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Date: October, 1952

Subject: BOILING AND SLURRY PROGRESS, October 1, 1952

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NOTE: The following is the progress report for slurry and boiling research for the quarter ending October 1, 1952, as submitted for the HRP Quarterly Report. It does not necessarily represent the exact text of the HRP report on this subject.

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SLURRY PUMPING STUDIES

Kitzes, Gallaher, Crowley, Hullings, Gifford

High Pressure Slurry Circulating System

The total operating time of the 250°C-1000 psi slurry system has reached just over 1200 hours of which 1120 hours represent the total time in which slurry was actually being circulated. The remainder of the time consists of short runs with water, nitric acid and tri-sodium phosphate solution which were used in preliminary tests of the equipment and in cleaning it between slurry runs. The operating time can be broken up as follows:

Test Run; 25 hours

Demineralized water at 250°C

S-1; 3 hours

78 gpl U as $UO_3 \cdot H_2O$

Shutdown when it was found that a portion of the slurry was circulating through the bearings and up through a condensate line to the pressurizer. This condition was remedied by moving an orifice in the main stream to a point down stream from the pressurizer.

Test Run; 30 hours

Demineralized water run to test the revised purge system.

[REDACTED]

[REDACTED]

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S-2; 113 hours

50 gpl of U - dropped during operation to 26 gpl, apparently due to accumulation in the pressurizer. After test, the main system was clean and there was no measurable wear of the bearings.

S-3; 171 hours

80 gpl of U - dropped to 20 gpl and finally clear water was obtained in sample from main flow stream. Again, apparently oxide accumulated in pressurizer.

Test Run; 15 hours

Demineralized water

S-4; 41 hours

229 gpl of U dropped in first 21 hours to 97 gpl and finally the system was shut down. During this run, a portion of the stream was by-passed to a point above the slurry surface in the pressurizer, but dried oxide was observed on the walls of the pressurizer, accounting for the drop in main stream concentration. No wear was observed on the bearings.

S-5; 160 hours

200 gpl as U dropped to 109 gpl. 2 1/2 hours after this run started the purge of condensate through the back of the motor was stopped. At the end of the run approximately 0.0005 inches wear was observed on the front Graphitar motor bearing.

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S-6; 179 hours

133 gpl as U dropped to 97 gpl. For some reason the power to the pump increased suddenly from 13.8 kw to 16.5 kw. The front bearing was found to have approximately 0.002 inches wear on the diameter. The rear bearing and both front and back journals showed no change.

S-7; 186 hours

175 gpl of U dropped to 34 gpl. After this test was started, it was found that the oxide was impure, for example it contained 120 ppm of nitrate. The position of the orifice was changed, and the orifice opening was increased to 1 inch. This raised the pump power demand to 15 kw. The total accumulated wear of the front bearing was unchanged after this test, that is, it remained at 0.002 inches.

After this test the equipment was torn down and examined carefully and no evidence of erosion was found. The system was then rebuilt as before, except that a new pressurizer was installed so that the entire process stream entered the pressurizer below the liquid surface and then passed out the bottom. In effect the lower part of the pressurizer was made part of the main flow system.

S-8; 95 hours

177 gpl of U dropped to 110 gpl in 70 hours, and dropped rapidly thereafter. In this test 100 psi Helium was used with steam for pressurization. It was found at the end of the test that the pressurizer was clean, but coating was observed in the main process piping.

S-9; 162 hours

The system was subjected to a partial pressure of 100 psi of oxygen at room temperature. 215 gpl of U, dropped in 18 hours to 116 gpl. 26 hours later the system pressure was increased by 100 psi (to 1100 psi) by raising the pressurizer temperature and 4 hours afterward a sample was taken which showed 190 gpl. The fact that the U content was greater than the initial concentration is attributed to the number of samples taken with low concentration which reduced the water inventory, and possibly to incomplete removal of the oxide coating after the preceding test. The pressure was then reduced again to 1000 psi and a day later the concentration was 180 gpl. 91 hours later the concentration dropped to 23 gpl and the system was shut down. Severe coating of the pipes was again observed, and the front pump bearing was found to be worn 0.009 inches. It was decided to replace the bearing with another graphitar one even though the bearing was not yet causing difficulty.

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The principal conclusions to be drawn from these tests are 1) maintenance of slurry concentration in a circulating system at 250°C has not yet been achieved, and 2) graphitar may be an unsuitable material for long operation in the front bearing of a pump, if slurry is to be permitted to enter the bearing.

The fact that increased pressure caused the concentration to recover is of interest, and an attempt will be made to observe this phenomenon again. In a subsequent test, now in operation, the addition of water to the system also caused a recovery of the concentration. The explanation in the latter case is that the flowing system is not completely full after several samples have been removed, and that adding water helps to sweep away the coating which accumulates in the partially filled pipes.

Since the new pressurizer has been installed, all coating has appeared in the pipes rather than the pressurizer. In most cases the coat is easily reslurried, and this lends support to the theory that the pipes are not completely full. There is no reason to believe that the problem of concentration drop cannot be solved, but at present there are insufficient experimental data to point positively to the solution of the problem.

It is believed that solution of the bearing problem lies either in a continuous purge of the bearings by water (perhaps condensate from the pressurizer as in the first 4 runs listed above) or in the use of harder bearing materials. A separate bearing test at room temperature has already indicated wear of graphitar against titanium carbide in slurry, but indicated no measurable wear with stellite to stellite under similar conditions.

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Glass Loop

A 100 gpm glass loop has been built to observe flow patterns and to develop sampling techniques. Minimum velocities to transport slurries of varying concentrations will also be determined.

Second High Temperature Loop

Consideration is being given to the design of a second high temperature slurry loop. The loop will be longer to provide a larger capacity for periodic sampling. Provision for heat transfer and pressure drop studies will be included. A number of flanged sections will be made available for insertion of test sections of other materials for corrosion and erosion studies. Low carbon steels and other alloy steels are some of the materials under consideration for use in a slurry reactor.

Viscosity Measurements

As the purity of available oxides has been improved, it has become increasingly difficult to determine the plasticity parameters using the apparatus described in previous quarterly reports. The settling rates of the pure oxides (low nitrate and uranyl ion content) slurries have increased so markedly (1-5 mm/sec) that solids settle out in the body of the cut-off valve and plug up the capillary tube. The data do indicate, however, that for concentrations up to 200 grams of uranium per liter, the coefficient of rigidity approximates the coefficient of viscosity for water and the yield stress, if any, is low.

Existing equipment has been modified to eliminate the settling of solids in the cut-off valve body and other techniques for measuring the apparent viscosity of $\text{UO}_3 \cdot \text{H}_2\text{O}$ slurries are also being studied to improve the reliability of the results obtained.

Crystal Growth

Uranium trioxide monohydrate crystals in the form of rods grew when autoclaved at 250°C for 24 hours or longer in stainless steel bombs. In 24 hours, the rods increased in size from 1-3 μ in diameter and 5-6 μ in length to 4 μ in diameter and 15-17 μ in length. No preceptible increase in dimensions was found when the rods were autoclaved at 250°C for longer periods of time.

The crystal structure of $\text{UO}_3 \cdot \text{H}_2\text{O}$ rods did not change when autoclaved for less than 48 hours in the presence of nitrate ions (KNO_3). Some platelets were found upon microscopic examination when the rods were autoclaved at 250°C for at least 48 hours in the presence of 100 ppm of excess nitrate ions. At this nitrate content, the platelets converted from rods grew until some reached 400-500 μ after 168 hours of autoclaving at 250°C. The conversion of rods to platelets and the rate of crystal growth of the platelets were not augmented by increasing the nitrate ion concentration above 100 ppm. No change was evidenced when the rods were autoclaved at 250°C in the presence of 40 ppm of excess nitrate ions.

Tests are being continued in which the uranyl ion content is varied to determine the effect of these ions on the crystal structure of both rods and plates. Information obtained by the Chemical Technology group indicates that in the presence of excess uranyl ions, both forms convert to the bipyramid form.

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Criticality Experiments

Equipment has been built and is being tested for determining the criticality of $\text{UO}_3 \cdot \text{H}_2\text{O}$ particles settling in a static slurry. Tests will include determination of settling rates of slurries containing 50-250 g of U per liter, reliability of level indicator and dump valve system.

The objective of these criticality experiments is two-fold:

1) to determine the critical height of a turbulent unstable $\text{UO}_3 \cdot \text{H}_2\text{O}$ light water slurry reactor of varying concentrations and for a given moderator (light water) height.

2) to determine change in reactivity at various concentrations as the turbulence (agitation) is removed and the particles settle.

It is anticipated that the equipment will be checked out and ready for installation in Building 9213 by October 1, 1952 provided no major alterations to the system need be made. The system consists of a canned rotor, fluid bearing pump to supply slurry to the reactor and also keep the slurry agitated in the storage tanks. An agitator will keep the particles suspended in the reactor which is baffled to prevent formation of a vortex. A quick opening dump valve in the bottom of the reactor and the immediate insertion of a safety rod on the means of controlling the reactor if it goes super-critical. Arrangements are being concluded for the preparation of enriched $\text{UO}_3 \cdot \text{H}_2\text{O}$ rods.

A second critical program to study the influence of eddying in pumped solutions and slurries has been terminated to provide better use of available manpower.

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150° Thorium Loop Test

A slurry of 100 gms of ThO_2 per liter (80 gm Th/l) has been circulated in the 150°-110°C slurry loop for over 100 hours (CF ORNL-1121). Heat transfer and abrasion studies were made.

Preliminary data from this one test showed that the ThO_2 was plating out on the walls of the heat transfer surfaces as evidenced by a continual decrease in the over-all heat transfer coefficients. Chemical analysis of samples drawn from the loop during operation also indicated abrasion as an increase in the iron, chromium, nickel content of the solids was found.

This work has been temporarily halted because the packed stuffing box in the pump has caused serious difficulty. Further use of this loop awaits construction of a new pump. A Richardson-Frithsen type 3 Hp pump appears suitable for this work, and parts are available for its construction.

BOILING REACTOR RESEARCH

The current boiling reactor research program is designed to provide the necessary information for a broad evaluation of boiling homogeneous reactors in comparison with other types of reactors. The required information falls into three categories: 1) information regarding the controllability of this type of reactor, 2) information regarding the possible operating levels of this type of reactor, and 3) information on the mechanics of actually designing, building and operating a boiling reactor for a practical application.

Reactor Physics; The Nuclear Stability of a Boiling Reactor

P. R. Kasten

In a boiling reactor, it is desirable from a control standpoint, that density changes in the reactor fluid be brought about by changes in the power level of the reactor. It is to be expected that changes in power level of the reactor will be associated with corresponding changes in the total energy held up in the reactor liquid superheat and in vapor bubbles. Of these two, the larger change in density with energy holdup is produced by the energy in the vapor bubbles. Thus a reactivity increase which increases the operating power level of the reactor and produces additional energy holdup in vapor bubbles would eventually be alleviated by the resulting reduction in density. In order for power surges resulting from an imposed reactivity increase to be limited effectively, it is important that the vapor bubbles form and grow in a manner closely related to the existing power level. The manner in which vapor generation actually occurs

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is also of prime importance in those stability studies which determine whether a small disturbance added to a steady state reactor system will initiate oscillations which will be damped or will increase in amplitude.

The influence of changes in power level on the density of the reactor fluid can be described as:

$$\rho - \rho_0 = \left(\frac{\partial \rho}{\partial H_t} \right)_{fv} \left[(H_t - H_{t0}) + \beta \int_0^{\infty} G(s) [H_t(t-s) - H_{t0}] ds \right] \quad (1)$$

where

ρ = average fluid density of core region

ρ_0 = ρ required for reactor criticality

$$\beta = \left[\left(\frac{\partial \rho}{\partial H_t} \right)_T - \left(\frac{\partial \rho}{\partial H_t} \right)_{fv} \right] / \left(\frac{\partial \rho}{\partial H_t} \right)_{fv}$$

G = normalized vapor - delay function

$\left(\frac{\partial \rho}{\partial H_t} \right)_{fv}$ = change in core fluid density per unit energy injected as liquid superheat

$\left(\frac{\partial \rho}{\partial H_t} \right)_T$ = change in core fluid density per unit energy injected as vapor

H_t = total energy content of the reactor core

H_{t0} = H_t evaluated under steady-state conditions

The restrictions necessary to insure stability of the linearized equations of motion* are dependent upon the form of $G(s)$. If the rate of vapor formation is directly proportional to the bulk liquid superheat,

$$G(s) = \nu e^{-\nu s} \quad (2)$$

where

ν = rate at which superheat energy is dissipated into
vapor energy, per degree superheat.

Under this condition, stability of boiling reactors appears assured. This corresponds to the situation where decomposition gas bubbles are generated internally in direct correspondence with the nuclear power, for these gas bubbles are then vapor bubble nuclei with superheat as the driving force for bubble growth. In regard to the formation of decomposition gases within water, L.D.P. King feels that in the Los Alamos Water Boiler the gases form as such within the liquid inasmuch as bubbles rising to the surface at temperatures below the boiling point have appeared to be so small that if they were formed on the wall or tubing they would not detach themselves from the metal. Also, in the November 1951 radiation burst of the Hanford Homogeneous Reactor, the killing of the reaction could only be attributed to the expansion of the liquid due to decomposition gases forming within the core.

Simulated volume boiling experiments at UCLA, however, have revealed vapor delay functions which can be approximated by

$$G(s) = \frac{\nu (\nu s)^n}{n!} e^{-\nu s} \quad (3)$$

* P. R. Kasten - Reactor Physics of Teapot -
Part IV, Linearized Kinetics,
August 15, 1952

where n = a measure of the time for a given nuclear power surge to be transmitted into vapor energy, for a given value of ν .

For the above situation, restrictions are necessary on ν to insure system stability, and these will increase with n , and decrease with power density.

In experimentally determining the stability of a boiling reactor, it is desirable that the results be applicable to homogeneous boiling reactors in general. To cover all aspects of these reactors, investigations should cover the effects of reactor size, geometry, fuel concentration, fuel enrichment, fuel type, and operating conditions as represented by operating pressure and fraction vapor within the core. To cover the above in one reactor experiment is obviously difficult and prohibitively expensive. From stability analyses it appears that large pressure and fraction vapor ranges affect stability to a much greater degree than the other variables, and on this basis a small reactor capable of operating over large pressure ranges is a reasonable one to build for a first experiment. Inherent in this conclusion is the fact that there is a large increase in energy content of a unit volume of vapor as the pressure increases, so that power density should increase with pressure.

At present calculations are in progress to find explicitly the effect of reactor size, fuel concentration, fuel enrichment and operating conditions on stability.

In regard to the power fluctuations which occur in a boiling reactor operating in a quasi-steady state, these are probably due to large vapor bubbles escaping from the reactor surface. If the assumption is made that bubble size

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increases with increased power level, these fluctuations will increase with the power density at any given pressure. However, if at a given power level the number of bubbles is constant, the fluctuations will decrease with increasing pressure.

Power Removal from a Boiling Reactor

R. V. Bailey
E. N. Lawson
H. A. MacColl
P. C. Zmola

The power removal analysis has been reviewed and extended in the direction of greater generality in an effort to determine how much each of the various heat removal mechanism contributes to the total heat removal under given operating conditions.

The ultimate utility of a boiling reactor depends upon the removal of appreciable quantities of energy from the unit without decreasing the mean density to the extent of requiring an excessive size or fuel enrichment. The problem of relating the power density in the core to the mean fluid density as a function of the system pressure was considered in terms of the three available mechanisms for energy removal. These mechanisms are:

1. Surface evaporation.
2. Bubble growth and rise in a fluid with negligible internal circulation.
3. Bubble growth and rise in a fluid with internal circulation velocities large compared to the relative bubble velocity.

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In considering these mechanisms, the following nomenclature is used:

P_{se} = Power density due to surface evaporation, $\text{kw } \ell^{-1}$

h = Heat transfer coefficient, $\text{B hr}^{-1} \text{ ft}^{-2} \text{ } ^\circ\text{F}^{-1}$

Δ = Temperature difference, $^\circ\text{F}$

$(h\Delta)_s$ = Heat flux in surface evaporation, $\text{B hr}^{-1} \text{ ft}^{-2}$

h_b = Heat transfer coefficient to the bubble, $\text{B hr}^{-1} \text{ ft}^{-2} \text{ } ^\circ\text{F}^{-1}$

Y = Height of reactor core, ft.

P = Power density, $\text{kw } \ell^{-1}$

ρ_ℓ = Density of liquid, lbs ft^{-3}

ρ_v = Density of vapor, lbs ft^{-3}

ρ_{av} = Average density of reactor core, lbs ft^{-3}

ρ_1 = Average initial core fluid density in circulating system, lbs ft^{-3}

ρ_2 = Average final core fluid density in circulating system, lbs ft^{-3}

ρ_i = Average fluid density in outside annular region of a circulating system, lbs ft^{-3}

ρ_o = Average fluid density in central region of a circulating system, lbs ft^{-3}

U_b = Maximum bubble rise velocity, ft sec^{-1}

U_1 = Average initial fluid velocity in circulating system, ft sec^{-1}

U_2 = Average final fluid velocity in circulating system, ft sec^{-1}

g = gravitational constant, ft, sec^{-2}

D_b = Diameter of bubble, ft.

f_D = Drag coefficient of bubble, dimensionless

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h_{fg} = Latent heat, B lb⁻¹

v_{fg} = Specific volume change in evaporation, ft³ lb⁻¹

A = Cross sectional area of cylindrical core, ft

A_1 = Initial flow area in circulating system, ft²

A_2 = Final flow area in circulating system, ft²

Ψ = Velocity potential function, dimensionless

r = Normalized radius, dimensionless

y = Normalized height, dimensionless

η = Fraction of vapor arising at top of reactor core which is entrained and recirculated, dimensionless

K_1 = Loss coefficient based on ρ_{av} , dimensionless

K_2 = Loss coefficient based on ρ_0 , dimensionless

Surface Evaporation

For a cylindrical reactor core with a height equal to the diameter and heat carried to a point near the surface by convection within the liquid, the contribution of surface evaporation to the power density, P_{se} , is given by

$$P_{se} = \frac{(h\Delta)_s}{96,500 Y} \quad (1)$$

Qualitative experimental data presented below indicates that for volume boiling with high power densities $(h\Delta)_s$ is of the order of 70,000 B hr⁻¹ ft⁻². From this the contribution of surface evaporation from a boiling reactor core appears negligible for high power density operation.

Natural Bubble Rise

The following postulations were made:

1. The maximum bubble rise rate is

$$U_b = \left[\frac{4g}{3} \left| \frac{\rho_l - \rho_v}{\rho_l} \right| \frac{D_b}{f_D} \right]^{1/2} \quad (2)$$

2. Bubble nucleation occurs uniformly in the reactor core.
3. The heat flux to a bubble is independent of position in the reactor core (uniform power density distribution).
4. The reactor core is a vertical right circular cylinder.

On the basis of the above postulations the following equation was developed for the power density due to natural rise and growth rates.

$$P = 0.01 \left(1 - \frac{\rho_{av}}{\rho_l} \right) \left(\frac{1}{Y} \right)^{2/3} \left(\frac{H_{fg}}{v_{fg}} \right)^{2/3} \left(\frac{h_b \Delta}{f_D} \right)^{1/3} \quad (3)$$

Plots of this expression are shown in Figure 1.

A limited amount of rough experimental information on volume boiling of water by electrical resistance heating has been obtained and is presented in Figure 2. The data represent boiling liquid heights from 0.1 to 1.5 ft and power densities from 0.8 to 12 kw per liter of boiling water. The pressure was one atmosphere.

The solid line in Figure 2 is a plot of equation (3) utilizing the rather optimistic value $\frac{h_b \Delta}{f_D} = 150,000$. It can be seen that the trend of the data appears to confirm the theoretical considerations. If the contribution to power removal by bubble rise and growth is taken as $\frac{h_b \Delta}{f_D} = 7500$ (value based on data

presented by Jakob), the dashed line represents equation (3). In this case the remainder of the power removal is due to surface evaporation and amount to approximately $70,000 \text{ B hr}^{-1} \text{ ft}^{-2}$ for this range of experimental work. These results can hardly be considered conclusive since an independent check on the value of $\frac{h_b \Delta}{f_D}$ should be obtained (from high speed photographs of the bubble rise and growth in a volume boiling system, for example).

Internal Circulation

For an internal circulation velocity in the vertical plane appreciably greater than the relative bubble velocity the average power density in a boiling reactor core is given by

$$P = \frac{U_1}{26.8} \left(\frac{A_1}{AY} \right) \left(\frac{h_{fg}}{v_{fg}} \right) \left(\frac{\rho_1}{\rho_2} - 1 \right) \quad (4)$$

where subscript (1) refers to the inlet condition and (2) refers to the terminal condition. A schematic design of two possible systems is shown in Figure 3.

In order to relate the average power density (equation 4) to the mean density of the reactor core, it is necessary to consider the circulation pattern and the manner of vapor formation in the core. Postulating that the circulation velocity can be derived from a potential function the equations for vapor generation and conservation of mass become, respectively

$$\frac{\partial^2 \psi}{y^2} + \frac{4}{r} \frac{\partial}{\partial r} \left[r \frac{\partial \psi}{\partial r} \right] + w''' = 0 \quad (5)$$

$$\frac{\partial}{\partial y} \left[\rho \frac{\partial \psi}{y} \right] + \frac{4}{r} \frac{\partial}{\partial r} \left[r \rho \frac{\partial \psi}{\partial r} \right] = 0 \quad (6)$$

where r and y are normalized to the core radius and height.

Figure 3 Schematic diagram of two idealizations of a cylindrical reactor core in which internal circulation exists. The center lines are axes of symmetry.

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The average density is

$$\rho_{av} = \frac{\iint r \rho \, dr \, dy}{\iint r \, dr \, dy} \quad (7)$$

If the volume generation function, w''' , is taken proportional to the product of the macroscopic fission cross section and the thermal neutron flux, it appears that an iterative process can be applied to determine w''' and hence ρ and ρ_{av} by utilizing the standard two group equations and taking advantage of the thermal neutron flux being relatively insensitive to density changes.

As a start, w''' has been taken proportional to the thermal neutron flux for the uniform density case $\left[J_0 [2.405 r] \sin [\pi y] \right]$. With this assumption, equations 5, 6 and 7 will provide a first approximation to the relationship between the core mean density and the initial and terminal densities, ρ_1 and ρ_2 . This calculation is being carried out by the Mathematics Panel.

Since the initial and terminal densities are unknown quantities, it is necessary to provide an additional relationship between them and the mean density in terms of a quantity which might be subject to estimation. The equation relating these densities in terms of the fraction of vapor recirculated is

$$\frac{\rho_{av}}{\rho_l} = \frac{\rho_{av}}{\rho_1} \left[\frac{1 - \eta \frac{\rho_1}{\rho_2}}{1 - \eta} \right] \quad (8)$$

where η is the fraction of the vapor which is recirculated.

In order to obtain a qualitative indication of the fraction of vapor recycled by the circulating fluid, a very simple flow pattern at the top (free surface) of the reactor core was postulated, and the following relation was obtained:

$$1 - \eta = 8 \left(\frac{1}{\frac{U_1}{U_b} + 1} \right)^2 \quad (9)$$

Rough calculations employing this equation indicate that internal circulation in a boiling reactor with a free surface may not permit any higher power density than could be obtained by natural bubble rise rates.

Power Removal by Natural Internal Circulation

In order to estimate the power removal due to natural circulation in the core of a cylindrical reactor, the following equations have been obtained

$$P = \frac{U_2 A_2}{26.8 A Y} \left(\frac{h_{fg}}{v_{fg}} \right) \left(1 - \frac{\rho_2}{\rho_1} \right) \quad (10)$$

$$U_2 = \left[\frac{2g Y}{K_1} \left(\frac{\rho_o - \rho_i}{\rho_{av}} \right) \right]^{1/2} = \frac{2g Y}{K_2} \left(1 - \frac{\rho_i}{\rho_o} \right)^{1/2} \quad (11)$$

Equation (10) is a rearrangement of the general expression for power density as previously presented in equation (4). Equation (11) provides the natural circulation velocity for use in equation (10). The densities ρ_o , ρ_i , ρ_2 , and ρ_1 , can be expressed in terms of the mean density of the reactor core and the fraction of vapor recirculated by using the potential flow solutions and equation (8).

Since the results of the potential flow considerations were not expected to be available for some time, some preliminary, qualitative estimations of natural circulation velocities and power removal for natural circulation were made to permit design of experiments. The equations for three postulated systems were developed for this purpose. The geometry considered is a right circular cylinder with height equal to the diameter. In all cases it was considered that the circulation velocity was sufficiently large compared with the relative velocity of the bubbles that the fluid could be considered homogeneous. Additional postulations and resulting equations for each case are as follows:

Case I

Postulated: The circulation pattern, bubble nucleation and bubble growth are such that

$$U_1 = U_2$$

$$\rho_0 - \rho_1 = \frac{\rho_1 - \rho_2}{2}$$

$$\rho_{av} = \frac{\rho_1 + \rho_2}{2}$$

Equations:

$$\left(\frac{\rho_i}{\rho_{av}} - 1 \right)^{\frac{P}{26.8}} = \left(\frac{\sqrt{2g}}{26.8} \right) \left(\frac{h_{fg}}{v_{fg}} \right) \left[\frac{\frac{\rho_1}{\rho_{av}} - 1}{K_1 Y} \right]^{1/2} \quad (12)$$

along with equation (8),

Case II

- Postulated: (1) The fluid flows downward in an annular region along the walls of the containing vessel to the bottom of the reactor core, reverses, and flows upward in the center to the top of the reactor core.
- (2) The cross sectional area of the riser, A_2 , is equal to that of the downcomer, A_1 .
- (3) The rate of vapor formation is uniform throughout the reactor core.

Equations:

$$U_2 = \frac{2g Y}{K_2} \left[1 - \frac{\ln \left[\frac{2}{1 + \frac{\rho_2}{\rho_1}} \right]}{\ln \left[\frac{1 + \frac{\rho_1}{\rho_2}}{2} \right]} \right]^{1/2} \quad (13)$$

$$\frac{\rho_{av}}{\rho_1} = \frac{\ln \left(\frac{\rho_1}{\rho_2} \right)}{\left(\frac{\rho_1}{\rho_2} - 1 \right)} \quad (14)$$

along with equations (8) and (10).

Case III

- Postulated: (1) Same as (1) of Case II
 (2) Same as (2) of Case II
 (3) The rate of vapor formation at any point
 is proportional to $J_0(2.405 r) \sin \pi z$

Equations:

$$\frac{\rho_{av}}{\rho_1} = \frac{\rho_0 + \rho_1}{2 \rho_1} = \frac{1}{2} \frac{1}{\left[1 + 0.184 \left(\frac{\rho_1}{\rho_2} - 1 \right) \right]^{1/2}} + \frac{\frac{\rho_2}{\rho_1}}{\left[1 - 0.78 \left(1 - \frac{\rho_2}{\rho_1} \right) \right]^{1/2}} \quad (15)$$

$$1 - \frac{\rho_1}{\rho_0} = 1 - \frac{\frac{\rho_2}{\rho_1} \left[1 + 0.184 \left(\frac{\rho_1}{\rho_2} - 1 \right) \right]^{1/2}}{\left[1 - 0.78 \left(1 - \frac{\rho_2}{\rho_1} \right) \right]^{1/2}} \quad (16)$$

along with equations (8), (10), and (11).

These three models are currently being examined and compared over a range of the pertinent variables.

A simple experiment is currently being planned in which air will be bubbled through a 6 foot diameter tank filled with water. Although no quantitative results applicable to water-steam systems are expected from this experiment, it appears that this study can yield information on the behavior of larger scale two-phase systems. In particular, the density decrease for various air volume throughput rates and the influence of circulation on density decrease for a given air throughput will be determined.

General Comments on Power Removal from Boiling Reactors

At the present time a number of tentative conclusions can be drawn from the work outlined:

1. Surface evaporation is probably a negligible factor in power removal except for very small reactors operating at low power.
2. For boiling reactors up to 3 or 4 feet in height, the predominant mechanism for power removal is natural bubble rise and growth.
3. For boiling reactors having a free surface and in which circulation exists, it appears that vapor entrainment in the circulating fluid will limit the power removal.

Criticality Calculations

In order to get a rough indication of permissible density decrease for power removal considerations, enrichment required for criticality was calculated for a number of UO_2SO_4 - D_2O systems. For each operating condition, the influence of decreasing the density ratio (ρ_{av}/ρ_l) was determined. Representative results for 250°C operation are shown in Figures 4 and 5. Figure 4 displays the influence of the density ratio for a 20.5 ft. diameter square cylindrical core. Figure 5

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shows the influence of core size for a density ratio of 0.6. Calculations were based on the two group criticality equation for bare cylinders. Uniform density was postulated.

Study of Full Scale Boiling Reactor Systems

P. C. Zmola

A study has been initiated of a large scale homogeneous boiling reactor which will exist only on paper (Paper Boiling Reactor). The purpose of the study is to help evaluate, clarify, and possibly uncover problems which would arise if an actual boiling reactor were designed for some specific economic objective. During the course of the study the specific application of the reactor may change in direction from time to time to provide the maximum understanding of the nature of boiling reactor problems. Initially the P.B.R. will be a power and plutonium producer. Because of the limited effort allocated to this program, only a preliminary outline of the problem is available.

Boiling Reactor Experiments

At least two boiling reactor experiments are planned in the future:

- 1) the Teapot, a small reactor capable of operating over a wide pressure range,
- and 2) a 6 foot reactor to operate at one atmosphere. To house these experiments as well as other reactor experiments which may be proposed, a building has been designed to provide maximum flexibility in changing from one reactor system to another.

(Briggs BRE Shielding Design report)

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Treatment of BRE Waste Gases

C. W. Oxford, C. G. Lawson

The off gas stream from the boiling reactor will contain xenon, krypton, hydrogen and oxygen and possibly elemental iodine and bromine or HI and HBR. For a reactor operating at 250 kw for a period of eight hours the quantity of gases that are formed assuming fission yields of A.O.C.-65 by Hunter and Ballow and decay rates of G.E. Nuclides are

$$\text{BR} - 7.3 \times 10^{-5} \text{ gms}$$

$$\text{I} - 6.24 \times 10^{-4} \text{ gms}$$

$$\text{KV} - 1.25 \times 10^{-3} \text{ gms}$$

$$\text{Xe} - 1.39 \times 10^{-2} \text{ gms}$$

$$\text{H}_2 + \frac{1}{2} \text{O}_2 - 2,176 \text{ gms (assuming 99\% efficient recombiner)}$$

The heat generation during decay of these gases if all γ energy and $1/3 \beta$ energy is converted to heat is

Time after 8 hrs operation, hours	Btu/sec.
0	1
1	.25
15	.03
24	.015
48	.005
120	.001

The heat generation of the bromine and krypton are negligible within 15 hours after shutdown. The remaining heat generation is distributed approximately even between the iodine and xenon. For further details see CF , C. W. Oxford.

The requirements for the off gas system are

- (1) to prevent the buildup of an explosive concentration of $H_2 + \frac{1}{2} O_2$,
- (2) prevent active iodine from being discharged to the atmosphere,
- (3) reduce the quantities of activity discharged to the atmosphere to within tolerance levels.

Design studies are being made on the following components to determine the optimum system for accomplishing the above aims.

I. Catalytic Recombination of $H_2 + \frac{1}{2} O_2$

- (a) platinized aluminum
- (b) heated copper

II. Removal of Iodine and Bromine

- (a) silver nitrate tower
- (b) charcoal adsorption

III. Reduce activity by Xe and Kr

- (a) charcoal adsorbent bed
- (b) dilution tanks combined with a breather tank operating between the reactor core and the fuel storage vessel.

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BRE Instruments

W. P. Walker

Contribution to the Boiling Reactor Experiment by the control group so far has consisted mainly of investigation into types of instruments necessary to perform the objectives of the experiment, while keeping in mind difficulties faced in operation of the H.R.E.

Nuclear instrumentation will consist of the standard nuclear instruments with additions necessary to measure flux transients and vertical flux distribution.

Safety requirements will be satisfied by two replaceable rupture discs and a quick opening dump valve. The dump valve to be interlocked with nuclear and process instruments.

Process instrumentation will provide pertinent temperatures and pressures. Increase emphasis has been placed on accountability of solution to at least 2% accuracy. A weight system will be provided to measure amount of solution in core vessel to at least 1%. Provision for a device to indicate average vapor fraction in the core has also been included. Under design at present is a valve test loop which should yield valuable design data for the selection of valves for the B.R.E.

Package nuclear instrumentation have already been purchased, and design of the B.R.E. should be frozen sufficiently in the next few weeks to enable selection of process instruments.

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