OAK RIDGE NATIONAL LABORATORY

Operated by

UNION CARBIDE NUCLEAR COMPANY

Division of Union Carbide Corporation

Post Office Box X

Oak Ridge, Tennessee

ORNL
CENTRAL FILES NUMBER

CF 58-5-101

External Dist. Authorized

COPY NO. 107

DATE: May 22, 1958

SUBJECT: Extended Length HRE-3 Slurry Dump Line to Replace Throttling
Dump Valve

TO: W. R. Gall

FROM: L. A. Haack

SUMMARY

From the standpoint of erosion, a long dump line may be preferable to a throttling dump valve to achieve the pressure drop from the HRE-3 slurry blanket to the dump tank. This study investigates extended length HRE-3 dump lines in which the maximum average velocity is 20 fps, the smallest allowable line size is 1/2 in., and the time for dumping is 10 minutes. Twenty-six parallel 1/2-in. Sch. 80 pipes, each 725 ft long, or four parallel 1-1/2-in. Sch. 80 pipes each 2,000 ft long are required. To avoid localized velocities considerably higher than 20 fps as a result of flashing, these pipes can be submerged in a 28,000 gal pool of water initially at 135°F and with 40°F allowable temperature rise. It can be concluded that if the velocity, line size, and dumping time are limited to the values listed above, use of restrictor piping to achieve the pressure drop is not very practical.

If higher velocities and flashing are allowed, a cursory study indicates that for an average velocity in the range from 100 to 200 fps, one 1-1/4-in. (or smaller) line of less than 250-ft length could be used. Flashing would occur, and sonic velocities with high erosion rates would exist at the exit. Experimental data will be required to evaluate friction factors, heat transfer characteristics, and erosive-corrosive effects of three-phase flashing flow.

NOTICE

This document contains information of a preliminary nature and was prepared primarily for internal use at the Oak Ridge National Laboratory. It is subject to revision or correction and therefore does not represent a final report.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

LEGAL NOTICE

This report was prepared as an account of Government sponsored work. Neither the United States, nor the Commission, nor any person acting on behalf of the Commission:

- A. Makes any warranty or representation, express or implied, with respect to the accuracy, completeness, or usefulness of the information contained in this report, or that the use of any information, apparatus, method, or process disclosed in this report may not infringe privately owned rights; or
- B. Assumes any liabilities with respect to the use of, or for damages resulting from the use of any information, apparatus, method, or process disclosed in this report.

As used in the above, "person acting on behalf of the Commission" includes any employee or contractor of the Commission to the extent that such employee or contractor prepares, handles or distributes, or provides access to, any information pursuant to his employment or contract with the Commission.

EXTENDED LENGTH HRE-3 SLURRY DUMP LINE TO REPLACE THROTTLING DUMP VALVE

Discussion and Results

This preliminary study considers the use of long lines rather than a throttling-type valve to control the pressure drop in the slurry flow from the HRE-3 blanket to the dump tank. Valves would probably require frequent maintenance because of the erosive-corrosive effects of slurry flow, particularly if flashing occurs across the port. Cooling of the slurry prior to the throttling process would therefore be important.

Small bore tubing of about 0.06 in. ID is currently proving adequate for letting down of high-pressure slurry in at least two test facilities in REED,* but occasional plugging has occurred. It has generally been accepted that for HRE-3 a 1/2-in. pipe is the smallest dump line that should be considered from the standpoint of tendency to plug.

To narrow the scope of the first part of this study, the design criteria assumed was that: (a) the blanket must be dumped in a maximum of ten minutes, (b) the maximum allowable average velocity is 20 fps, and (c) flashing must be negligible. Simplifying assumptions were also made that: (a) steady state conditions exist, i.e., the blanket pressure remains essentially at 1000 psia for the major portion of the dump, it having been estimated that the blanket pressure drop to the saturation pressure corresponding to the bulk blanket temperature within about 10 seconds after a dump is initiated; (b) the only heat to be removed from the slurry is the sensible heat, amounting to a rate of about 50×10^6 Btu/hr, and that the decay heat is negligible.

Table I shows the lengths calculated for the 1/2-in. and 1-1/2-in. dump lines. The relationships between the saturation temperature of light water and the calculated slurry temperature along the dump line length are shown in Figures 1 and 2. There would be a greater tendency to flash near the exit of the line, but even at this location flashing does not appear likely if the dump line is submerged for its entire length in a pool of about 28,000 gal capacity initially at no higher temperature than about 135°F. Figure 3 shows the temperature rise of the cooling water pool as a function of the elapsed time after the start of a dump. Although high velocities will exist initially in the entering section of the dump line, as indicated in Figure 4, they are expected to diminish in less than 10 seconds to the assumed average velocity of 20 fps.

* E. C. Hise is using 0.0625-in. ID restrictor tubing about 10-ft long to control a pressure drop from about 1500 psia to 15 psia in a test loop containing 1600°C fired slurry having a specific gravity of 1.7.

R. B. Gallaher is using 0.060-in. ID tubing 30-ft long to control a pressure drop from 1500 psia to 15 psia in a loop containing slurry with a concentration of about 1800 g Th/kg H₂O.

It may be noted that the line lengths required are quite long and that parallel paths, or circuits, would be required for both the 1/2-in. and 1-1/2-in. cases. The space requirements for the lines and for the cooling water pool would be considerable, particularly if short-radius bends are to be avoided in the dump line. Also, on the basis of present knowledge of slurries, there is some uncertainty that parallel dump lines are feasible because of the rather elaborate purging facilities that would be required to assure that the lines were operable. It can be concluded that if the maximum velocity is limited to 20 fps, the minimum pipe size to 1/2-in., and the time permitted for a dump to 10 minutes, use of restrictor piping to achieve the pressure drop is not very practical.

Table I. Comparison of 1/2-in. and 1-1/2-in. Dump Lines

	<u>1/2-in. dia.</u>	<u>1-1/2 in. dia.</u>
Number of parallel lines required	26	4
Length of each line, ft	725	2000
Total length of pipe in all lines, ft	18,850	8000
Overall heat transfer coefficient, Btu/hr ft ² °F	140	110
Water film coefficient, Btu/hr ft ² °F	330	300
Velocity at start of dump, fps	270	270
Cooling water required per pipe, gal	1080	6750
Cooling water required for entire system, gal	28,000	27,000
Final temperature of slurry at line exit, °F	190	205

The use of a long submerged dump line to achieve enough cooling ahead of a throttling-type dump valve to prevent flashing in the valve port was also investigated. This arrangement might have some utility in that the pressure drop to be borne by the valve would also be reduced considerably, but as indicated in Table II, the line lengths required are also impractically long and it is doubtful if all flashing could be prevented. While a double-pipe heat exchanger (slurry in the inner pipe, water in an outer pipe) would reduce the linear lengths somewhat, this design would be difficult to fabricate, easy to plug, and would probably not represent as efficient a heat transfer arrangement as would other types.

If the design is not restricted to a 10-minute dump and to velocities of 20 fps or less, so that flashing would be permitted, a variety of pipe sizes and lengths are possible. Three cases which may be considered typical are presented in Table III. The velocities listed are average values calculated on the basis that sonic velocities are not reached. Actually, after flashing occurs, however, the velocities will be very much greater and sonic velocities could be expected near the exit. In this case, the line lengths required would be considerably less than the values shown. A calculation of L. F. Parsly⁽¹⁾ indicates that a choke, or restrictor, made of 1/2-in. OD 14-gage tubing and 54-in. long would throttle from about 900 psia to 150 psia, but that sonic velocities would no doubt exist at the exit. (About 30 such tubes, arranged in parallel, would be required to dump the HRE-3 volume in 10 minutes).

Fig. 1 Calculated Slurry Temperature in 1/2-in Dia Line.

Fig. 2. Calculated Slurry Temperature in 1-1/2-in Dia Line.

Fig. 3. Temperature of Cooling Water During Dump.

Fig. 4. Velocity of Slurry During Initial Surge Through Lines.

Experimental data will be required to substantiate three-phase flow friction loss estimates and to evaluate the erosive and corrosive effects.

Table II. Line Lengths Required to Prevent Flashing in Dump Valve

<u>Pipe Size</u>	<u>Parallel Paths</u>	<u>Length</u>
3-1/2 in.	1	5100 ft
1-1/2 in.	4	1800 ft
1/2 in.	26	500 ft

Table III. Special Cases with High Velocities

<u>Assumed Conditions</u>	<u>Calculated Results</u>
<u>Case I</u>	
50 fps average velocity Single dump line 10-minute dump time Water-cooled	2-in. Sch. 80 pipe size 1250-ft length 100 Btu/hr-ft ² -°F overall heat transfer coefficient Flashing starts within the first 300 ft of pipe and continues for the remaining length
<u>Case II</u>	
200 fps average velocity Single dump line 3-1/2-in. Sch. 80 pipe size No cooling	1-minute dump time 100-ft length Flashing occurs throughout entire length
<u>Case III</u>	
100 fps average velocity Single line 10-minute dump time Water-cooled	1-1/4-in. Sch. 80 pipe size 250-ft length 110 Btu/hr-ft ² °F overall heat transfer coefficient Flashing occurs throughout the entire length of line

Method of Analysis

Pipe Lengths

Pipe lengths were calculated from the Fanning friction equation (see sample calculations in Appendix.). Values of the Fanning friction factor, f , were taken from the data presented by Thomas.⁽²⁾ Slurry properties were those in general use for 1600-C-fired ThO₂ in D₂O at a concentration of 1000 g Th/liter (at 536°F).⁽³⁾⁽⁴⁾⁽⁵⁾⁽⁶⁾

Calculations were simplified by using average values of slurry properties, although these values were not necessarily constant throughout the dump line length. As a check on the validity of this simplifying assumption, the length of 1/2-in. dump line was determined by evaluating slurry properties every 100 ft and the length so determined, 770 ft, compared with the length of 725 ft calculated by using average properties. This difference is judged insignificant and no greater than the difference arising from discerning friction factors from the available charts.

Heat Transfer

Properties influencing heat transfer also vary along the length of pipe. However, rates calculated at the entrance, mid-section, and near the exit showed that the overall coefficient did not change significantly, and that it was within the required accuracy of this study to assume that the overall coefficient was essentially constant.

In determining the overall coefficient, individual coefficients were determined for the slurry film on the inside of the pipe, the pipe wall thickness, the scale deposit on the outer pipe surface and the water natural convection film, the latter being the controlling resistance.

Flashing was considered to have been prevented if the bulk slurry temperature was less than the saturation temperature of light water at the pressure existing at the corresponding point in the pipe. The slurry temperature was calculated from equations derived by McLain (See Appendix C).

Velocities

The average assumed velocity was used in determining friction factor values, and the number of parallel circuits required.

At assumed average velocities higher than 20 fps flashing three-phase flow which may reach sonic velocities will exist for a major portion of the pipe length, thereby reducing the velocity of slurry in the entering section of the pipe, which has not yet flashed, to below the assumed average velocity. Even in these cases, however, the average assumed velocities were used since values of both friction factor and sonic velocities during flashing three-phase are not amenable to calculation.

References

1. Memo, L. F. Parsly, Jr., to E. H. Bell, "300 SM Loop Dump Choke and Dump Valve Requirements," April 30, 1958.
2. D. G. Thomas, Hedstrom Plot for the Calculation of Laminar Flow Pressure Drop for Bingham Plastic Materials with Hedstrom Numbers from 0 to 10^{15} . ORNL CF 57-6-111, June, 1957.
3. P. R. Crowley and A. S. Kitzes, Physical Properties of Thorium Oxide Slurries. ORNL CF 54-5-59, May, 1954.
4. M. Tobias, Certain Physical Properties of Aqueous Homogeneous Reactor Materials. ORNL CF-56-11-135. November, 1956.
5. E. H. Gift, Graphs plotted from data presented by Tobias (8).
6. R. C. Robertson, et al., Preliminary HRE-3 Design Data (Revised to November 15, 1957). ORNL CF-57-11-74, November, 1957.
7. C. G. Lawson, Heat Transfer to Bingham Plastics, ThO₂ Slurries Flowing Turbently in Tubes: An Exploratory Study. ORNL CF-56-9-132, Sept., 1956.
8. W. H. McAdams, Heat Transmission. McGraw-Hill Book Company, Inc., New York, Second Edition, 1954.
9. B. F. Dodge, Chemical Engineering Thermodynamics, McGraw-Hill Book Company, Inc., New York, First Edition, 1944.

APPENDIX A

Sample Calculation

1. Line Length Required for Total Pressure Drop in 1/2-in Sch. 80 Dump Line.

From the Fanning equation:

$$L = \frac{\Delta p \cdot 2 \cdot g_c \cdot D}{\rho \cdot 4f \cdot v^2}$$

where f is evaluated as follows:

$$N_{Re} = \frac{DV\rho}{\eta} = \frac{(0.0455)(20)(3600)(124)}{(2.42)} = 1.68 \times 10^5$$

$$N_{He} = \frac{g_c \rho \tau_y D^2}{\eta^2} = \frac{(32.2)(129)(0.1) * (0.0455)^2 (3600)^2}{(2.42)^2} = 1.83 \times 10^6$$

$$\frac{\eta_s}{\mu_w} = \frac{2.42}{0.41} = 5.9$$

From (2) Fig. 1

$$f = 2.9 \times 10^{-3}$$

$$\text{and, } L = \frac{(985)(144)(64.4)(0.0455)}{(124)(4)(2.9 \times 10^{-3})(20)^2} = \sim 725 \text{ ft}$$

2. Number of Lines Required

$$\text{Total weight of: } (512)(116) = 59,300 \text{ lb slurry in blanket}$$

$$\begin{array}{l} \text{Cross sectional area required} \\ \text{not to exceed an average} \\ \text{velocity of 20 fps in a 10-min} \\ \text{dump} \end{array} = \frac{(59,300)(144)}{(10)(20)(116)(60)} = 6.14 \text{ in}^2$$

$$\begin{array}{l} \text{Number of 1/2-in. dia} \\ \text{Sch. 80 pipes required} \end{array} = \frac{(6.14)(4)}{(\pi)(0.546)^2} = \sim 26 \text{ pipes}$$

* The flow would still be turbulent and the value of f the same even if values of τ_y were as high as 1.0 lb/ft^2 .

3. Overall Heat Transfer Coefficient

$$\frac{1}{U} = \frac{1}{h_s} + \frac{x_p}{k_p} + \frac{1}{h_o} + \frac{1}{h_c}$$

At the entering section of pipe, from an equation presented by Lawson(7) p. 17.

$$\frac{h_s D}{k} = 0.023 \left(\frac{DV\rho}{\eta} \right)^{0.8} \left(1 - \frac{T_y}{T_w} \right)^3 \left(\frac{c h}{k} \right)^{1/3}$$

$$\frac{DV\rho}{\eta} = \frac{(0.0455)(72,000)(116)}{(2.42)} = 1.57 \times 10^5$$

$$T_w = \frac{0.023 \rho V^2}{g_c \left(\frac{DV\rho}{\mu_w} \right)^{0.2}}$$

$$\frac{DV\rho}{\mu_w} = \frac{(0.0455)(72,000)(116)}{(0.27)} = 1.41 \times 10^6$$

$$1 - \frac{T_y}{T_w} = 0.9404$$

$$\frac{c h}{k} = \frac{(0.500)(2.42)}{(0.39)} = 3.03$$

$$\therefore h_s = 3500 \pm 50\% \text{ Btu/hr ft}^2 \text{ } ^\circ\text{F}$$

say, $h_s = 1750 \text{ Btu/hr ft}^2 \text{ } ^\circ\text{F}$, conservatively.

A value for the heat transfer of the scale deposit, h_o , of $500 \text{ Btu/hr ft}^2 \text{ } ^\circ\text{F}$ was selected from McAdams (8) Table 7-2, p. 189.

Initially, h_c was estimated to be $350 \text{ Btu/hr ft}^2 \text{ } ^\circ\text{F}$.

Therefore

$$\frac{1}{U} = \frac{1}{1750} + \frac{0.147}{(12)(10)} + \frac{1}{500} + \frac{1}{350}$$

$$U = 150, \text{ say } 140 \text{ Btu/hr ft}^2 \text{ } ^\circ\text{F}.$$

Using this value of U the slurry temperatures at various locations in the pipe after a 10-minute dump were calculated (sample calculations appear in Section 4 following) and the results plotted in Fig. 1.

The value of h_c initially assumed was then checked using the method of McAdams (8) pp. 118 and 411 as follows:

In general, the quantity of heat transferred through a one-ft length of pipe can be written

$$q = \frac{\Delta t}{\Sigma R}$$

where

$$\Sigma R = \frac{1}{h_s \pi D_i / 12} + \frac{x_p}{k_p \pi D_{mp} / 12} + \frac{1}{h_o \pi D_o / 12} + \frac{1}{h_c \pi D_o / 12}$$

The heat that must be removed from the slurry is

$$q = w c (\Delta t)_s$$

$$w = \frac{(59,300)(60)}{(10)(26)} = 13,700 \text{ lb/hr of slurry through one pipe}$$

$(\Delta t)_s$ was read from the calculated slurry temperature of Fig. 1, at 0 ft and 20 ft from the line entrance.

The average quantity of heat removed per ft of length from one pipe then is

$$q = \frac{(13,700)(0.48)(545 - 516)}{20} = 9540 \text{ Btu/hr}$$

$$\Sigma R = \frac{(1)(12)}{(1750)(\pi)(0.546)} + \frac{(0.147)(12)}{(12)(10)(\pi)(0.693)} + \frac{(1)(12)}{(500)(\pi)(0.840)} + \frac{(1)(12)}{(350)(\pi)(0.890)}$$

$$\Sigma R = 0.0320 \text{ } ^\circ\text{F-hr/Btu}$$

$$(\Delta t)_{so} = \frac{R_{so}}{\Sigma R} (\Delta t)_t$$

$$(531 - t_o) = \frac{(0.00400 + 0.00676 + 0.00910)(531 - 135)}{(0.00400 + 0.00676 + 0.00910 + 0.0130)}$$

$$t_o = 292^{\circ}\text{F}$$

$$t_s = \frac{292 - 135}{2} = 214^{\circ}\text{F}$$

$$\frac{\Delta t}{D'} = \frac{292 + 135}{0.840} = 188$$

From McAdams⁽⁸⁾ Fig. 7-11 p. 178 $h_c = 330 \text{ Btu/hr ft}^2 ^{\circ}\text{F}$

Then,

$$\frac{1}{U} = \frac{1}{1750} + \frac{0.147}{(12)(10)} + \frac{1}{500} + \frac{1}{330}$$

$$U = 146 \text{ Btu/hr ft}^2 ^{\circ}\text{F} \text{ which is still greater than the 140 used in the calculations.}$$

If $\tau_y = 1.0$ rather than 0.1 lb/ft^2

$$1 - \frac{\tau_y}{\tau_w} = 0.484$$

$$\text{and } h_s = \frac{(3500)(0.484)^3}{0.852} = 466 \pm 50\% \text{ Btu/hr ft}^2 ^{\circ}\text{F}$$

$$\text{say, } h_s = 233 \text{ Btu/hr ft}^2 ^{\circ}\text{F}$$

and

$$\frac{1}{U} = \frac{1}{233} + \frac{0.147}{(12)(10)} + \frac{1}{500} + \frac{1}{330}$$

$$U = 95 \text{ Btu/hr ft}^2 ^{\circ}\text{F}$$

For this value of the overall coefficient and the same cooling water conditions as before, the calculated temperature of the slurry is 217°F indicating that flashing would occur.

4. Calculated slurry temperatures at various locations in 1/2-in. diameter line at the end of a 10-minute dump.

From an equation derived by McLain (Appendix C)

$$t_s = \frac{t_s^o - t_w}{\frac{AD}{e w_{cs}}} + t_w$$

At a location 100 ft from the entrance,

$$t_s = \frac{545 - 175}{\frac{(18.1)(140)}{13,700(0.42)}} + 175 = 413 \text{ } ^\circ\text{F}$$

Table III. Calculated Slurry Temperatures at Various Points in the 1/2-in. Diameter Line at the End of a 10-Minute Dump

Distance from entrance, L	Temperature of slurry t_w	Pressure at this point	Saturation temp. of H_2O at this pressure
ft	$^{\circ}\text{F}$	psia	$^{\circ}\text{F}$
0	545	1000	545
100	413	874	528
200	328	728	507
300	273	592	485
400	235	456	457
500	215	320	423
600	201	184	375
700	191	48	278
725	190	15	212

5. Quantity of cooling water required.

$$T = \frac{m_{cw}}{w_{cs}} \left(\frac{\frac{AU}{e w_{cs}}}{\frac{AU}{e w_{cs}} - 1} \right) \ln \left(\frac{t_w^o - T_s^o}{t_w - T_s^o} \right)$$

$$\frac{AU}{w_{cs}} = \frac{(\pi)(0.693)(725)(140)}{(12)(13,700)(0.42)} = 3.21$$

The initial temperature of the cooling water is assumed to be 135°F, and increase to 175°F at the end of the 10-minute dump.

$$\frac{10}{60} = \frac{m (1)(24.78)}{(13,600)(0.42)(24.78 - 1)} \ln \left(\frac{135 - 545}{175 - 545} \right)$$

$m = 8800$ lb of cooling water required per pipe.

For 26 pipes, $(8800)(26)(0.01637)(7.48) = 28,000$ gal of cooling water required.

6. Temperature of cooling water during dump.

$$\frac{m c_w}{w_{cs}} \left(\frac{e^{\frac{AU}{w_{cs}}} - 1}{\frac{AU}{w_{cs}}} \right) \ln \left(\frac{t_w^o - t_s^o}{t_w - t_s^o} \right)$$

At $T = 2$ min.

$$\frac{2}{60} = \frac{(8800)(1)(24.78)}{(13,600)(0.42)(24.78 - 1)} \ln \left(\frac{135 - 545}{T_2 - 545} \right)$$

$$t_2 = 144^\circ\text{F}$$

Temperatures at other times during dump are shown in Table IV.

Table IV. Temperature of Cooling Water During Dump

Time after start of dump, T Min.	Temperature of cooling water, T_w °F
0	135
2	144
4	152
6	160
8	168
10	175

7. Velocity of slurry during first 10 seconds after start of dump.

From the Bernoulli Equation as stated by Dodge⁽⁹⁾ pp. 347, 348

$$Z_2 - Z_1 + (p_2 - p_1)_v + \frac{v_2^2 - v_1^2}{2g} = F_c + F_p + F_f + F_e$$

Assume: $Z_2 - Z_1 = 0$

$V_1 = 0$

$F_f = 0$ (Conservative)

$F_e = 0$ (Conservative)

$F_c = \frac{K V_2^2}{2g}$

$F_p = \frac{2fLV_2^2}{g_c D}$

The velocity 40 ft from the entrance can be determined by trial and error calculations.

At 40 ft, assume $V = 97$ fps

$F_c = \frac{(0.5)(97)^2}{(2)(64.4)} = 73 \text{ ft-lb}$

$F_p = \frac{(2)(2.9 \times 10^{-3})(40)(97)^2}{(32.2)(0.0455)} = 1489 \text{ ft-lb}$

$\frac{(15-1500)(144)}{125} + \frac{V_2^2 - 0}{64.4} = -1562$

$V_2 = 97$ fps, which checks with the assumed velocity at this point.

The velocity at the beginning and at the end of each interval of length was averaged to determine the approximate time required to flow through that length.

Time required to flow from 60 to 80 ft $= \frac{(80 - 60)}{(97 + 81)(0.5)} = 0.26 \text{ sec}$

Table V. Velocity Estimates of Initial Slurry Flow in 1/2-in dia Pipes

Distance from Entrance	Velocity at this Point	Total Elapsed Time
<u>ft</u>	<u>fps</u>	<u>sec</u>
0	270	-
5	200	0.02
10	165	0.05
20	129	0.1
40	97	0.3
60	81	0.5
80	71	0.8
95	65	1.0
200	46	2.9
300	38	5.3
400	32	8.1
460	30	10.0

APPENDIX B

Step-Wise Calculation of Pipe Length

The length of 1/2-in dia pipe was determined by evaluating f approximately every 100 ft, and this value assumed to exist over the next 100 ft. A better method might have been to evaluate f near the midpoint of a length over which it would be used. However, the method actually used is satisfactory since it was found that the value of f did not change too much over the entire pipe length. The general equation used was:

$$L = \frac{193.2 \Delta p D}{\rho f V^2}$$

At section 100-200 ft

Properties evaluated at 100 ft from entrance

Table VI. Step-Wise Calculations for Length of 1/2-in. Diameter Pipe

Length	Pressure	Sat. Temp. of H ₂ O	Slurry Density	N _{Re}	N _{Hc}	η μ	f	Δp
L ft	P psia	°F	ρ lb/ft ³	$\times 10^5$	$\times 10^6$		$\times 10^{-3}$	
0 to								
100	1000	545	116	1.57	1.70	8.96	2.7	119
100 to								
200	881	530	117	1.59	1.72	8.65	2.7	120
200 to								
300	761	513	118	1.60	1.73	8.34	2.8	125
300 to								
400	636	493	119	1.61	1.75	8.08	2.8	126
400 to								
500	510	469	121	1.64	1.76	7.80	2.8	128
500 to								
600	382	440	122	1.66	1.79	7.34	2.9	134
600 to								
700	248	401	124	1.68	1.83	6.73	2.9	138
700 to								
770	110	335	126	1.71	1.85	5.50	3.0	105
770	15	212	129	1.75	1.90	3.06	3.2	

$$N_{Re} = \frac{DV\rho}{\eta} = \frac{(0.0455)(72,000)(117)}{(2.42)} = 1.59 \times 10^5$$

$$N_{He} = \frac{g_c \rho \tau_y D^2}{\eta^2} = \frac{(32.2)(117)(0.0455)^2(3600)^2}{(2.42)^2}$$

$$= 1.72 \times 10^6$$

$$\frac{\eta}{\mu} = \frac{2.42}{0.28} = 8.65$$

$$f = 2.7 \times 10^{-3}$$

$$\Delta p = \frac{(100)(117)(2.7 \times 10^{-3})(400)}{(193.2)(0.540)}$$

From Table VI, the effect of f increasing markedly at the end of the pipe is to decrease the length of pipe actually needed from the 770 ft length calculated, and more closely approach the 725 ft length calculated using average slurry properties.

APPENDIX C

Derivation of Equations for Heat-Transfer Between Slurry and Cooling Water*

The arrangement essentially is a pipe containing slurry submerged in a tank of cooling water. The water is not mechanically stirred, and is at atmospheric pressure.

At any instant after the start of dump

$$dq = -wc_s dt_s = U dA (t_s - t_w)$$

$$A = \int_0^A dA = - \int_{t_s^0}^{t_s} \frac{wc_s dt_s}{U(t_s - t_w)}$$

Assume $\frac{wc_s}{U} = \text{a constant}$

$$A = \frac{-w c_s}{U} \ln \left(\frac{t_s - t_w}{t_s^0 - t_w} \right) = \frac{w c_s}{U} \ln \left(\frac{t_s^0 - t_w}{t_s - t_w} \right)$$

$$\frac{t_s^0 - t_w}{t_s - t_w} = e^{\frac{AU}{wc_s}}$$

or,
$$t_s = \frac{t_s^0 - t_w}{\frac{AU}{wc_s}} + t_w$$

Another equation can be written

$$mc_w \frac{dt_w}{dT} = w c_s (t_s - t_s^0)$$

Assume m , w , c_s , and c_w are constants

$$T = \int_0^T dT = - \frac{mc_w}{wc_s} \int_{t_w^0}^{t_w} \frac{dt_w}{(t_s - t_s^0)}$$

* Derived by H. A. McLain

$$= \frac{m c_w}{w c_s} \int_{t_w}^{t_w^o} \frac{dt_w}{\left(\frac{t_s^o - t_w}{e \frac{AU}{wc_s}} \right) + t_w - t_s^o}$$

$$T = \frac{m c_w}{w c_s} \left(\frac{\frac{AU}{wc_s}}{e \frac{AU}{wc_s} - 1} \right) \ln \left(\frac{t_w^o - t_s^o}{t_w - t_s^o} \right)$$

Nomenclature

c	Specific heat at constant pressure, Btu/lb °F; c_s for slurry, 0.500 at 536°F, 0.42 average; c_w for water, 1.
D	Diameter, ft; D_i for inside diameter of pipe, D_m for mean diameter of pipe; D_o for outside diameter.
f	Fanning friction factor, dimensionless.
F_c	Mechanical energy converted to heat by friction in sudden contractions in pipes, ft-lb/lb of fluid; F_e for sudden enlargements, F_f for fittings, F_p for straight pipe.
g_c	Conversion factor, 32.2 ft/sec ² .
h	Coefficient of heat transfer, Btu/hr ft ² °F; h_c for natural convection of water; h_o for scale deposit on outside of pipe, 500; h_s for slurry.
k	Thermal conductivity, Btu/hr ft ² °F/ft; for slurry unless otherwise noted, 0.39 at 536°F; k_p for SS 347 pipe, 10.
K	Empirical constant for use in equation determining F_c , dimensionless, 0.5.
L	Length of pipe, ft.
m	Weight of cooling water, lb.
N_{He}	Hedstrom number, dimensionless.
N_{Re}	Reynolds number, dimensionless.
Δp	Friction drop in pipe, psf, (985 x 144).
q	Rate of heat-transfer, Btu/hr.
R	Individual thermal resistance, °F hr/Btu; R_{so} from slurry to outside surface of scale deposit on pipe; ΣR total thermal resistance.
t	Temperature, °F; t_o for surface temperature of scale; t_f for average water film temperature; t_s for slurry temperature; t_w for water temperature; superscript where used is time in minutes after start of dump.

Δt	Temperature difference, $^{\circ}\text{F}$; $(\Delta t)_s$ for temperature difference of slurry at two locations in pipe; $(\Delta t)_t$ for total difference in temperature between slurry and ambient cooling water temperature. $(\Delta t)_{so}$ from slurry to outside surface of scale deposit on pipe.
T	Time after start of dump, min.
U	Overall coefficient of heat transfer, $\text{Btu/hr ft}^2 ^{\circ}\text{F}$.
V	Velocity, fps; (average slurry velocity 20 fps).
v	Specific volume, ft^3/lb .
w	Mass rate of flow of slurry, lb/hr .
x_p	Thickness of pipe wall, ft.
Z	Vertical distance above an arbitrary datum plane, ft.
η	Coefficient of rigidity for slurry, 2.42 lb/hr ft .
μ	Viscosity of water, lb/hr ft ; 0.27 at 536°F , 0.41 average.
ρ_x	Density of slurry, ft^3/lb ; 116 at 536°F , 124 average.
τ_y	Yield stress of slurry, 0.1 lb/ft^2 .
τ_w	Shear stress of slurry at the wall of the pipe, lb/ft^2 .

DISTRIBUTION

1. HRP Director's Office
Rm 259, Bldg. 9204-1
2. G. M. Adamson
3. S. E. Beall
4. A. M. Billings
5. E. G. Bohlmann
6. S. E. Bolt
7. E. S. Bomar
8. J. R. Brown
9. W. D. Burch
10. R. H. Chapman
11. R. D. Cheverton
12. H. C. Claiborne
13. E. L. Compere
14. R. S. Crouse
15. J. S. Culver
16. D. G. Davis
17. R. J. Davis
18. J. R. Engel
19. J. L. English
20. D. E. Ferguson
21. J. D. Flynn
22. C. H. Gabbard
23. W. R. Gall
24. J. C. Griess
25. R. S. Greeley
26. P. A. Haas
27. P. H. Harley
28. P. N. Haubenreich
29. J. W. Hill
30. E. C. Hise
31. C. J. Hochanadel
32. G. H. Jenks
33. D. T. Jones
34. S. I. Kaplan
35. P. R. Kasten
36. F. Kertesz
37. J. O. Kolb
38. R. B. Korsmeyer
39. C. G. Lawson
40. R. E. Leuze
41. R. A. Lorenz
42. M. I. Lundin
43. R. N. Lyon
44. W. L. Marshall
45. J. P. McBride

46. H. F. McDuffie
47. H. A. McLain
48. R. A. McNees
49. J. R. McWherter
50. R. L. Moore
51. L. F. Parsly, Jr.
52. M. L. Picklesimer
53. S. A. Reed
54. D. M. Richardson
55. G. W. Rivenbark
56. R. C. Robertson
57. M. W. Rosenthal
58. H. C. Savage
59. C. L. Segaser
60. E. M. Shank
61. M. D. Silverman
62. M. J. Skinner
63. I. Spiewak
64. R. W. Stoughton
65. J. A. Swartout
66. E. H. Taylor
67. D. G. Thomas
68. D. S. Toomb
69. W. E. Unger
70. R. Van Winkle
71. A. M. Weinberg
72. K. W. West
73. J. C. Wilson
74. C. E. Winters
75. F. C. Zapp
- 76-77. REED Library
- 78-79. Central Research Library
- 80-81. Document Reference Library
- 82-96. Laboratory Records
97. ORNL-RC
98. R. E. Aven

EXTERNAL

99. F. C. Moesel, AEC Washington
- 100-106. Westinghouse PAR Project
- 107-121. TISE-AEC