit the use of slugs having discontinuities larger than those permitted on the 4" slugs.

Such discontinuities may roughly be considered as gaps in the bonding layer between the uranium and the jacket. The effect of the discontinuities is to prevent the flow of heat through the area. This causes a high temperature "ring" on the jacket surrounding the area during the use in the pile (i.e., when heat is flowing from the center of the slug to the surface). It was believed that the thicker jackets would permit the use of slugs with discontinuities greater than the 1 mil diameter permitted for 4" slugs. The reason for the belief was that the thicker aluminum should tend to permit more heat flow along the jacket and thus "smooth out" the jacket surface temperature profile. Before the investigation could be completed, the cause of slug rejection was discovered and rectified. The investigation is being continued but at a much slower rate.

Preliminary considerations indicate that void areas 25% greater than the present limit might be tolerated in the 3" slugs. This is largely due to the fact that the 3" slugs have jacket thicknesses 25% greater than the 4" slugs. However, it is believed that a re-evaluation of the actual increase in surface temperature for a given discontinuity is in order. Thus, the problem is being approached from an absolute temperature standpoint rather than from a relative one. Since the problem is not pressing, and since it is very difficult mathematically, it will be assigned a low priority.

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MEASUREMENT OF SLUG BOND COEFFICIENTS - D. E. Aros

In order to keep slug uranium temperatures at a minimum, the temperature drop between the uranium and aluminum jacket must be low. Metallurgy is considering the use of bonds other than Al-Si. To determine the proper choice, the heat transfer properties of these bonds must be measured experimentally.

Calculations on the temperature drops resulting from heat fluxes comparable to those in the piles (100 watts/cm²) showed drops of 1000°C/in. in uranium. In order to run the experiment with as low a temperature as possible, an arrangement of 1" copper and aluminum cylinders separated by a 1/4" uranium disc was chosen. The temperature drops across the various metals are approximately:

Copper	70°C
Uranium	250°C
Aluminum	<u>130°C</u>
Total	450°C

An examination of these figures shows that small thermocouples must be used to obtain accurate temperature measurements since the drop in the uranium is about 100°C/in. Thermocouples from 3 to 10 mils in diameter were considered satisfactory.

A heater, into which the copper end of the test specimen is inserted, is being designed for 700 watt operation. Water flowing across the aluminum end of the specimen will remove the heat. The whole apparatus will be insulated, and thermocouples placed in grooves in the metal at convenient intervals will provide a check on heat losses as well as the total flux through the specimen.

This apparatus is being constructed. It is expected to take several weeks before experiments will start.

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PRESSURE DROP FILM STUDIES - K. G. Tryda, H. H. Greenfield, and P. RoachTest Facilities

A survey of facilities available for a study of the effects of film or scale formation on temperature drop between the slug jacket and cooling water was conducted. The purpose of the survey was to determine whether any equipment from other experimental units could be adapted for use concurrently with the film investigation. Tests for determining heat transfer data are to be performed on the short tube heat transfer rack-up in 189-D. The major needs from an economic and time consideration are that of procurement of heat exchangers, temperature indicating and recording devices, and water flow indicators.

Film formation runs can be conducted at 105-D flow lab and 189-D, two at the former and one at the latter. These facilities are now available if no temperature difference between the heater tube and process tube is desired. Thus, conditions during film formation will be such that the heater surface temperature is equal to the bulk water temperature. Some facilities for maintaining a temperature difference between the heater tube and water can be made available in the 105-D flow laboratory.

Preliminary data for calculation of clean tube, water heat transfer coefficients in the short scale rack-up have been obtained. The purposes of the runs were:

- (1) To obtain reference points as basis upon which subsequent film data will be compared and correlated.
- (2) To test reliability of the short scale heat transfer apparatus and to obtain data for comparison with accepted film coefficient correlations.

Combination of operating conditions listed below were used for determination of clean tube heat transfer coefficients:

Average bulk water temperature, °C: 25, 55, 85
 Heater tube (slug) specific power, KW/ft: 1, 7.5, 12
 Water flow rate, GPM: 10, 20, 30

Comparison of experimental data was made with Colburn's empirical correlation, plotting $h_0/Pr^{1/3}$ on the ordinate and Re_f on the abscissa.

h_0 = Nusselt number, hd/k
 Pr = Prandtl number $(C_p \mu)/k$
 Re = Reynold's number $\frac{DG}{\mu}$

h = film coefficient, BTU/(hr)(sq ft)(°F)
 D = equivalent diameter, ft.
 k = thermal conductivity of water, BTU/(ft)(ft²)(°F)/(ft)
 C_p = Specific heat of water, BTU/(lb.)(°F)
 G = mass velocity of water lb/(ft²)(hr)
 μ_f = viscosity of water based on average film temperature, $\frac{lb}{ft-hr}$

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Calculations are not entirely completed. The results available show the experimental data to lie in the region between + 15% and - 20% of the accepted Colburn empirical equation. A typical set of results from two of the runs are shown in Figure 1.

The primary source of deviation between the experimental and Colburn correlation appears to be the result of temperature measurement. The magnitude of errors in each of the measuring systems for water and heater tube is of the order of $\pm 3^{\circ}\text{F}$. The figure of 3°F was arrived at by assuming that the thermocouple and recorder are accurate to $\pm 0.5^{\circ}\text{F}$ and graph readings to $\pm 1^{\circ}\text{F}$. If both heater tube readings and water readings are considered together, limits of errors become twice 1.5°F or $\pm 3^{\circ}\text{F}$ total.

The absolute values of these deviations cannot be reduced. However, the effects of the errors can be minimized by increasing heater tube surface-to-water temperature drops. Future tests will be conducted at higher specific powers to increase temperature drops.

Currently, film formation tests on one standard annulus process tube are being conducted on the short tube heat transfer rack-up. The operating conditions used for film formation are:

- (1) Average bulk water temperature, 185°F
- (2) Water flow rate, 20 gpm
- (3) Average heater wall temperature, 185°F
(the internal heating of heater tube)

Possible changes in heat conductance between "clean" and "scaled" tube conditions were determined after one week of continuous operation. Data for the scaled tubes were taken at the same conditions as for clean tube tests. Thus, for similar specific power, water flow rate, and water temperature, any temperature-drop increase due to scale can be obtained directly by comparison.

Results of calculations for several runs are tabulated in Table I. Some of the inherent errors of the temperature measurements already have been pointed out. Similar deviation must be expected for the film-build-up tests. Temperature drop increases as a result of scale formation were from less than 1 to 4°F for a specific power of from 7.5 to 12.0 KW/ft. The calculated scale conductances are given in the table and change from 32,000 to as high as 153,000. This is due to the fact that the amount of scale formed on the heater tubes during the week's operation has been very low. Small apparent pressure drop increases have been observed with the Holco pump. These indicate a small amount of scale formation.

Film formation operation on the heater tube is continuing. Heat transfer testing procedure will continue for a period covering at least a month's scale formation.

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FIGURE 1

CORRELATION OF EXPERIMENTAL RESULTS

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TABLE I

Comparison of "Clean" and "Sealed" Tube Results

Run Number	Position From Upstream-Inches	h _{clean}	u _{overall}	(K/L) Scale $\pm 60,000$	Temperature Increase $^{\circ}\text{F} \pm 3^{\circ}$
1	9 1/4	4825	4220		0
	19 1/4	4800	5010	32,900	4.1
	27 1/4	5530	5180	-	-
	36 1/4	5650	5170	82,000 60,500	1.9 2.6
2	8 1/4	5175	4230		
	19 1/4	5320	5140	74,000	0.5
	27 1/4	5500	5060	153,000	0
	36 1/4	6560	5740	54,000 46,300	0.5 1.2
3	3 1/4	4835	4320		
	18 1/4	4800	4870	40,300	2.5
	27 1/4	5530	5220	81,300	-
	36 1/4	5650	5190	63,800	1.0 1.7

Operating Conditions

Run Number	Water Rate gpm	Specific Power Kw/ft.	Avg. Bulk Water Temperature- $^{\circ}\text{F}$
1	20		
2	20	12.0	135
3	20	7.5	185
		12.0	185

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HW-23448

RESISTANCE HEATING OF SLUGS - R. Reider

Slug stresses have been a major consideration in the determination of the cause of slug ruptures. Although calculations have been made on stresses resulting from thermal gradients, valuable information could be obtained if slugs could be heated to thermal conditions simulating pile heated slugs. Slugs so heated could then be subjected to many of the thermal conditions occurring presently or expected to occur in the pile.

Calculations indicate that the heat generation patterns resulting from an electrical current passing through a uranium slug are about the same as those for a pile heated slug. Consequently, a similar temperature and thermal stress distribution can be expected. Design of equipment and preliminary tests for a resistance slug heater have been started. Fabrication of test equipment will be started in the near future.

Calculations have been completed on the preliminary electrical resistivity test that was partially reported on in the last monthly report. These calculations and tests indicate that the apparent electrical resistance of the metallurgical bond between the uranium and the end cap remains constant for the variable currents and resulting temperatures tested (1000 to 2200 amperes and 60°C to 294°C). The resistance of the bond, apparently, should cause no overheating at that point. However, if the bond should fracture from thermal stresses, the resistance could increase to an intolerably high level and cause partial melting of the end cap. Test stoppage would result. To gain as much information on this problem as possible, another preliminary test was conducted. This experiment essentially tested the strength of the metallurgical bond. The slug was uniformly heated to 330°C and quenched in water. The slug had normally bonded on caps but had no cap covering the uranium. The initial shock of the water should have generated temperature gradients which would cause thermal stresses in the bond. After quenching, one end cap fell free of the slug and the other was bonded by about 1/20 of the original bonded area. During quenching, the initial temperature gradient probably was more severe than will actually be encountered during the stress testing. Also, since a compressive force of 450 pounds will be applied to the caps during the experiments, a low bond resistance might still be maintained. However, these tests, although not conclusive, do show that bond fracture could cause a critical problem and that other bonding means should be investigated.

The use of the motor-generator set at the 189-D Building for direct current power will be available for heating the slug during tests. However, an extension of the electrical bus system will be necessary. The location of the equipment will be between the switch gear and the short tube mockup. Apparently, enough copper bus is available here on the plant to splice onto the bus of the short tube.

A Pyrex pipe has been proposed to house the slug in order to channel the flow of cooling water over the specimen. This will permit observation of slugs while under test.

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HW-2344B

Calculations of end pressure exerted on a slug in the pile indicate that the only critical factor causing end pressure is the pressure head in the process tube upstream from the slug charge. This end force exerted on a slug amounts to approximately 450 pounds. To simulate this pile condition on test slugs, the design of a hydraulic press to exert this end force has been started and will be included in the testing equipment. The end pressure will also help maintain a good electrical contact between the uranium and aluminum end caps.

From the preliminary test on apparent electrical resistivity of uranium it was learned that the uranium resistivity varies almost directly with the temperature of the uranium. Further calculations have now been made to determine the over-all effective resistivity of a uranium slug while being tested. This resistivity was then used for calculating the power generation in a slug at maximum permissible generator current. With the surface and axial resistivities at 34×10^{-6} ohm-cm and 50×10^{-6} ohm-cm respectively, the effective resistivity was calculated to be 41.7×10^{-6} ohm-cm. Further, the apparent power generation per slug was found to be 12.5 KW, or 37 KW per foot (assuming 16,500 amperes to be available). If this is true, the high power output of a slug will allow slug studies up to power levels well beyond present pile power levels.

The design of all the necessary components for the resistance heater unit should be completed and fabrication started in February. Further preliminary tests will be run to check on problems that arise should it soon necessary. Investigation of a stronger bond between the uranium and end caps will be continued.

INDUCTION HEATING OF SLUGS

An induction heater coil has been built for the purpose of studying slug thermal stresses in the standard four (4) inch uranium slug. Due to the limited amount of power available (50 KW at the necessary 3000 CPS) the coil was designed for heating one slug at a time. Although induction heating offers many advantages for use in heating slugs, the temperature distribution induced in the slug is appreciably different than that of a pile heated slug. For this reason induction heating has not been pushed to the extent of resistance heating. Resistance heating compares favorably in temperature distribution with that of a pile heated slug.

Inlet and outlet nozzles for admitting and rejecting the slug cooling water were finished early in January. Before making trial tests with power to the coil, a check for water leaks was made on the nozzles and the cooling tube. The nozzles proved to be satisfactory; however, bad water leaks were detected in the cooling tube. The heater was returned to the machine shop for repair.

As time permits, the heater will be tested to determine its ability for cycling of slugs having high axial to surface temperature gradients. The relative efficiency between heating canned and bare slugs will also be investigated.

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THERMOCOUPLE SLUG - W. D. Gilbert

Fabrication of a thermocouple slug has been delayed due to manufacturing difficulties. A thermocouple slug unit had been completed, but after inspection, it was found to have a scratch 0.006 inch. deep on the surface. The use of such a slug in the pile would be undesirable. Thus, new thermocouple slugs will be completed as soon as possible.

Design work has been started on a new type of thermocouple slug. An attempt will be made to place a butt-welded thermocouple on the surface of the uranium metal adjacent to the aluminum jacket. The slug and thermocouple will then be canned. The success of this type of thermocouple slug will depend upon the thermal stability of the insulation on the wire. Tests are being conducted to determine the effects of the canning baths on the thermocouple insulation.

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CORRELATION OF GRAPHITE TEMPERATURE MEASUREMENTS - H. H. Greenfield

Comparisons of temperature readings of the graphite filler blocks at the B, D, and F Piles obtained from the G thermocouples, thimble thermocouples, and C-Test Hole thermocouples are being made. The purpose of this study is to determine the reliability of the temperature readings of the G thermocouples. The comparisons of the G thermocouple readings with those from nearby thimble thermocouples and C-Test Hole thermocouples furnishes some evidence as to this reliability.

Preliminary results of these comparisons indicate that under conditions of same local heat flux, the G-14 thermocouple at F-Pile is reading from 2 to 4% higher than the closest C-Test Hole and thimble thermocouple. G-13 thermocouple at F-Pile is reading about 10% higher than the closest thermocouples for the same local heat flux.

However, due to the errors involved in this type of comparison such as difference in mounting the thermocouple junctions, distance between location of thermocouple junctions where temperatures are being measured, gas gaps, and heat transfer paths, no conclusions can be drawn as to the actual reliability of the G-thermocouples from these comparisons.

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COMPARISON OF TEMPERATURES MEASURED IN BURNOUT TUBES AT F PILE-H. H. Greenfield

A comparison was made of the theoretically calculated temperature differences between a thermocouple located in a process tube channel and in the adjacent filler block of the lattice cell. In addition, comparisons were made with thermocouples in filler blocks outside of the lattice cell. Temperature data from the two graphite burnout experiment samples located in process tube block channels at F Pile were compared to nearby thimble thermocouples. Figure 2 shows the location of the thermocouples used in the comparisons.

From the following table, it is seen that very good agreement between the observed and theoretical temperature differences were obtained considering the errors involved in this type of comparison. Differences in graphite conductivity, neutron or heat flux, and method of mounting of thermocouple wires are some of the errors involved in these temperature comparisons.

TABLE II

Comparison of Temperature Readings of
Burnout Experimental Graphite Samples with Nearby Thermocouples

	Average Temperature °C	
Burnout Tube No. 2777	386	
Thimble Thermocouple 31-3	348	
Observed ΔT	38	
*Theoretical ΔT	40	
Burnout Tube No. 2682	390	398
Thimble Thermocouple 25-3	336	
Thimble Thermocouple 26-2		364
Observed ΔT	54	34
Theoretical ΔT	40	
Burnout Tube No. 2682	390	
Thimble Thermocouple 19-3	368	
Observed ΔT	22	
Theoretical ΔT	15	

*These theoretical temperature differences were reported in Technical Activities Report, HL-22611, for a local heat generation in the metal of 25 KW/foot.

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FIGURE 2. BURNOUT TUBES AND NEARBY THIMBLE THERMOCOUPLES
AT F PILE

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TEMPERATURE READINGS FROM PROCESS TUBE BLOCK CHANNEL THERMOCOUPLES AT F PILE
H. H. Greenfield

A stringer of thermocouples was installed in the F Pile process tube block channel 2167, early in December, under PT 105-470 P. These thermocouples are located in graphite cylinders which extend along the channel opposite the metal charge in the adjacent process tubes. There are 18 thermocouple locations spaced about one foot apart. The thermocouple wires are 30 gage chromel-alumel. At two of the locations, there are, in addition to the above thermocouples, a 20 gage chromel-alumel and a 20 gage iron-constantan thermocouple. These additional thermocouples are at the same location along the length of the channel as the 30 gage chromel alumel but at different circumferential positions in the graphite cylinder. The thermocouples were not calibrated before installation in the pile.

The available temperature readings for two periods of equilibrium pile operation have been analyzed. The data indicate that the 30 gage chromel-alumel thermocouples have been reading consistently with nearby thimble thermocouples. Table III shows, however, that the temperature readings from the large gage thermocouples have not been consistent with the 30 gage chromel-alumel thermocouple readings or with themselves.

Some of the temperature differences from the large couples may be attributed to possible differences in contact of the hot junction with the graphite as well as the size of the hot junction formed by the wires. The effect of irradiation on the different wires of the thermocouples may be a possible cause of differences in the temperature readings. The large changes in the temperature comparisons between thermocouples at the same location for the two operating periods are unaccounted for.

The thermocouples located at position #8 in the channel are adjacent to the filler block graphite containing the thimble thermocouple 23-4, Figure 3. Also, the C-2 Test Hole thermocouple is located in a filler block outside the lattice cell containing these channel thermocouples. Temperature comparisons were made between the #8-30g-chromel-alumel channel thermocouples and the thimble and C-Test Hole thermocouples. The results of these temperature comparisons were in good agreement with the theoretical as well as the observed temperature comparisons for the burnout tubes, reported elsewhere in this report. Although there is a block of four "B" tubes between the channel and C-Test Hole thermocouples, the symmetry of the prism pattern is such that it was assumed that the effects on the temperature of the thermocouples would be about the same.

In making the temperature comparisons, the thimble thermocouple was assumed to be reading about 12°C too low. This assumption was based on the results of a temperature correlation between this particular thimble thermocouple, 23-4, and the C-2 Test Hole Thermocouple.

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TABLE III

Temperature Comparisons of Thermocouples

The following is the temperature reading difference observed between the 20 gage thermocouples and 30 gage chromel-alumel thermocouples for the three positions in the tube channel.

20 Gage Thermocouple Composition	Operating Period	
	Dec. 7-13	Dec. 22-27
	ΔT	ΔT
Position #4		
Iron-Constantan	90	95
Chromel-Alumel	135	60
Position #6		
Iron Constantan	60	-75
Chromel-Alumel	65	-50
Position #13		
Iron-Constantan	55	-30

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The diagram illustrates a test specimen with a central vertical channel. The specimen is divided into two main sections by this channel. The left section is labeled with numbers 19, 20, 21, 22, and 23 in the first column of a grid. The right section is labeled with numbers 68, 69, and 70 in the first column of a grid. The grid consists of five rows and six columns. The central vertical channel is a thick vertical bar running through the middle of the specimen. Various thermocouples are indicated: a 'THIMBLE THERMOCOUPLE 23-4' is located in the first row of the left section, pointing to a circle in the fourth column; a 'CHANNEL THERMOCOUPLE' is located in the second row of the left section, pointing to a circle in the fourth column; a 'C-2 TEST HOLE THERMOCOUPLE' is located in the third row of the right section, pointing to a circle in the fourth column; and a '"B" METAL' is located in the fourth row of the right section, pointing to a circle in the fourth column. The circles represent the locations of the thermocouples and the metal. The circles in the first, second, and fifth rows of the left section are empty. The circles in the first, second, and fifth rows of the right section are empty. The circles in the third and fourth rows of the right section are shaded with diagonal lines.

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RELIABILITY OF TEMPERATURES MEASURED BY G-THERMOCOUPLES - H. H. Greenfield

There is some doubt as to the reliability of the temperature readings obtained from the G-thermocouples in the B, D, and F Piles. As indicated elsewhere in this report, there is evidence to indicate that some of the couples may be reading as much as 10% high. If the reliability of these readings can be determined, the G-thermocouples may possibly be disregarded or new graphite temperature limits established for use with these thermocouples.

Therefore, to help insure maximum production levels from a graphite burnout temperature limit consideration, a production test is being considered that might enable the reliability of the temperature readings to be more firmly established for the G-thermocouples at the B, D, and F piles. This would be done by comparing temperature readings between specially located process tube channel thermocouples with special G-Test Hole thermocouples and with the G-thermocouples. A stringer of channel thermocouples would be installed in a tube block adjacent to a stringer of G-thermocouples. In addition, a stringer of channel thermocouples would be installed in a tube block adjacent to one of the special G-Test Hole thermocouple locations.

It must be realized that it is impossible to determine exactly how much the G-thermocouples read above the actual temperature of the filler block graphite being measured. However, the approximate reliability of the temperature readings of the G-thermocouples would be obtained from temperature comparisons. These comparisons would be of the differences between the temperature readings obtained from the G-thermocouples and its adjacent channel thermocouples with the differences between the temperature readings obtained from the special G-Test Hole thermocouples and its adjacent channel thermocouples.

Further consideration will be given to this problem. If a production test seems practical, such a test will be prepared in the next few weeks.

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PROCESS TUBE CHANNEL THERMOCOUPLES FOR MONITORING GRAPHITE TEMPERATURES

- H. H. Greenfield

The thimble thermocouples which have been used to monitor graphite temperatures are to be removed. In their place, thermocouples are to be installed in process tube channels to monitor the graphite temperatures. The proper temperature relationship between the channel thermocouples and the G-thermocouples and C-Test Hole thermocouples must be established to help insure maximum operating levels.

When using channel thermocouples for graphite monitoring, it would theoretically be possible to maintain the graphite temperatures below the maximum limits by as much as 25 to 30°C. This unnecessary reduction in operating level would be due to improperly locating the channel thermocouples with respect to the G and C-Test Hole thermocouples when determining the temperature relationships between them. In order to determine the proper temperature relationship between the G and C-Test Hole thermocouples and the channel thermocouple, the latter must be located at least one tube row away from the other thermocouples. The reason for this is to assure that the heat generation and heat flow paths are not disturbed in the lattice cell containing the G or C-Test thermocouples. The temperature readings will then indicate how much higher channel thermocouples read than G and C-Test Hole thermocouples when these latter thermocouples have their normal value of heat generation.

Based on calculations of the temperature difference between a channel thermocouple and a G or C-Test Hole thermocouple, Technical Activities Report, HW-22611, the following illustration is offered. The purpose of the illustration is to show the importance of locating the channel thermocouples one tube row away from the four tubes that are adjacent to the G or C-Test Hole thermocouples whose temperatures are to be compared.

Figure 4 shows the temperature distribution in the lattice cells for the case where the channel thermocouple is located one tube row away from the four tubes adjacent to the G or C-Test Hole thermocouple. If it is assumed that this latter thermocouple is reading around 380°C, then the expected temperature reading of the channel thermocouple for a local heat flux in the metal of 25 KW/ft would be about 420°C. A small ring of graphite surrounding the channel thermocouple would be at a temperature of about 405°C. Thus, a small quantity of graphite would be above the graphite burnout temperature limit. The rest of the filler block graphite with the same conductivity and heat generation would be at the graphite burnout limit of 380°C.

Figure 5 shows the temperature distribution in the lattice cells for the case where the channel thermocouple is located in one of the tube blocks that are adjacent to the G or C-Test Hole thermocouple. If it is assumed that the latter thermocouple is reading around 380°C, then the expected temperature reading of the channel thermocouple would be about 395°C. However, the filler block graphite in the adjacent lattice cells with the same conductivity would be at a temperature of about 355°C. Thus, although the filler block graphite surrounding the G or C-Test Hole thermocouple would be at 380°C, the rest of the filler block graphite in the pile would be kept about 25°C below the graphite burnout temperature limit. This would represent a large loss in production.

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A report on the use of channel thermocouples for monitoring graphite temperatures will be issued soon. A production test to determine the proper temperature relationships between channel thermocouples and G and C-Test Hole thermocouples for monitoring of graphite temperatures will be prepared.

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FIGURE 4. TEMPERATURE DISTRIBUTION IN PACKING

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FIGURE 5. TEMPERATURE DISTRIBUTION IN PACKING

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PILE OPERATION DURING CRITICAL ELECTRICAL POWER OUTAGES - W. D. Giltbert

A study has been in progress for the last two months on the possibility of operating the piles during a Critical Power Outage - Grade Y (commonly called Critical Y). Present 100 Area operating procedures specify that the piles may be operated during a Critical Power Outage - Grade W. However, the pile or piles must be shut down if a Critical Y exists. From an electrical supply standpoint, there is essentially no difference between a Critical W and a Critical Y. A Critical W is the planned removal of electrical back-up facilities. A Critical Y is the unplanned or emergency removal of the same back-up facilities.

In most cases, it appears that when a Critical Y occurs, existing switch gear may be used to provide the necessary power, and the pile could be returned to safe operation. In all 100 Areas, suitable auxiliary switch gear are installed and available to tie-in the back-up power facilities without overloading existing transformers, buses, or feeder cables. Thus, after a Critical Y occurs, it may be possible to resume operation of the pile within the maximum allowable service time (approximately 40 minutes).

Approximately two to four Critical Y outages may occur each year. If operation of all piles could be recovered within the maximum allowable service time, a production gain of approximately 5,000 to 10,000 MWD yearly might be realized.

The study of this problem will be continued. A document will be issued setting forth the results and conclusions of the study.

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CALCULATION AIDS - S. R. Fields

To determine various pile temperatures, it is often necessary to solve one or more equations a number of times for various conditions. Values for some of the variables in the equations are obtained from pile instruments, others must be determined or chosen as orientation factors. Specifically, the information available might include values for such variables as:

- (1) U -The cooling water flow in GPM.
- (2) Δt -The temperature difference of the water between inlet and outlet ends of a process tube in $^{\circ}\text{C}$.
- (3) t_i -The inlet water temperature in $^{\circ}\text{C}$.

From the above, one may want to compute variables such as the power output of a process tube, the bulk water temperature at an arbitrary point, x , along the active zone, or the local heat flux at the arbitrary point, x .

In order to facilitate making these calculations, several equations have been reduced to a series of alignment charts. The charts, a discussion of some factors involved in their construction, and an example are contained in the document which is to be issued soon.

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STUDIES OF HIGH DENSITY CONCRETE SHIELDS - C. Warren

Work is continuing on the study and evaluation of problems which will be encountered in using high density concrete for biological shields. For the present, the work has been resolved into two distinct parts: (1) The consideration of iron-limonite concrete for biological shielding in the pile presently being designed, and (2) Studies of other types of high density concrete which would be suitable for future piles.

A report is being issued which provides a discussion of the engineering properties of iron-limonite concrete for use as shielding. It was concluded, on the basis of investigations conducted at sites other than Hanford, that iron-limonite concrete has mechanical and thermal properties which make it acceptable as an engineering material for use in a biological shield. This conclusion was reached under the assumption that the concrete would not be affected adversely by irradiation.

In studying other types of heavy aggregate concrete which might be suitable for use as shielding material, there is a considerable amount of basic information that must be secured. Such information would consist of not only an evaluation of high density minerals from a physical properties standpoint, but also cost comparisons and availability studies of these minerals. If the use of materials other than iron-limonite appears economically feasible, extensive physical tests will probably be required before such materials can be recommended for use on a pile. Information is being obtained which will make it possible to estimate the cost of the necessary tests.

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HW-23448

DISTORTION AND STRESS IN BIOLOGICAL AND THERMAL SHIELDS OF B, D, AND F PILES

- C. Warren

Originally, work was started toward defining the stress and strain problems in all of the existing piles. After reviewing the current status of pile reactions, it was decided to concentrate at present on B, D, and F Piles.

The distorted condition of the shields of the old piles is, of course, not as serious now as it was before the introduction of CO₂ into the piles. The presence of CO₂ caused higher graphite temperatures, and part of the graphite tended to anneal. However, it is felt that problems in shield distortion still exist due to lack of graphite annealing in the fringe zones of the piles.

At the present pile power levels there are probably no large stresses in the biological shields due to thermal gradients alone. Moreover, at higher levels large thermal stresses are unlikely unless secondary effects are considered. That is, large stresses might possibly be introduced at points of restraint or contact if the temperatures are high enough to cause appreciable strains in the iron-resonite blocks.

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PILE PROCESS SPECIFICATIONS - W. D. Gilfort

Recommendations for pile operating specifications pertaining directly to the Heat Studies Group have been completed. These recommendations, together with the basis for each, are summarized below.

1. Process Tube Water Supply - Tube Boiling Limitations

Basis

If boiling of water in a process tube were to be initiated, sufficient header pressure must be available to sweep out any steam which might be formed. The header pressure required depends upon the power at which the tube is being operated. Several factors affect the tube power, and thence the tube temperature rise limits. These are: (a) water flow rate, (b) header pressure, (c) film build-up, (d) inlet water temperature, (e) vertical elevation of tubes in the pile, (f) type of tube fittings, and (g) type of tube loading.

Specifications

- (1) Process water temperature rise limits, based upon a standard tube loading, 20°C inlet water temperature, and tubes loaded in Row 46 of the pile, are given in Figure 6 for E, D, and F Piles, and in Figure 7 for DR and H Piles.
- (2) The temperature rise limit may be increased by the amount obtained from Figure 3 as the inlet water temperature decreases from 20°C.
- (3) The temperature rise limit may be increased by the amount obtained from Figure 4 for tubes located below Row 46.
- (4) The temperature rise limits are based on the present standard nozzles, details, and fittings installed on each pile.
- (5) If a dummy charge 3.6 feet in length is placed upstream of a standard tube loading, the Δt limit for each pile may be obtained from Figure 6 or 7, and the correction added for the corresponding orifice zone as follows:

<u>Orifice Zone</u>	<u>Additional Δt Correction</u>
0.285	+ 4.5°C
0.240	4.6
0.200	5.6
0.175	6.7

2. Water Reduction to Process Tubes During Shutdown Periods

Basis

After a pile shutdown, heat is generated in the pile and sensible heat remains in the pile components. Cooling water must be supplied to remove this heat to prevent a process tube from boiling dry and from causing excessive temperatures in the metal. The temperature and water flow limitations are based on slug surface temperatures. It was conservatively calculated that the maximum slug surface temperatures will be within $\pm 5^\circ\text{C}$ of the outlet water temperatures at reduced process water flow rates.

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Specifications

- (1) In an emergency shutdown the pile header pressure shall not be reduced more rapidly than shown in Figure 5, Document HW-21065. In a normal shutdown, the header pressure may be reduced in accordance with HW-21065, but shall not be reduced to less than 85 psig until 5 minutes after the Vertical Safety Rods have been inserted.
- (2) When necessary and with tube temperature monitoring to insure that no tube outlet water temperature exceeds 70°C, the total water flow to the pile may be reduced below the value corresponding to 35 psig riser pressure. The minimum crossheader pressure shall be equivalent to 20 inches of water with the rear crossheader valved to the drain.
- (3) Minimum water flow to the pile shall not be less than 2000 gpm.
- (4) In cases of emergency and with constant tube temperature monitoring, the header pressure may be throttled at a time after shutdown to permit a tube outlet water temperature greater than 70°C, but not to exceed 90°C.

3. Water Cut-off to Process Tubes During Shutdown PeriodsBasis

Water may not be shut off indefinitely from a process tube shortly after a shutdown. Depending upon the length of time after a shutdown, boiling of the water in the tube or excessive slug temperatures may result if the water is turned off indefinitely. The following general bases were used for determining the length of time water may be turned off a single tube or a single crossheader.

- (1) Heat is generated in the pile after shutdown according to the Borst-Wheeler curve for infinite exposure, HW-10475, pg. 512.
- (2) The water shut-off time is based on the heat generation of a hot-test tube.
- (3) The inlet water temperatures were assumed to be 20°C.
- (4) A "drained tube" refers to a tube in which the water flow has been shut off, and the water has been allowed to drain from the tube.
- (5) A "tube with water" refers to a tube in which the water flow has been turned off, but in which the water remains.

Specifications

- (1) Water flow may be shut off from single tubes and single cross-headers in accordance with Figures 8 through 16.
- (2) Except in cases of emergency for the case of a "tube with water" the slug or water temperature may not be permitted to exceed 90°C.
- (3) Except in cases of emergency, the slug temperatures in a "drained tube" may not be permitted to exceed 170°C.

4. Process Water Supply - Horizontal Control Rod Cooling WaterBasis

To prevent excessive temperatures at the horizontal rod tip, the outlet water temperature must be maintained well below the boiling point.

Specifications

- (1) The maximum inlet rod water pressure shall not exceed 75 psi.
- (2) The minimum outlet rod water pressure shall not be less than 20 psi, and the maximum pressure drop across a rod shall not exceed 40 psi.
- (3) The rod water temperature rise shall not exceed 20°C.

5. Process Water Supply - Thermal Shield Cooling WaterBasis

Water pressure must be maintained on the loop header at the face of the pile to provide uniform circulation of cooling water through the thermal shield cooling pipes. To prevent excessive temperatures in the biological shield, the number of cooling pipes out of service must be restricted.

Specifications

- (1) During pile operation, a minimum of 300 gpm of filtered or process water shall be supplied to the inlet loop header at a minimum pressure of 25 psi.
- (2) The water temperature rise between inlet and outlet loop headers should not exceed 15°C at a power level of 600 MW or less.
- (3) At power levels up to 600 MW, flow may be shut off alternate thermal shield cooling pipes.
- (4) Flow may not deliberately be shut off two adjacent cooling tubes during pile operation.

6. Process Water Supply - Riser Pressure LimitsBasis

Adequate water pressure in the risers must be maintained to supply sufficient water to the process tubes. If boiling were initiated in a tube, sufficient excess pressure must be available to sweep out steam which might be formed. Mercuric switches are provided on the risers which will trip the No. 1 Safety Circuit if the riser pressure falls below the established minimum value.

Specifications

- (1) The trip point for the mercuric switches on the pile process water risers will be set within 92% of the nominal riser pressure during pile operation. The pile will be shut down when the pressure falls below this value.

7. Process Tube Water Supply - Allowable Tube Pressure Drop IncreaseBasis

Film formation on tube and slug surfaces causes a decrease in flow rates and lowers the heat transfer coefficient from slug to water. These effects increase the slug temperature and may increase slug corrosion rates.

Specifications

(1) The maximum standard pressure drop increase in the control zones, referred to 20.4 gpm flow rate, will be as follows:

<u>Orifice Zone</u>	<u>Riser Pressure</u>	<u>Standard Pressure Drop Increase</u>
0.240	350	40 psi
0.240	400	33
0.285	400	32

8. Panellit Trip LimitsBasis

The Panellit System Alarm may indicate substandard water flow to a process tube. The alarm may be actuated by either of two types of Panellit gage trips as follows:

- (1) An upper Panellit trip, which may indicate a restriction to water flow downstream from the orifice.
- (2) A lower Panellit trip, which may indicate a decrease of water flow caused by a ruptured front pigtail or nozzle cap, or by a restriction upstream from the orifice.

The Panellit range should be adequate to detect either type of pressure change.

Specifications

(1) Minimum and maximum Panellit trip limits for the Panellit gages should be as follows:

<u>Orifice Size</u>	<u>Panellit Trip Range</u>	
	<u>Lower Limit</u>	<u>Upper Limit</u>
0.140	50 psig	150 psig
0.175	50	135
0.200	100	225
0.240	150	265
0.285	200	325

(2) For orifices smaller than 0.140, the lower trip limit should not be less than 45 psig.

9. Panellit Setback Delay TimeBasis

Loss of water from a process tube brought about by plugging or rupturing of the tube fittings may result in serious consequences to the pile. For example, the aluminum cans enclosing the process metal may melt. This may

generally be prevented by shutting down the pile within a short time after decreased flow has been detected. The allowable shutdown time-delay depends upon the specific power of the slugs.

Specifications

- (1) The pile shall be shut down with the No. 1 Safety Circuit after a Panellit Alarm within the following period of time. However, if the Panellit pressure which caused the alarm returns to normal within the delay period, the pile shall not be shut down.

<u>Power Level - MW</u>	<u>Time Delay - Seconds</u>
450-500	5
500-550	4
550-600	3
600-650	2

10. Accuracy of Measuring Process Water Temperatures and Pressures

Basis

To insure the necessary degree of accuracy in measuring the heat loads of process tubes, it is necessary to maintain the accuracy of certain measuring instruments within specified limits.

Specifications

The instruments measuring temperatures and pressure to determine the pile heat loads shall be calibrated and maintained to give the following accuracies:

- (1) Outlet bulk water temperature $\pm 0.5^{\circ}\text{C}$
- (2) Inlet bulk water temperature $\pm 0.5^{\circ}\text{C}$
- (3) Tube Panellit Pressure ± 5 psi
- (4) Supply crossheader pressure ± 2 psi
- (5) Outlet water temperature with Crown Temperature Monitor System $\pm 1^{\circ}\text{C}$

11. Nozzles, Pigtails, and Fittings on Pile Process Tubes

Basis

Standard nozzles, pigtails, and crossheader fittings for pigtails exist on each pile. Changes in these fittings would alter boiling limits.

Specifications

- (1) Crossheader fittings for pigtails, pigtail connections, and inlet and outlet nozzles shall be in accordance with the following drawings.

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Drawing Number and Date (Front Face)

<u>File</u>	<u>Nozzle</u>	<u>Pigtail</u>	<u>Fitting</u>
B,D,F	H-1-2534* H-1-2536	5-16-50 6-6-50	HD62835-XI-A 11-19-47 HW-63056-A 11-7-47
DR	P-3393	10-17-49	HD62835-XI-A 11-19-47 H-1-8216-DR 3-10-49
H	P-3393	10-17-49 P-2369	2-10-49 P-1317-1-X 11-29-49

*Field revision not shown on print is necessary to taper bore inlet for not over 0.5 inch with a maximum diameter of 1-9/16 inches.

(Rear Face)

B,D,F	H-1-2535 H-1-2537	6-15-50 5-16-50	HD62835-XI-B 11-19-47 HD63056-A 11-7-47
DR	H-1-2535 H-1-2537	6-15-50 5-16-50	HD62835-XI-B 11-19-47 H-1-8216-DR 3-10-49
H	P-3674 P-3675	2-23-49 10-10-49	P-2769 2-10-49 P-1302-1-S 11-29-49

(2) Orifice sizes shall be in accordance with the following drawings:

<u>Orifice Size - Inch</u>	<u>Drawing Number</u>
0.140	P-2858/P-6 10-17-49
0.175	P-2858/P-7
0.200	P-2858/P-8
0.240	P-2858/P-9
0.285	P-2858/P-10

The 0.120 orifice shall have same tolerances as shown on the above drawing.

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FIGURE 6

ΔT LIMITS FOR B, D, AND F PILES

DOWNSTREAM DUMMY SLUGS:

TOP ROW TUBE:

FOUR 8" SOLID ALUMINUM

20° INLET TEMPERATURE

ELEVEN 8" PERFORATED DUMMIES

NO UPSTREAM DUMMY SLUGS

ONE 5" PERFORATED DUMMY

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FIGURE 7

ΔT LIMITS FOR DR AND H PILES

TOP ROW TUBE:

20" INLET TEMPERATURE

NO UPSTREAM DUMMY SLUGS

DOWNSTREAM DUMMY SLUGS:

FOUR 8" SOLID ALUMINUM

ELEVEN 8" PERFORATED DUMMIES

ONE 5" PERFORATED DUMMY

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FIGURE 8

WATER SHUT OFF TO SINGLE TUBE AFTER SHUT DOWN

TUBE POWER ~ 475 KW (2x 650 MW PILE LEVEL)

WATER IN TUBE

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SLUG SURFACE TEMPERATURE, °C

FIGURE 9

WATER SHUT OFF TO SINGLE TUBE AFTER SHUT DOWN
TUBE POWER=375 KW (~500 MW PILE LEVEL), WATER IN TUBE.

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SLUG SURFACE TEMPERATURE, °C

FIGURE 10

WATER SHUT OFF TO SINGLE TUBE AFTER SHUT DOWN
TUBE POWER=275 KW (~ 375 MW PILE LEVEL), WATER IN TUBE.

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SLUG SURFACE TEMPERATURE, °C

FIGURE 11

WATER SHUT OFF TO SINGLE CROSS-HEADER AFTER SHUT DOWN
TUBE POWER=475 KW (~650 MW PILE LEVEL) WATER IN TUBE

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SLUG SURFACE TEMPERATURE, °C

FIGURE 12

WATER SHUT OFF TO SINGLE CROSS-HEADER AFTER SHUT DOWN
TUBE POWER=375 KW (~ 500 MW PILE LEVEL) WATER IN TUBE

DECLASSIFIED

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SLUG SURFACE TEMPERATURE, °C

FIGURE 13
WATER SHUT OFF TO SINGLE CROSS-HEADER AFTER SHUT DOWN
TUBE POWER=275KW(~ 375MW PILE LEVEL). WATER IN TUBE

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FIGURE 14
WATER SHUT OFF TO SINGLE TUBE AFTER SHUT DOWN
TUBE POWER=475 KW (~ 650 MW PILE LEVEL), TUBE DRAINED

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SLUG SURFACE TEMPERATURE, °C

FIGURE 15

WATER SHUT OFF TO SINGLE TUBE AFTER SHUT DOWN
TUBE POWER=375 KW (~500 MW PILE LEVEL), TUBE DRAINED

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FIGURE 16
WATER SHUT OFF TO SINGLE TUBE AFTER SHUT DOWN
TUBE POWER - 275 KW (~ 375 MW PILE LEVEL)
TUBE DRAINED

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