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HRP-CP: HEAT REMOVAL FROM A PROPOSED
HYDROCLONE UNDERFLOW POT GEOMETRY
FOR A VOLUME HEAT SOURCE

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October 5, 1955

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Underflow Pot Geometry for a Volume Heat Source

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INTRODUCTION

The design of the hydroclone underflow pot for the HRP chemical processing plant is partly dictated by the requirements for removing heat from the fission product volume heat source. A design based on assuming all heat was removed by conduction was impractical. Assuming conductive heat transfer only would require that all the two gallons or more of pot solution were within one-half inch of a cooled wall. The objective of this study was to determine if convective heat transfer was efficient enough to permit using a pot geometry of a simple cylinder with a coolant jacket.

The studies were limited to determining if the simplest pot geometry permitted removal of an adequate amount of heat for below 100°C operation. The geometry tested was a 6-in.-i.d. vertical cylinder 2-ft long (3.0 gallons volume) with cooling water flowing upward through an annular jacket. The fission product volume heating was simulated by electrical volume heating of the pot solution. The solution was open to atmospheric pressure; this imposed the atmospheric boiling point of the solution as an upper temperature limit. Temperature distributions in the pot were determined by use of a moveable thermocouple. Flow patterns and flow velocities were also studied.

A literature search was made to determine if empirical or theoretical methods would give firm values of temperature differences or permit extrapolation of below 100°C results to 250-300°C. Very few literature reports deal with volume heat sources and no directly applicable equations were found. Additional correlations of free convection theory and experimental results are needed in addition to presently reported work (1, 2, 3) before theoretical calculations will be dependable.

SUMMARY

Convective heat transfer was shown to be effective enough to permit use of a simple cylindrical geometry with an annular cooling jacket for the HRP-CP hydroclone underflow pot. Electrical resistance heating of UO_2SO_4 solution was used to simulate the volume heating of fission products in a 6-in.-dia., 24-in. long pot. For steady-state temperatures with the 2.1 kw heat input being removed by the cooling water, the temperature difference between the hottest and coldest pot solution was less than 30°C. The flow pattern in the pot was a core of solution rising at about 2 in./min and a thin layer falling near the cooled wall at 10 to 15 times the velocity of the rising solution. The lower soup viscosity and greater density decrease per degree of temperature increase would make convective heat transfer more effective at the HRP-CP conditions of 250-300°C.

TEMPERATURE DISTRIBUTIONS

Power input rates of up to 2.1 kw were investigated; no appreciable temperature gradients (less than 1°C) were detectable across any pot diameter (see Table I and Figure 1). A vertical gradient of 8 to 9°C per foot existed throughout the center section of the pot (see Figure 1, Tables 2, 3 and 4). Larger gradients near the pot ends resulted in a total difference of 28 to 30°C between the two electrodes. The shape of temperature distributions calculated theoretically (1) agree with those found in the underflow pot. The theory predicts the shape of temperature gradients only and not their magnitude. The temperature distributions could be explained by a core of warm solution rising and a layer of cool solution falling at the cooled walls of the pot (see Figure 2). The existence of this flow pattern was confirmed by flow rate determinations (see section on "Flow Patterns and Flow Rates").

During these studies, a certain axial temperature gradient seemed to be required to maintain the convective flow. This gradient did not increase proportionally as the power input and heat removal rates increased; i.e., increases in power density increased the solution flow rate more than they increased the solution temperature gradients. At the HRP-CP conditions of $250\text{--}300^{\circ}\text{C}$, the lower solution viscosity and larger density change per degree temperature increase should result in lower temperature gradients than for the same fluid velocities in these below 1000°C experimental studies.

FLOW PATTERNS AND FLOW RATES

The observed flow pattern was a core of slowly rising solution throughout the center of the pot and a rapidly falling layer near the cooled pot walls (see Figure 2). This pattern held throughout the middle two-thirds of the pot. Near the ends, the flow was eddying with the only fixed pattern being a net flow to the pot center at the bottom and to the pot wall at the top.

Upward velocities of KMnO_4 clouds near the pot centerline ranged from $1\text{--}1\frac{1}{2}$ to $3\text{--}1\frac{1}{2}$ in. per minute with observed values centering at about 2.3 in./minute. These are comparable to 2.2 to 3.7 in./minute velocity calculated from the volume heat source, heat capacity, and temperature gradients of the pot solution (see section on "Calculations and Tabulated Data"). These calculated values would be high since they assume that solution moving up the pot center loses no heat until it reaches the top and moves out to the walls. Observed velocities for MnO_2 particles near the pot walls were 7. to 47 in./minute. An estimated average velocity of the fastest falling layer of solution was 25 in./minute. From the estimated velocities, the thickness of the layer of falling solution would be between $1/8$ and $1/4$ inch (see section on "Calculations and Tabulated Data"). This type of velocity distribution has been predicted by theoretical calculations (1).

For convective heat transfer of the type studied, the temperature gradients will level out at values which give sufficient convection to remove the heat being added. The temperature gradients cause the density differences and thus the pressure differences which cause flow. At 300°C , the density change per

FIGURE 1 TEMPERATURE DISTRIBUTION IN A
SIMULATED HYDROCLONE UNDERFLOW POT

Fig. 2. Temperatures and Flows in a Vertical Pot Cross Section.

$^{\circ}\text{C}$ is five times that at 80°C . It is estimated that 6 kw of heat could be removed from a 6-in.-dia. by 24-in. long CP hydroclone underflow pot without exceeding the 50°C pot solution temperature gradient limit. It is estimated that fluid velocities at the pot centerline would be on the order of 1 to 2 in./min per kw of volume heating in the pot.

BIBLIOGRAPHY

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APPENDIX

Pot Construction

The underflow pot volume heating and geometry were obtained by 60-cycle a.c. electrolysis of UO_2SO_4 solution between two electrodes 24 in. apart in a 6-in.-dia. Pyrex pipe (see Figures 3 and 4). The 3-ft length of Pyrex pipe provided the electrical insulation required for electrolysis and permitted visual observation of the pot interior. The electrodes of 6-in.-dia. plates of 1/8-in. thick stainless steel were installed 6 in. from the ends and were slanted several degrees to permit escape of gas bubbles. This 6 in. of unheated volume on each end provided thermal insulation to the ends and room for coolant jacket seals on the outside of the Pyrex pipe. A liquid expansion and gas disentrainment volume was provided by not completely filling the pipe with solution. Heat removal for an initial test was found to be 500 watts or less with a fan blowing air around an unjacketed pot. Then a 1/2-in. thick annular cooling water space was provided by sealing a 26-in. long cylindrical jacket to the outside of the Pyrex pipe with rubber sleeves cut from a truck inner tube. The initial stainless steel jacket cylinder was later replaced by a transparent Lucite jacket. Cooling water entered the bottom at one side and left the top of the jacket at the other side. Water flows of up to 4.3 gpm were measured by a Flowrator and inlet and exit temperatures were measured by thermometers in the water lines.

Temperature measurements in the pot were made by a thermocouple in a 36-in. long glass tube. The thermocouple junction was in a mercury or oil-filled thin wall bulb on the tube end. A 0-150 $^{\circ}\text{C}$ Wheelco galvanometer-type indicator with 2 $^{\circ}\text{C}$ -scale divisions was used with this thermocouple. The a.c. current used for volume heating required the use of non-electronic equipment to minimize the effects of induced emf's in the thermocouple leads. The thermowell pivoted in a loose-fitting rubber stopper in the pot top end plate. Pins and markers in a plywood board mounted on top of the pot were used to position the top end

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FIGURE 3 **SIMULATED**
HYDROCLONE UNDERFLOW POT

PHOTO 15292

Fig. 4. Simulated Hydroclone Underflow Pot for Heat Transfer Studies.

of the thermowell and thus the bulb and thermocouple junction. The whole pot assembly was supported by a steel cable over commercial electric power line insulators.

Power Supply for Volume Heating

The power supply to give controlled volume heating in the simulated underflow pot consisted of a 208 v input variac feeding two 5-to-1 isolation transformers in series (see Figures 5 and 6). This power supply was set up for experimental evaporator studies on D_2O recovery. The high voltage output of the transformers was connected through the ammeter to the pot end plates with a voltmeter across the leads. A safety switch and an on-off switch were installed in the 208-v, 60-cycle a.c., single phase supply to the 12 kva Powerstat.

The two high-voltage transformers acted as isolation transformers so that normally neither pot electrode was at a potential relative to ground. The micro-switch (see Figure 5) in the 208-v supply to the variac was installed so that opening the gate in the barricade around the enclosure cut the power supply.

Experimental Methods

The results reported were for steady-state operation with constant temperatures, power inputs, and cooling water flows. Steady-state conditions were reached in two hours or less for a fixed water flow rate and variac setting.

The moveable thermowell was lowered or raised and pivoted at the top end plate to determine temperature distributions. The known thermowell length and the position of the end out of the pot located the thermocouple junction in the pot. Visual confirmation through the transparent walls of the pot was also possible for most points.

The 1/4-in.-dia. glass bulb in which the thermocouple bulb was located would average out the temperature over an area of at least this diameter. This probably prevented measurement of the true temperature of the coldest solution near the wall even though the thermowell bulb was in contact with the wall. Conduction along the thermowell wall and perturbation of the flow pattern by the thermowell probably also caused minor errors. Check temperature determinations with a long-stem mercury-filled thermometer gave temperatures within $\pm 1/2^\circ C$ of the thermocouple temperatures.

Flow patterns and flow rates were determined by observing $KMnO_4$ clouds or small particles of precipitated MnO_2 . The average of the most consistent of repeated cloud or particle rates of motion were reported as the liquid flow rates. Scraps of plastic loaded with steel wire to give a combined specific gravity equal to that of warm water, and scraps of paper were not dependable flow rate indicators. Adherence of air bubbles and the large individual scrap size together caused the poor results with the plastic-steel or paper scraps.

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FIGURE 5 SIMULATED UNDERFLOW POT POWER SUPPLY

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PHOTO 15293

Fig. 6. Simulated Hydroclone Underflow Pot and Associated Equipment.

Calculations and Tabulated Data

If the solution at the pot centerline is assumed to lose no heat while rising through the middle section of the pot, a heat balance can be used to calculate an upward velocity from the temperature gradient. Since there is some conductive heat transfer and some mixing of solution at all times, this calculated velocity would be expected to be higher than the true velocity. The calculation for the simulated underflow pot was made using the following equation:

$$\text{Velocity} = \frac{P}{\Delta T C_P}$$

where: P is power density in power input per unit volume,
 ΔT is the temperature gradient along the vertical axis, and
 C_P is heat capacity.

For one period of steady-state pot operation:

$$P = \frac{(5.5 \text{ amperes})(385 \text{ volts})}{(0.392 \text{ cu. ft})} = 5,400 \frac{\text{watts}}{\text{cu.ft}}$$

$$C_P = 117,000 \text{ watt}\cdot\text{sec}/\text{ft}^3\cdot^{\circ}\text{C}$$

$$\text{velocity} = \frac{5,400}{117,000 \cdot T} = \frac{2.766}{\Delta T} \frac{^{\circ}\text{C}}{\text{min}}$$

$$\text{for } \Delta T = 9^{\circ}\text{C}/\text{ft} = 0.75^{\circ}\text{C}/\text{in.}, \text{ velocity} = 3.7 \text{ in.}/\text{min}$$

$$\text{for } \Delta T = 30^{\circ}\text{C}/2 \text{ ft} = 1.25^{\circ}\text{C}/\text{in.}, \text{ velocity} = 2.2 \text{ in.}/\text{min}$$

From a material balance, the net flow of solution across any pot cross section must be zero. From estimated average velocities and assuming symmetry in the pot, the thickness of the layer of falling solution near the pot wall can be calculated.

Let r = radius of core of rising solution

3-r = thickness of layer of falling solution

Estimate 2. in./min as average velocity of rising solution

18. in./min as average velocity of falling solution

$$2 \pi r^2 = 18 \pi [(3)^2 - r^2]$$

$$\text{Solving: } r = 2.846, \quad 3-r = 0.154$$

Therefore, the layer of falling solution would be about 5/32-in. thick.

The rate of heat removal can be calculated by two methods from temperatures and flow rates of pot solution and cooling water. A calculation of heat gained by the cooling water would be high because some of the heat would come from the room through the water jacket. A calculation of heat transferred from the tem-

perature difference and calculated heat transfer coefficients would probably be high because some resistances can only be estimated. Some of the electrical energy input is probably lost as heat through the pot ends. For one period of steady-state operation:

$$\begin{aligned}\text{Electrical energy input} &= (160 \text{ v})(11.9 \text{ amp}) \\ &= 1.9 \text{ kw} \\ &= 6,500 \text{ Btu/hr}\end{aligned}$$

$$\begin{aligned}\text{Cooling H}_2\text{O heat gain} &= [(0.40)(60)(\text{gal/hr})] [8.3 \text{ lb/gal}] (30^\circ\text{F}) \\ &= 6,000 \text{ Btu/hr}\end{aligned}$$

For overall heat transfer coefficient

$$h_{\text{glass}} = \frac{k}{t} = 24.5 \text{ Btu/hr}\cdot\text{ft}^2\cdot^\circ\text{F}$$

$$\text{Estimated } h_{\text{solution}} = 80 \text{ Btu/hr}\cdot\text{ft}^2\cdot^\circ\text{F}$$

$$\text{Estimated } h_{\text{H}_2\text{O}} = 1000 \text{ Btu/hr}\cdot\text{ft}^2\cdot^\circ\text{F}$$

$$q = U A \Delta T = \frac{2 \cdot 1/2 \cdot \pi}{\frac{1}{24.5} + \frac{1}{80} + \frac{1}{1000}} \Delta T = 57.5 \Delta T$$

$$\Delta T = 51^\circ\text{C} = 92^\circ\text{F}$$

$$q = (57.5)(92) = 5,300 \text{ Btu/hr}$$

Similar calculations for another steady-state period gave:

$$\text{Heat input} = 2.2 \text{ kw} = 7,500 \text{ Btu/hr}$$

$$\text{Cooling water heat gain} = \sim 7,000 \text{ Btu/hr}$$

$$q = (57.5)(117) = 6,700 \text{ Btu/hr}$$

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Table I

Conditions and Heat Balances for Steady-State TestsConcentration - 10 g U/kg H₂O, varying amounts of KMnO₄Pot Geometry - 6-in.-i.d., 24 in. between electrodes, about
8-in.-o.d. stainless steel or Lucite cooling
H₂O jacket

Test No.	Electrical Input (kw)	Temperatures (°C) for:					Cooling H ₂ O				Calculated Heat Trans. thru glass pipe (kw)
		Distance above bottom electrode (in.)	Radial Position				Flow (gpm)	Temperature		Heat Gain (kw)	
			Center line	2 in. from wall	1 in. from wall	Wall		In	Out		
1	2.0	18	87.	87.	87.	87.	3.14	19.	----	----	1.8
2	0.8	18	48.8	---	---	49.	3.14	19.	----	----	0.64
3	2.2	14	82.5	---	---	83.0	3.14	19.	21.5	2.1	1.97
4	1.9	13	79.8	80.3	80.2	79.3	0.40	20.0	36.6	1.75	1.55
5	2.1	8	81.3	81.3	81.0	80.8	0.65	18.5	29.8	1.93	1.82
6	1.9	15	81.0	---	---	---	1.20	20.5	26.5	1.89	1.70

Table 2

Temperature Distributions During Steady-State Operation

Test 3

Concentration - 10 g U/kg H₂O
H₂O Inlet Temperature - 19°C
H₂O Exit Temperature - 21.5°C
H₂O Flow Rate - 3.14 gpm
H₂O Jacket - Stainless steel cylinder
Electrical Power Input - 2.2 kw (5.5 amp at 400 v)

Distance Above Bottom Electrode (in.)	Temperatures (°C)	
	Centerline	Wall
1	72.0	
2	73.0	
3	74.0	
4	74.6	74.8 ^a
5 ^a	75.3	
6	76.0	
7	77.0	
8	77.8	
9	78.5, 78.0	78.8 ^a
10	79.0	
11	80.0	
12	80.7	
13	81.9	
14	82.5	83.0 ^a
15	83.5	
16	84.5	
17	86.0	
18	87.5	
19	90.0, 90.0	
20	92.0	
21	96.5 ^b	
22	101.6 ^b	
23	102. ^b	

^aThese values for distances uncorrected for angularity of thermowell. True position is 0.1-0.4-in. above those tabulated.

^bSlight amount of boiling in top few inches of pot resulted in a section at a constant (boiling point) temperature.

Table 3

Temperature Distribution During Steady-State Operation

Test 4

Concentration - 10 g U/kg H₂O; unknown amount of KMnO₄
H₂O Inlet Temperature - 20.0°C
H₂O Exit Temperature - 36.4 to 36.8°C
H₂O Flow Rate - 0.40 gpm
H₂O Jacket - Lucite cylinder
Electrical Power Input - 1.9 kw (11.9 amp at 160 v)

Distance Above Bottom Electrode (in.)	Temperatures (°C)			
	Centerline	2 inches from wall	1 inch from wall	Wall
2	68.0, 69.0			67.0
3	69.6			
4	71.2			70.6
5	72.5, 72.5			71.7
6	73.8			
7	74.8			74.5
8	75.8			
9	76.5	77.0	76.8	76.0
10	77.6			
11	78.3	78.5	78.5	77.8
12	79.1, 79.5			
13	79.8	80.3	80.2	79.3
14	80.7, 81.5			
15	81.6, 81.7, 81.6			
16	81.8, 82.0			
17	82.3, 82.5			
18	83.3, 83.6			
19	84.1			
20	85.0			
21	86.0			
22	87.0			
23	87.9			

Table 4

Temperature Distribution During Steady-State Operation

Test 5

Concentration - 10 g U/kg H₂O; unknown amount of KMnO₄
H₂O Inlet Temperature - 18.2 to 18.8
H₂O Exit Temperature - 29.6 to 30.0
H₂O Flow Rate - 0.65 gpm
H₂O Jacket - Lucite cylinder
Electrical Power Inlet - 2.1 kw (6.4 amp at 330 v)

Distance Above Bottom Electrode (in.)	Temperatures (°C)			
	Centerline	2 inches from wall	1 inch from wall	Wall
2	73.3	73.2	73.5	72.5
3	75.8	75.3	75.3	74.7
4	77.0	77.0	77.0	76.3
5	78.5			
6	79.3			78.5
7	80.5			
8	81.3	81.3	81.0	80.8
9	81.5			
10	82.2			
11	83.0			
12	83.6			
13	84.6			
14	85.2			
15	86.0			
16	86.3			
17	86.7			
18	87.2			
19	88.0			
20	89.0			
21	90.0			
22	91.7			
23	92.2			

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