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SUBJECT: The Relationship of Aqueous ThO_2 Slurry Physical
Properties to the Engineering Design of a
Reactor System

TO: Distribution

FROM: D. G. Thomas

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THE RELATIONSHIP OF AQUEOUS ThO_2 SLURRY PHYSICAL PROPERTIES
TO THE ENGINEERING DESIGN OF A REACTOR SYSTEM

by

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I. SUMMARY

In a reactor system the principal components affected by slurry properties are the blanket vessel, pressurizer, heat exchanger and dump tank. The particular properties that affect the operation of these components are: caking, degree of flocculation, foaming, and slime formation. These properties are related to the characteristics of components in a reactor system through experience gained in the operation of slurry loops. It is pointed out that the optimum slurry for one component may not necessarily be the optimum for another.

II. INTRODUCTION

Based upon technical factors and economic analyses of various configurations of aqueous homogeneous reactors, the two region, forced circulation type, operating on the thorium- U^{233} cycle, possesses the potential for lowest cost power for the plant sizes now contemplated.¹⁷ The thermal and radiation instability of thorium nitrate makes a thorium oxide slurry appear to be the most promising material for the blanket of a two region aqueous homogeneous reactor. This report gives the status of the engineering program of the Homogeneous Reactor Project in its attempt to develop a suitable slurry for use in blanket systems.

The overall objective of the slurry program is the acquisition of the ability to design and operate a system that will remove heat at rates up to 600,000 BTU/hr/lb slurry from a slurry whose concentration is dictated by the nuclear requirements of the system. In order to do this the slurry must be circulated from the blanket region to a heat sink in a system which must be capable of being shut down and started up. As a result the system must handle aqueous thorium-oxide slurries at temperatures from 25 to 300°C, pressures from atmospheric to 2000 psi and thorium concentration from 0 to 1000 grams/kg H₂O.

The peculiar properties of slurries which make the design of an engineering system difficult arise largely because slurries are two phase systems; the situation is further complicated by the change of slurry properties with time as well as by the existence of three phases in some equipments. As a result slurries can be both erosive and corrosive, slurries can foam at a liquid-vapor interface, metal surfaces can be coated with a layer of slime, the solid phase can settle out in regions of low velocity, or the solid can separate out over the whole system as a dense, hard, intractable cake.

Slurry systems can be either flocculated or deflocculated. In a flocculated slurry the particles stick together in the form of loose, irregular clusters in which the original particles can still be recognized. As flocculated slurry is characterized by:¹

1. zero or very small charge on the particles,
2. a rapid settling rate due to aggregate formation, however in blanket systems of interest the concentration desired will usually be above that of the settled bed so that in quiescent systems essentially no settling will be observed.

3. A large sedimentation volume because the particles preserve the haphazard positions in which they touched each other initially,
4. a sedimented bed exhibiting a yield stress,
5. a sedimented bed having a viscosity dependent on the rate of shear (because the rate of aggregation is so large that even in flow the aggregates do not completely disappear).

In a deflocculated slurry the particles repel each other and the original particles are not in contact. A deflocculated slurry is characterized by:¹

1. large charge on the particles,
2. a slow settling rate due to the small size of the independent discrete particles,
3. a small sedimentation volume (because the large charge creates a repulsive force allowing the particles to roll over one another to positions of minimum potential energy giving a densely packed bed, but one in which the particles still do not touch each other because of their large charge),
4. a sedimented bed which does not exhibit a yield stress,
5. a sedimented bed having a very high Newtonian viscosity so that even for large stresses the flow remains exceedingly slow,
6. being more difficult to prepare than a flocculated system.

Those factors which affect the slurry properties include the method of preparation, the calcination temperature, the mean particle size, the particle size distribution, the slurry concentration, the electrolyte concentration, the temperature, the pH, and the mechanical design of the system in which the slurry is being handled.

Local abrasive attack can be expected in slurry systems at regions of high velocity or rapid acceleration. Such regions are: the heat exchanger tube entrances, letdown valves, impeller, casing and seal rings of centri-

fugal pumps and the valves of pulsafeders. It is known² that the abrasive attack is a function of particle diameter as well as slurry velocity and acceleration; in all the ensuing discussion it will be assumed that abrasive attack will be minimized by using slurries having very small particle sizes, 90-95% less than 0.5 micron.

The overall problem is of a twofold nature: first, a definition of the relative importance of the slurry properties as they affect the performance of the reactor components, and second, a knowledge of the quantitative relationships among those factors affecting slurry properties in order that those properties which are most critical for the successful operation of the components in the system can be optimized. In all probability the final specification of a slurry will be based on a compromise to minimize the least undesirable slurry properties.

III. THE EFFECT OF SLURRY PHYSICAL PROPERTIES ON THE OPERATING CHARACTERISTICS OF SYSTEM COMPONENTS

The major components in a slurry reactor system are shown schematically in Figure 1. These components are:

- A. Blanket Region of Reactor
- B. Pressurizer
- C. Heat Exchanger
- D. Pump
- E. Letdown Valve
- F. Dump Tank

Each particular component will be discussed in turn and where possible the effect of degree of flocculation will be shown quantitatively.

Fig. 1. Major Components in a Slurry
Reactor System

A. One of Two Region Core

The four major difficulties that can be anticipated for either a one or two region core containing a slurry are a) caking, b) slime coating of walls, c) settling of slurry particles in low velocity regions and d) the development of localized hot spots due to lack of natural convection in a flocculated slurry.

The caking problem appears to be equally serious for all components, because in at least one high temperature loop test the thorium-oxide cake which formed covered all surfaces of the circulating system, was from 1/8 to 1/4-inch thick, and reduced the concentration of the circulating stream by a factor of 2. The cake had a bulk density greater than 5 grams/cu.cm. and a modulus of rupture of 360 lb/sq in. The subject of cake formation is covered more completely in a separate series of reports.^{3,4} It is believed that the mechanism of cake formation is understood,⁵ forthcoming experiments are planned to test the various hypotheses.

The slime problem is less serious in the one region system than in a two region system because of the high heat fluxes at the core-blanket wall in the latter case. In neither case does it appear to be particularly serious, because in a one region core the lower flux at the wall eases the problem of controlling the wall temperature and in the two region core, the high velocities¹⁴ needed to prevent boiling¹³ at the core-blanket interface would also tend to remove a slime deposit.

If appreciable amounts of slurry are allowed to settle out, the purpose of the reactor system is largely defeated. Since the core-blanket regions contain the largest free volumes in the system, as well as having some very low velocities, the settling problem can be particularly acute.

The question whether to operate the core region with a flocculated or a deflocculated slurry depends to a large extent on the concentration of the slurry and the rate of shear in the core. A flocculated slurry might be desirable to minimize the settling problem in a high concentration two region core, i.e., for a sufficiently high concentration essentially a settled bed would be circulated. However, a flocculated slurry usually has a yield stress at a concentration suitable for a two region machine. Since the shear stress in the core vessel is low, it is entirely possible that there would be laminar flow with the accompanying high slurry viscosity. Thus, a mixing due to natural convection would be low and local hot spots might develop. A set of baffles has been suggested to increase the slurry velocity in the core (blanket) either by direction changes, by imparting a swirling motion to the slurry or by an induced recirculation within the blanket region. This should increase the shear in a flocculated slurry sufficiently to ease the circulation problem. At the same time, if a deflocculated slurry is chosen, the increased velocity would help prevent the slurry particles from settling out. As yet there is no information available on the pump power required to maintain either type of slurry in suspension in the blanket region.

B. Pressurizer

Current homogeneous reactor concepts include pressurization with steam. This concept has been adopted for slurry systems as a long vertical tube with a radial inlet in the bottom third and an axial outlet at the bottom. The pressurizer may be operated with a bypass line to the top two-thirds of the vessel through which an appreciable flow is taken. Vapor is removed from the top of the pressurizer and condensed for use as a lubricant for pump bearings.

Although the pressurizer concept appears to be very simple, the actual operation with slurries is rather complicated. Consider first the operation without a bypass line, the slurry being either flocculated or deflocculated. Experience with high temperature slurry loops in which the pressurizer volume is about the same as the loop volume has shown that in a deflocculated system there is essentially clear water in the main body of the pressurizer, even at a water removal rate of 20 liters per hour/per square foot free surface. Under these circumstances soluble ions such as chloride, sodium, (and chromate under basic conditions) were concentrated in the top of the pressurizer, which presents the possibility of removing these contaminants in a side stream. On the other hand, in a flocculated system the pressurizer acts as a slurry reservoir, often becoming almost completely plugged with a deposit having a high yield stress, gaps of several inches being bridged in regions of low flow because of the high yield stress. However under no circumstances was the plug serious enough to interfere with operation of the pressurizer as a source of pure water. Limited experience with the bypass line does not allow any conclusions to be drawn at this time about its usefulness in improving the operating characteristics of pressurizers.

Operation of the pressurizer with the solids up to the top of the liquid in the pressurizer can allow foaming to take place in the free space. Slurry can be deposited on the walls by the foam, or the foaming can allow carryover of solids to the condenser and attendant contamination of the back of the pump.

The presence of slime or cake on the walls can materially affect the heat transfer coefficient of the pressurizer heaters, even to the extent of requiring a reduction in loop operating temperature.

At present the operation of the pressurizer with a deflocculated slurry appears more satisfactory from the foaming standpoint as well as the ease of obtaining pure water for pump lubrication. Operation of the pressurizers with flocculated slurry appears undesirable from the plugging standpoint, although more experience with the operation of the bypass line will perhaps indicate changes which will alleviate the problem.

C. Heat Exchanger

The design of heat exchangers to handle deflocculated slurry may be done using the conventional generalizations for Newtonian fluids with appropriate corrections for the volume fraction solids. However the use of flocculated slurries adds several new variables, associated with the non-Newtonian characteristics of the slurry, to the design calculations.

For convenience, most thorium oxide slurries may be considered as Bingham plastic materials characterized by the relation

$$\frac{dv}{dr} = \frac{g_c}{\eta} (\tau - \tau_y) \quad (1)$$

where:

- $\frac{dv}{dr}$ = rate of shear stress, sec.^{-1}
- τ = shear stress, lb/sq ft.
- τ_y = yield stress, lb sq ft.
- η = coefficient of rigidity, lb/(ft)(sec).

Application of criteria proposed by B.O.A. Hedstrom⁶ to data reported in the literature^{7,8} shows that many flocculated Bingham plastic slurry systems are in turbulent flow only at Reynolds numbers greater than 10^4 to 10^6 . Qualitative data⁹ indicate further that the critical velocity for the onset of

turbulence is a strong function of slurry yield stress, depending only weakly on the coefficient of rigidity and being almost independent of pipe diameter. A typical set of curves illustrating this is shown in Figure 2.

Preliminary heat transfer measurements¹⁰ with flocculated thorium oxide slurries indicated that the transition region for slurries extended to from four to five times the critical velocity given by the Hedstrom criteria. Beyond this transition region the slurry heat transfer coefficient was essentially that of a Newtonian fluid having the same density and viscosity.

Design calculations were made¹¹ for a system consisting of a pump, one hundred feet of pipe and a heat exchanger to remove one Mw of heat from various aqueous thorium oxide slurries. The rheological properties of the slurries were varied over a range of yield stresses from 0 to 1.5 lb/sq ft and of coefficients of rigidity from 1/2 to 2 centipoise. The velocity used in the calculations was either twice that given by the Hedstrom criteria or 10-ft/sec, whichever was greater. The effect of slurry properties on the pump head required for the heat exchanger alone are shown in Figure 3 for an axial temperature drop of 40°F, corresponding to a flow of 200 gpm/Mw. Figure 4 shows the effect of slurry properties on pump hydraulic horsepower per Mw for the heat exchanger alone for the same conditions. If the tube length is kept constant (the velocity being fixed by the same criteria used previously) and the axial and radial temperature drop allowed to vary then the overall heat transfer coefficient decreases by 10 to 30% as the yield stress increases from 0 to 1.5 lb/sq ft. Under these circumstances the effect of slurry physical properties on the pump head and flow ratio are shown in Figures 5 and 6. The pump hydraulic horsepower as a function of slurry properties is shown for 40-ft tube length heat exchangers and for the total system in Figure 7.

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Fig. 2. Effect of Slurry Physical Properties on Velocity for Onset of Turbulence

Fig. 3. Effect of Slurry Properties on Pump Head for Heat Exchanger (No External Piping)

Fig. 4. Effect of Slurry Properties on Pump Hydraulic Horsepower per MW for Heat Exchanger (No External Piping)

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Fig. 5 Effect of Slurry Properties on Pump Head for 40ft. Tube Length Heat Exchanger and for Total System (Variable Axial and Radial ΔT)

Fig. 6 Effect of Slurry Properties on Pump Flow Rate for 40 Ft. Tube Length Heat Exchanger (Variable Axial and Radial ΔT)

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Fig. 7 Effect of Slurry Properties on Pump Hydraulic HP per MW for 40 Ft. Tube Length Heat Exchangers and for Total System (Variable Axial and Radial ΔT)

For a yield stress of 1.5 lb/sq ft the electrical pump horsepower corresponds to about 5% of the heat power produced by the blanket for the heat exchanger alone and from 8 to 15% for the total system, depending on the tube diameter (and consequently on the axial temperature drop). If, instead of two, a critical velocity four times the Hedstrom criteria is used, then the pump horsepower for the heat exchanger alone is increased to 20% of the heat power produced by the blanket, and from 30 to 60% for the total system, depending on the tube diameter. However this situation would be alleviated somewhat by the increase of the slurry heat transfer coefficient to essentially that of a Newtonian fluid of the same viscosity and density. Reduction of the yield stress from 1.5 to less than 0.1 lb/sq ft gives better than a 20 fold reduction in the pump power requirements. Clearly a slurry having a yield stress less than 0.1 lb/sq ft would greatly simplify the pump and heat exchanger development problems.

The slime, caking, and plugging problem at low velocities together with the severe attack at the heat exchanger tube entrance at high velocities represent the major difficulties expected in the operation of the heat exchanger. Operation at a lower tube velocity would alleviate the attack at the tube entrance but would increase the uncertainty in the heat transfer coefficient as well as increasing the probability of slime and/or cake formation and tube plugging.

D. Pump

The prospects for a satisfactory low-head slurry pump appear to be quite good at this time.¹² The major source of difficulty that can be expected is severe bearing wear if slurry comes into contact with the bearings. Bearing

wear can be minimized by continuously purging the bearings with pure water vaporized from the pressurizer and injected into the back of the pump. Again, caking in the pump casing, inlet or diffuser would not be desirable. The degree of flocculation does not appear to affect pump operation because of the high rates of shear in the pump.

E. Letdown Valve

The letdown valve may be operated either intermittently or continuously. If it operates intermittently then it may become plugged up or caked over so that it is inoperable when needed. Conversely if it is operated continuously extreme abrasive wear can occur at the seat of the valve. A solution to the problem of intermittent valve operation is suggested by the practice in fluidized catalyst systems. Valves are flushed with air immediately before opening in order to free them of plugs and again immediately before closing in order to free the valve seat from solids, thus reducing wear on the valve seat. Air could not be used in slurry systems, but the use of a water or a steam jet seems feasible. The solution to the abrasion problem appears to be the use of hard materials.

F. Dump Tank

Many ingenious dump tank designs have been or are being tested.¹⁵ Most of those currently under study involve the "air-lift" principle to maintain the slurry in suspension, with steam being used as the working fluid. Tests have shown that 0.004 to 0.007 cfm steam per lb of slurry supplied at a pressure of 3 psig are required to maintain a flocculated slurry in suspension with one such device.¹⁶ No particular difficulty has been encountered in

resuspending most of the slurries even after several weeks of shutdown merely by increasing the steam pressure from the normal operating pressure to 9 psig. From time to time there has been a serious foaming problem, which appears to be worse when operating with air than with steam but there have been no studies made of the reason for foaming. Foaming was eliminated either by a design change or by a slurry change with little contribution to our understanding. It does not appear that a slime coating would particularly interfere with the operation of the dump tanks, however, cake formation would be most undesirable. The choice between operation with a flocculated system or with a deflocculated system would be of little consequence as long as a uniform concentration could be maintained. Indications are that the concentration can be maintained uniformly, even with a flocculated system.

IV. CONCLUSION

- A. A deflocculated slurry or a flocculated slurry having a yield stress less than 0.1 lb/sq ft appears to be desirable for the successful operation of the heat exchanger.
- B. A slurry having a very low settling rate is desirable for successful operation of the reactor blanket. This slurry could be either so highly flocculated that essentially a settled bed was being circulated or completely deflocculated. It appears that the pumping power would be less for a deflocculated slurry.
- C. A deflocculated slurry is desirable for the pressurizer operation, primarily for ease of obtaining pure water for flush systems.

- D. A deflocculated slurry is more difficult to prepare than a flocculated slurry. This is clearly seen when it is realized that heat and radiation are the classical methods for flocculating dispersed systems. However, recent tests with oxide fired at 1600°C and with slurries containing electrolyte additives have been most promising.

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