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CENTRAL FILES NUMBER

60-4-93

DATE: April 21, 1960

SUBJECT: Some Experiments on the Accuracy of Thoria Slurry Samples

TO: Distribution

FROM: R. P. Wichner

COPY NO. 98

ABSTRACT

Tests were performed on a thoria slurry flowing in a 3 in. diameter pipe to determine the magnitude of the possible error involved in the sampling process. Experimental conditions ranged between:

150 to 1000 g Th/kg H₂O in concentration
 28° to 83°C in temperature
 4.3 to 13 ft/sec slurry velocity
 1.5 to 12 cc/sec sampling rate (corresponds to 3 to 64 ft/sec sample nozzle velocity)

It was found that by utilizing sufficiently incorrect procedure the error may be as great as 48 g ThO₂/kg H₂O at room temperature or 160 g ThO₂/kg H₂O at 300°C. This latter value was obtained by extrapolation of data from 80°C assuming that the relative motion of particle and fluid remains in the viscous regime.

Evidence indicates that a correct sample is obtained by withdrawing the sample isokinetically (i.e., by facing the sampler into the flow and adjusting the sampler velocity to match the ambient velocity) provided that the sampler is larger than some minimum diameter that is dependent on the mean eddy length and/or the mean particle size.

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INTRODUCTION

Large differences (20%) in slurry concentration obtained from neighboring sample points on the high temperature 300 SM vessel⁽¹⁾ prompted an investigation to determine if such differences could be attributed to sampling errors.

The effort was also directed toward estimating the sample error under different experimental conditions in order to determine a procedure or develop a slurry sampling probe with which a minimum error is associated. To this end, the effects of temperature, slurry velocity, slurry concentration, sampling rate and sample probe geometry on the sampling error were determined for ThO₂-water slurries with the following range in experimental conditions:

150 to 1000 g. Th/kg H₂O concentration
 28°C to 83°C temperature
 4.3 to 13 ft/sec slurry velocity
 1.5 to 12 cc/sec sampling rate (equivalent to a range of 3 to 64 ft/sec)

It was found that a correct sampling method becomes more necessary as the slurry temperature and velocity increase and concentration decreases. Samples withdrawn from low velocity, temperature and highly concentrated slurry streams vary little with sampling method, while at 300°C and 10 ft/sec variation of the sampling method are believed to cause differences in the sample concentrations of up to 160 g ThO₂/kg H₂O. This latter value is based on an extrapolation of data from 80°C assuming that the relative flow between thorium particle and surrounding water remains in the viscous regime, and that the effective particle size remains the same as the temperature is increased from 80°C to 300°C.

The true thorium concentration was not known in any of the runs made and consequently the actual sampling error could not be calculated. Instead a sampling characteristic termed the experimental sampling difference (ESD), which is equal to the maximum difference in concentration observed while changing the orientation of the probe to the slurry velocity, was used as a measure of the sampling error.

A study of the sampling of coal dust-air suspensions by J. Howard Griffiths⁽²⁾ provides useful information on the two-phase sampling problem. Although he dealt with solids concentrations much below those of interest to thorium slurry technologists, the results are still useful to the present investigation because, as will be shown, the coal dust-air system and the ThO₂-H₂O system at 300°C are closely related from a particle dynamics point of view, especially if there is some degree of flocculation present in the thorium system to increase the effective particle size. It is therefore believed that the sampling characteristics exhibited in the coal dust tests are similar to that which would be exhibited by slurry at elevated temperatures.

The samplers that Griffiths tested were all tubes colinear with the pipe axis and opening upstream; the only geometry effect tested was the change in sampler diameter. He found that a correct sample was obtained when the sample velocity and mean suspension velocity in the pipeline were

approximately equal, provided that the sampler is larger than some critical diameter. Also, much larger effects on the concentration due to sampling rate and ambient velocity were observed in the coal dust tests than were observed using thorium oxide slurries.

ANALYSIS OF THE PROBLEM

Problem statement:

- (1) What is the best way to sample a slurry?
- (2) What is the sampling error associated with a given sampling situation?

Some insight into the problem may be gained by writing the equation of motion of a particle in the vicinity of a sampler probe. Applying Newton's Law:

$$m \ddot{\underline{r}}(t) = \underline{F}(\underline{r}, t) \quad (1)$$

where:

The dot denotes differentiation with respect to time and

m = mass of the particle

$\underline{r}$ = position vector of the particle at time, t

$\underline{F}$ = force acting on the particle.

The force vector is written as a function of position and time to emphasize that the flow is turbulent. However, the position is itself a function of time so that the equation is more properly written:

$$m \ddot{\underline{r}}(t) = \underline{F}(\underline{r}(t), t) \quad (1a)$$

The forces on the particle may be caused by:

- (1) Liquid drag from a relative velocity between fluid and solid.
- (2) Gravity.
- (3) Inter-particle interactions such as:
 - (a) Physical collisions
 - (b) Electrostatic repulsion
 - (c) van der Waals force

It is difficult to account for particle-particle interactions quantitatively and they will be neglected; consequently, the following analysis is restricted to sufficiently dilute slurries where this effect is small. It will also be assumed that the relative motion of the fluid and the particle is in the viscous regime even though the gross flow is itself turbulent. This is a reasonable assumption for the micron sized particles of interest, which are approximately $1/2500$ of the mean eddy size at the pipe centerline.

Some experimental verification that this is actually the case, at least under the conditions of the thorium slurry sampling tests, is reported later in this memo.

The force in equation (1a) is therefore given by Stokes' equation:

$$F(\underline{r}(t), t) = 3 \pi \mu d_p [\underline{V}(\underline{r}(t), t) - \dot{\underline{r}}(t)] \quad (2)$$

where:

d_p = particle diameter (assumed spherical)

ρ_p = particle density

ρ_L = fluid density

$\underline{V}(\underline{r}(t), t)$ = fluid velocity at position $\underline{r}(t)$ at time, t

$\dot{\underline{r}}(t)$ = particle velocity at time, t

Substitution of equation (2) into (1a), specification of the z-direction to coincide with that of gravity, and rearrangement yields:

$$\ddot{\underline{r}}(t) + \alpha \dot{\underline{r}}(t) = \alpha \underline{V}(\underline{r}(t), t) - \hat{k} \left(\frac{\rho_p - \rho_L}{\rho_p} \right) g \quad (3)$$

where:

$$\alpha = 18 \mu / d_p^2 \rho_p$$

$\hat{k}$ = unit vector in the z-direction

The trajectory parameter α , in units of reciprocal time, determines the response rate of the particle to the driving function $\underline{V}(\underline{r}(t), t)$. The larger the value of α , the quicker is the response, and in fact when α becomes sufficiently large equation (3) reduces to:

$$\dot{\underline{r}}(t) = \underline{V}(\underline{r}(t), t)$$

i.e., the particle and fluid velocities are always equal. Therefore, when α is very large any reasonable sampling method produces a representative sample. Some values of α are listed below:

Table I

Some Values of the Trajectory Parameter, $\alpha = 18 \mu / d_p^2 \rho_p$

Solid	Fluid	ρ_p g/cm ³	d_p microns	α sec ⁻¹
Thorium particle	Water 20°C	10	2	450,000
Thorium particle	Water 80°C	10	2	160,000
Thorium particle	Water 300°C	10	2	41,000
Typical Thorium Floc.	Water 20°C	5	40	2,200
Typical Thorium Floc.	Water 300°C	5	40	200
Coal dust(2)	Air 25°C	2	6	4,500

We will now assume that both the fluid and solid velocities at a certain point may be written as a sum of a temporal mean and a fluctuating component.

$$\underline{V}(\underline{r}, \theta) = \underline{\bar{V}}(\underline{r}) + \underline{\tilde{V}}(\underline{r}, \theta) \quad (4a)$$

$$\underline{\dot{r}}(\underline{r}, \theta) = \underline{\bar{\dot{r}}}(\underline{r}) + \underline{\tilde{\dot{r}}}(\underline{r}, \theta) \quad (4b)$$

where θ is time measured on an absolute scale as opposed to the time t , measured from the initial point of interest on the particle's trajectory. Equation (4a) is a commonly made assumption in fluid flow theory, and it seems that (4b) is on a similar basis. Substitution of (4) into (3) gives:

$$\frac{d}{d\theta} \left[\underline{\bar{\dot{r}}}(\underline{r}) + \underline{\tilde{\dot{r}}}(\underline{r}, \theta) \right] + \alpha \left[\underline{\bar{\dot{r}}}(\underline{r}) + \underline{\tilde{\dot{r}}}(\underline{r}, \theta) \right] = \alpha \left[\underline{\bar{V}}(\underline{r}) + \underline{\tilde{V}}(\underline{r}, \theta) \right] - \underline{k} \left(\frac{\rho_p - \rho_L}{\rho_p} \right) g \quad (5)$$

We now again fix attention to a particular point in space arrived at by a particle. A second particle arriving at this point some time later will be subjected to a different drag force due to the fluctuating part of the liquid velocity and will also have a different velocity due to its different past history. However, under the assumption made in Equation (4) we may average the velocities of a sufficiently long period of time, $\Delta\theta$, during which a large number of particles have arrived at this point. Thus, applying the averaging operator

$$\frac{1}{\Delta\theta} \int_{\theta}^{\theta+\Delta\theta} d\theta$$

to equation (5) yields the simple result:

$$\frac{d}{d\theta} \underline{\bar{\dot{r}}}(\underline{r}) + \alpha \underline{\bar{\dot{r}}}(\underline{r}) = \alpha \underline{\bar{V}}(\underline{r}) - \underline{k} \left(\frac{\rho_p - \rho_L}{\rho_p} \right) g \quad (6)$$

The significance of equation (6) is that the proper average particle velocity is obtained by considering only time average fluid velocities. This is true only in the special case being considered, that of viscous flow existing between the particle and fluid which allows the drag force to be proportional to the relative velocity. In all other cases, the drag force is proportional to a non-linear function of the relative velocity and so the fluctuating components of the particle velocity do not nicely disappear after averaging. In these non-linear situations, the magnitude and distribution of the turbulent fluctuations must be known in order to calculate the particle trajectory.

Although the turbulent fluctuations drop out of equation (6), there is still the implied restriction that the path is actually irregular. For example consider the problem of determining whether or not a certain particle's path is intercepted by a disc of diameter d_s (such as the opening of a sampler tube). Solution by means of equation (6) is meaningless unless d_s is greater than some value, $d_{s, \text{crit.}}$ depending on the magnitude of the kinks in the trajectory caused by the turbulent nature of the flow.

The gravity term in (6) may be safely neglected for reasonable fluid velocities. For example, in the case of high temperature thorium slurry with particle flocculation, α may be as low as 200 sec^{-1} (Table I). Even so, the gravity and velocity terms in equation (6) do not become equal until the velocity drops to $1/8 \text{ ft/sec}$, well below the velocity existing about a sampler.

There is one other special case (besides the one of $\alpha \rightarrow \text{large}$) that must result in a true sample of the slurry being withdrawn. That is the situation where:

- (1) $\bar{V}(\underline{r}) = \text{constant} = \bar{V}_0$
- (2) gravity force is negligible
- (3) The sampling tube is oriented parallel to $\bar{V}_0$ and the sampling velocity $\bar{U}$, uniform across the sampler orifice, is made equal to $\bar{V}_0$.

Then equation (6) reduces to:

$$\bar{F}(t) = \bar{U} = \bar{V}_0$$

These are the conditions for isokinetic sampling. The restriction that $d_s > d_{s, \text{crit.}}$ must still apply. It is plausible that in this case $d_{s, \text{crit.}}$ not only depends on the turbulent kinks in the particle trajectory but also on the relative size of the sampler with respect to the particle diameter. In other words, the sampler must be large enough so that the number of particle paths deviated by the sampler wall itself is small compared to the number of paths entering undisturbed in the orifice.

Solution of equation (6) requires knowledge of $\bar{V}(\underline{r})$, the flow field in the vicinity of the probe. Except for the case of isokinetic flow, this can at best only be guessed, and furthermore all reasonable guesses lead to difficult non-linear, coupled differential equations. However, if $\bar{V}(\underline{r})$ is known then in principle one can compute the probable sampling error. The procedure would be the following:

- (1) Assume a uniform distribution of particles of size d_p far from the probe. At $t=0$, each particle has a known position.
- (2) Using the boundary conditions that far from the probe, the particle velocity equals the fluid velocity, calculate from equation (6) the trajectories of all particles entering the probe in a time interval Δt .
- (3) Since the volumetric sampling rate $Q = 1/4 \pi d_s^2 U$ has been pre-set, the solids concentration of the sample is the number of particles entering during Δt divided by $Q\Delta t$.
- (4) The procedure (1) to (3) must be repeated for other particle sizes representative of the slurry.

Note that to apply the above method in the determination of thorium slurry sampling errors, the thorium floc size and density must be known.

J. Howard Griffiths⁽²⁾ et al, made an experimental study of the sampling of coal dust-air suspensions. In their tests a 1 in. diameter sampler was placed coaxial with a 12 in. diameter wind tunnel with the open end of the sampler facing into the flow. Measurements were made of the:

- (1) mean wind tunnel velocity
- (2) mean sampler velocity
- (3) sample solids concentration
- (4) wind tunnel solids concentration

A comparison of the coal dust-air and thorium oxide-water (to be described later) sampling systems are given below.

Table II
Comparison of Coal Dust-Air⁽²⁾ to ThO₂ - H₂O Sampling Systems

	<u>Coal Dust-Air⁽²⁾</u>	<u>ThO₂ - H₂O</u>
Solids concentration	0.009 - 0.0002 g/l	1000 - 150 g ThO ₂ /kg H ₂ O
Conduit diameter	12 in.	3 in.
Mean particle size	6 microns	2 microns
Sampler diameter	1 in.	0.125 - 0.049 in.
Ratio of $\frac{\text{sampler diameter}}{\text{particle size}}$	3500	1600-620
Ratio of $\frac{\text{sampler diameter}}{\text{mean eddy length}}$	1.20	0.62 - 0.24
$\alpha = \frac{18 \mu}{\rho_p d_p^2}$ at 20°C	$4.5 \times 10^3 \text{ sec}^{-1}$	$4.5 \times 10^5 \text{ sec}^{-1}$

In Table II, the mean eddy length was taken to be the Prandtl mixing length which equals 14% of the conduit radius at the center of the conduit when the Reynolds number exceeds 10^5 (3). It is not known how well this applies to non-Newtonian slurries. Note that Griffiths' sampler was the larger of the two, both with respect to the particle size and the mean eddy length.

The solids concentration in the two experiments differed vastly, and there was also a factor of 100 difference in the particle trajectory parameter, α . However, α being proportional to the viscosity of the medium, decreases rapidly in the thorium oxide slurry system as the temperature increases (see Table I) so that at 300°C its value differs not too much from the coal dust value. Therefore, the observed sampling characteristics of coal dust suspensions should approximate the ThO₂ slurry sampling characteristics at elevated temperatures more nearly than the 20°C and 80°C sampling data described in this report.

Griffiths' experimental results are summarized below:

- (1) Fixing the mean sample velocity (V) to be less than the mean pipeline velocity (V_{iso}) resulted in a greater than representative sample concentration. This is illustrated in Figure 1 where data from reference (2) are plotted. All the data were taken with a 1 in. diameter sampler and the appended numbers to each point are the respective mean wind tunnel velocities in ft/sec. Also,

$C(V)$ = Sample concentration when the sampler mean velocity equals V.

$C(V_{iso})$ = Sample concentration when the mean sampler velocity equals the mean wind tunnel velocity.

THE RATIO: CONCENTRATION AT SAMPLER VELOCITY, V TO THE
ISO KINETIC CONCENTRATION VS SAMPLER VELOCITY / PIPE VELOCITY

FOR COAL DUST-AIR (2)

CHART 1-1-10-1
MAY 1955

FIG. 1

As the velocity of sampling increases the sample concentration decreases, but an error in this direction appears to be quite small compared to that resulting from a too low sampling rate. As expected, the correct sample is obtained near the isokinetic point ($V/V_{iso} = \text{unity}$).

- (2) The sample velocity was found to affect the particle size distribution of the resultant sample. High sampling velocity yielded a greater than representative amount of fines and while a low sampling velocity yielded more coarse particles. The $d_{50\%}$ sizes in the coal dust experiments were changed ± 2 microns simply by changing the sampling velocity. Typical size distribution curves obtained are shown in Figure 2.

This follows naturally since at a low sampling rate the higher-than-representative number of particles that enter the sampler do so by crossing fluid streamlines. Since the larger particles are much more apt to accomplish this (α decreases as d_p^2) the sampler so operated acts as a size classifier and tends to collect the larger particles. Conversely, when the sampling velocity is high, the larger particles tend to be left behind the fluid, and the smaller-than-average diameter particles appear in the collected sample in larger-than-representative amounts.

- (3) One series of runs was performed to test the effect of sampler size on the isokinetic sample concentration. It was found that the sample became highly erroneous when the sampler diameter was reduced from 1-1/8 in. to 1/4 in., even though at all times the ratio V/V_{iso} was held at unity. As noted earlier, this may be a consequence of either the turbulent nature of the flow or particle-sampler interactions. (Another down-to-earth reason must be mentioned: It was attempted to collect approximately equal sized samples so that the small sampler runs were of longer duration and perhaps more difficult to accomplish.)

Griffiths reported that the 0.4 in. diameter sampler tube was the smallest one which yielded a proper isokinetic sample from which it may be inferred that $d_s/d_p > 1700$ and/or $d_s/\bar{l} > 0.48$ are the limiting requirements for good sampler performance, where d_s is the sampler diameter and $\bar{l}$ the mean eddy length.

For 2 micron diameter thoria particles in a 3 in. pipe, the first criterion would require a minimum allowable isokinetic sampler size of 0.1 in., and the second criterion 0.2 in. However, if the effective particle were actually 40 micron flocs, the first criterion would require the sampler to be about 2 in. in diameter.

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20 X 20 PER INCH EFFECT OF SAMPLING RATE ON THE SIZE
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FIG. 2

THO₂ SLURRY SAMPLING TESTS

Object

- A. To determine the magnitude of the sampling error with different orientations of the sampler with respect to the fluid velocity direction.
- B. To determine the maximum possible sample error when sampling from a slurry of unknown velocity.
- C. To determine how the sample error varies with:
 - 1. Slurry temperature
 - 2. Slurry concentration
 - 3. Slurry velocity
 - 4. Sampler velocity
- D. To utilize several sampler geometries and select one which yields a nearly true sample under a wide range of conditions.

Description of the Equipment and Experiment

Since the true concentration in these experiments was not known, the actual sampling error could not be determined. Instead, an experimental sample difference (hereafter referred to as ESD) was defined and measured.

To obtain the value of the ESD for a particular set of conditions, three samples were obtained, one at each of the three extreme orientations of the probe: upstream, cross-stream, and downstream. The difference between the maximum and minimum concentrations so obtained is defined as the ESD. Thus:

$$\text{ESD} = \text{maximum concentration} - \text{minimum concentration} \quad (7)$$

The ESD defined above approximates the possible error involved in sampling from a slurry stream of unknown direction such as may exist in vessel tests. In such a case, if the selected orientation of probe to velocity direction happened to be the poorest possible, then the sample error should be approximated closely by the ESD measured in a pipeline with the same sampler, and slurry temperature, concentration and velocity. For all other orientations, the sampling error will be somewhere between zero and the ESD. The chief advantage of using this experimental quantity is that it is much more easily determined than the true sampling error which requires knowledge of the true slurry concentration.

The conduit from which flowing slurry was sampled was a straight run of 3 in. pipe which formed a portion of the room temperature slurry core loop. (Operation of this core loop is the subject of reference 4.) The nearest upstream disturbance from the sampling station was a long radius ell approximately 50 diameters away.

The four sampler types that were tested (shown in Fig. 3) were installed on the pipe in such a way that their orientation with respect to the pipe axis could be changed without their being removed. (Installation shown in Fig. 4.)

1/4 IN. O.D., .084 IN. I.D. TUBE

10 cc/s SAMPLING RATE =
10 ft/s SAMPLING VELOCITY

.09 IN. O.D., .049 I.D. TUBE

10 cc/s SAMPLING RATE =
29 ft/s SAMPLING VELOCITY

KIEL PROBE

10 cc/s = 53 ft/s

SPHERICAL PROBE

FIVE, 1/16 IN D. RADIAL HOLES

SLURRY SAMPLERS USED IN TESTS

FIG. 3

TOP VIEW

END VIEW

INSTALLATION OF SAMPLER ON 3 in. PIPE

FIG. 4

A typical run proceeded as follows:

1. The tare weights of the sixty, 2 oz. sample bottles were checked.
2. The loop conditions were set and allowed to run steadily for one-half hour prior to the run.
3. The operator then practiced sampling at the specified rates, checking himself against a stopwatch while sampling into a graduate cylinder. The prescribed sampling rates were held to approximately $\pm 20\%$.
4. The sampler was then faced upstream and a sample withdrawn; then downstream and crosstream for two more. This cycle was repeated from four to ten times. If the run was one of the higher temperature ones, the samples were placed into an ice bath immediately.
5. The weights of the samples were obtained using a chemical balance. They were then dried at 120°C for two days and re-weighed. The average concentration at each orientation was determined and the ESD recorded.

The precision of the data was best in the high concentration runs where the s.d. of the sample concentrations obtained at each orientation ranged between 0.5 and 1.8 g $\text{ThO}_2/\text{kg H}_2\text{O}$. The largest sample s.d., obtained in run II, was 5.96 g $\text{ThO}_2/\text{kg H}_2\text{O}$.

The slurry physical properties are listed in Appendix A.

RESULTS

The experimental sampling data are reported in Table III. All concentrations reported are averages of from four to ten determinations.

In runs I and II, a 1/4 in. OD 0.084 in. ID tube was the sampler tested; it is a common type utilized in the slurry blanket mockup and other loops. The ESD was determined at a high and low sampling rate each at a high (80°C) and low (30°C) temperature.

In runs III, V, VI, a Kiel velocity probe, a small diameter tube and a spherical head sampler were tested. In run V the sampling velocity was kept uniformly high (35 ft/sec) while the slurry temperature and velocity were varied to determine if high velocity sampling yields uniform samples irrespective of orientation and ambient velocity. In run VI the ESD was determined for a spherical sampler at various sampling and ambient velocities at a slurry temperature of 80°C .

Run VII was a duplication of Griffiths' experiment described earlier in this report. The sampler position at the pipe axis was held constant while the slurry velocity and sampling rates were varied.

Runs Q, R, and T were largely repeats of I and VI at a lower slurry concentration.

Table III

Thorium Oxide Sampling Data

Run No.	Nominal Slurry Concentration g Th/Kg H ₂ O	Temp. °C	g ThO ₂ /Kg H ₂ O			No. Samples Averaged	Average Slurry Velocity in Pipe ft/sec	Sampling Rate cc/sec	Simultaneous Isokinetic Sample Concentration g ThO ₂ /Kg H ₂ O	Sampler Type (Fig. 3)	Exptl. Sample Diff. %	(ESD) Experimental Sample Difference g ThO ₂ /kg H ₂ O
			Sampler Facing Upstream	Sampler Perpendicular to Flow	Sampler Facing Downstream							
I	500 "	30 "	618.95±2.90	603.53±1.62 594.36±1.78	607.69±1.19	10 "	12 "	10 ¹ 3		0.25 OD heavy wall "	2.5	15.42
II	500 "	79 "	537.66±4.43 540.45±2.56	498.60±3.51 488.05±2.93	494.74±5.96 498.75±5.15	7 "	12 "	7 3		0.25 OD heavy wall "	8.7 10.7	42.92 52.40
III	500 " " "	28 " 83 "	536.35 534.35 504.40 542.36	506.88 506.96 453.68 513.56	512.11 485.98 463.55 555.14	5 " " "	12 " " 4.5	5 ² 1 7 "		Aerotech Kiel Probe " " "	5.8 10.0 11.1 8.1	29.47 48.37 50.72 41.58
15 V	500 " " "	29 " 78 81	502.80 497.43 478.91 466.49	500.97 489.61 473.01 450.00	498.30 477.10 466.00 418.51	5 " " "	4.3 12 4.3 12	12 ³ " " "		0.090 OD, 0.047 ID Tube " "	0.9 4.3 2.8 11.5	4.50 20.33 12.91 47.98
VI	350 " " "	80 " " "	393.27 407.72 416.04 424.34	404.51 392.60 422.17 420.36	397.70 394.06 425.33 413.82	4 " " "	12 " 4.9 "	10 3 10 3	421.12 " 431.38 "	Spherical head " " "	2.9 3.8 2.2 2.5	11.24 15.12 9.29 10.52
VII	1000 " " " " " " " " " " " " " " "	80 " " " " " " 30 " " " " " " " "	1192.8±1.4 1189.5±0.5 1190.6±0.8 1053.1±0.5 1049.3±0.6 1048.9±1.3 944.81±0.87 941.16±0.45 940.70±1.29 936.08±0.22 933.99±1.03 934.44±0.83			5 4 " " " " " " 5 4 5 " 4	12 " " 4.5 " " " 13 " 4.5 " "	4.5 10 2 1.5 5 10 2 4.5 10 1.5 5 10		0.090 OD, 0.047 ID Tube " " " " " " " " " " "		

¹10 cc/sec = 10 ft/sec²10 cc/sec = 53 ft/sec³10 cc/sec = 29 ft/sec.

Table III(Cont.)

Run No.	Nominal Slurry Concentration g Th/Kg H ₂ O	Temp. °C	Thorium Oxide Sampling Data						Simultaneous Isokinetic Sample Concentration g ThO ₂ /Kg H ₂ O	Sampler Type (Fig. 3.)	Exptl. Sample Diff. %	(ESD) Experimental Sample Difference g ThO ₂ /kg H ₂ O
			Sampler Facing Upstream	Sampler Perpendicular to Flow	Sampler Facing Downstream	No. Samples Averaged	Average Slurry Velocity in Pipe ft/sec	Sampling Rate cc/sec				
Q	150	30	175.41	164.86	154.95	4	13	5		0.25 OD heavy wall	13.2	20.46
	"	"	176.26	171.16	166.12	"	4.5	"		"	6.1	10.14
	"	80	177.57	153.31	129.21	"	13	"		"	37.4	48.30
	"	"	190.95	182.75	158.31	"	4.5	"		"	20.6	32.64
R	150	30	174.24	169.94	167.51	4	13	10		Spherical head	4.0	6.73
	"	"	174.13	174.76	175.13	"	4.5	"		"	0.6	1.00
	"	"	175.65	167.53	168.80	"	13	5		"	4.8	8.12
	"	"	175.72	173.29	170.75	"	4.5	"		"	2.9	4.97
T	150	80	176.68	174.00	168.96	4	13	10	187.65	Spherical head	4.6	7.72
	"	"	202.95	199.37	186.12	"	4.5	5	203.02	"	9.0	16.83
	"	"	187.20	165.90	175.08	"	13	"	(187.65)	"	12.8	21.30
	"	"	189.58	194.63	194.25	"	4.5	10	(203.02)	"	2.7	5.05
Q	150	30	175.41	164.86	154.95	4	13.5	5		1/4" OD heavy wall	13.21	20.46
	"	"	176.26	171.16	166.12	"	4.5	"		"	6.10	10.14
	"	80	177.57	153.31	129.21	"	13.5	"		"	37.43	48.36
	"	"	190.95	182.75	158.31	"	4.5	"		"	20.62	32.64
R	150	30	174.24	169.94	167.51	4	13	10		Spherical sampler	4.02	6.73
	"	"	174.13	174.76	175.13	"	4.5	"		"	0.57	1.00
	"	"	175.65	167.53	168.80	"	13	5		"	4.85	8.12
	"	"	175.72	173.29	170.75	"	4.5	"		"	2.91	4.97
T	150	80	176.68	174.00	168.96	4	13	10	187.65	"	2.93	4.96
	"	"	202.95	199.37	186.12	"	4.5	5	203.02	"	9.04	16.83
	"	"	187.20	165.90	175.08	"	13	"		"	12.84	21.30
	"	"	189.58	194.63	194.25	"	4.5	10		"	2.66	5.05

DISCUSSION OF RESULTS

1. The ESD (as defined by equation (7)) is plotted against slurry temperature in Fig. 5. As expected from earlier discussion, the error was found to increase with temperature corresponding to a decrease in value of the trajectory parameter, α . In fact, in all cases except one (the spherical sampler at high ambient velocity; the shaded "D" in the graph) the increase in ESD was approximately proportional to the increase in $1/\alpha$, a quantity which is proportional to the fluidity. The fluidity of water is plotted on the right hand ordinate in Fig. 5 to illustrate this correspondence which is an indication that under these experimental conditions at least, the relative motion of liquid and solid is in the viscous regime.

Extrapolation of the ESD curve to 300°C by running it parallel to the fluidity of water curve, yields values of the experimental sample difference of 160 g ThO₂/kg H₂O in the most adverse cases, i.e., high ambient slurry velocity. The main assumption involved in this extrapolation is that the relative fluid-solid velocity remains viscous, while the floc size remains constant as the temperature is increased to 300°C. The validity of this assumption is not known and if it were untrue, i.e., if a turbulent relative velocity appears before 300°C is reached, then the ESD and all other sampling characteristics would thereafter be less sensitive to further changes in temperature.

2. The ESD unexpectedly did not decrease with the slurry concentration. If one assumes (as was assumed earlier in this memo) that particle-particle interactions form a small part of the force acting on the particle entering the probe, then it follows that the ESD should be directly proportional to the concentration of solids, for after some initial low concentration is reached, all additional particles added to the slurry to concentrate it further merely repeat phenomena already exhibited. As seen in Figure 6, however, the ESD actually decreased with increasing concentration in four of the six cases where comparison is possible. This indicates that even at 400 g ThO₂/kg H₂O (4.3 volume % solids) particle-particle forces are important in the determination of the trajectory into the sampler either directly or indirectly such as by altering the velocity field or turbulence intensity. Nevertheless, it seems that particle-particle forces tend to decrease the sampling error.
3. The ESD, as defined by equation (6), increased with increasing pipeline slurry velocity regardless of the sampling velocity (see Fig. 7). This is to be expected since the sampling error will be smallest in cases where the particles follow the fluid streamlines entering the probe most closely, and this tendency to follow curving streamlines diminishes as the momentum of the particles prior to entering the vicinity of the probe increases.
4. Logically, there must be some sampling velocity that is sufficiently high so that the sample concentration is independent of the ambient slurry velocity and probe orientation to the flow. The sample concentration in this case would be less than the true concentration. The results of run V show that this sampling velocity is greater than 35 ft/sec even when the ambient slurry velocity is as low as 4.3 ft/sec.

VARIATION OF THE EXP. SAMPLE DIFF. (Eq. 6) WITH TEMPERATURE

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$\frac{gThO_2}{kg H_2O}$

EXPERIMENTAL SAMPLE DIFFERENCE, EQ. 6

FLUIDITY OF WATER, cp'' (PROP. TO α, p)

FIG. 5

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 ESD $\frac{g ThO_2}{kg H_2O}$

FIG. 6

VARIATION OF THE WITH AMBIENT SLURRY VELOCITY

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FIG. 57

Conversely though, the results of run II (see Table III) show that the sample concentration becomes more sensitive to orientation effects as the sample rate decreases.

5. The spherical sampler proved to be substantially less sensitive to orientation effects than all other tested. Compare, for example, runs II and VI in Table III; both run at approximately 80°C. At the same slurry velocity and approximately equal sample velocities, the ESD value (which is an indication of orientation sensitivity) for the spherical probe is approximately 25% that of the 1/4 in. diameter sampler. Similarly in the low concentration runs (Q, R, and T), the ESD for the spherical probe is about 1/2 that for the 1/4 in. diameter probe at the same temperature, velocity and sampling rate.

Also, as seen in Fig. 5 the spherical head sampler, when the sampling rate was high, had a much slower increase of the ESD with temperature than was observed for other samplers. This is worthy of further investigation since in such a case the extrapolated value of the ESD at 300°C is much less than with other samplers.

6. The Kiel probe proved to be the most sensitive to orientation effects.
7. Run VII is essentially a repeat of Griffiths' experiment for thorium oxide slurry. Unfortunately, this was carried out at the high concentration of 1000 g ThO₂/kg H₂O so that particle interactions are a complicating effect not present in the coal dust experiment. It was found that the sample concentration was much less sensitive to changes in the sample rate relative to the slurry velocity than the coal dust samples were (Fig. 8). This is attributed to a higher value of α , and particle interactions in the thorium oxide slurry.

In Figure 8, the ratio $C(V)/C(V_{iso})$ is plotted against V_{iso}/V . The nearly horizontal line illustrates the slow variation, characteristic of the data of run VII. The straight line of next steeper slope represents the coal dust data already presented in Figure 1. The line of steepest slope, whose equation is:

$$\frac{C(V)}{C(V_{iso})} = \frac{V_{iso}}{V},$$

is the curve that would be obtained if the paths of the entering particles were unaffected by fluid velocity changes about the probe.

CONCLUSIONS AND RECOMMENDATIONS

Wherever possible, samples should be withdrawn isokinetically. Further experimental work is required, however, to determine positively the minimum allowable isokinetic sampler size. It seems that a system in which the ThO₂ concentration is known accurately, independent of sampling data is required for this. Based on the coal dust-air sampling results(2), the sampler should be at least as large in diameter as:

1. 1700 times the mean particle diameter.
2. 0.48 times the mean eddy size.

VARIATION OF SAMPLE DENSITY WITH SAMPLE VELOCITY

V = SAMPLE VELOCITY

V_{150} = AMBIENT SLURRY VELOCITY

$C(V)$ = CONCENTRATION OF SAMPLE
TAKEN WITH VELOCITY V

$$\frac{C(V)}{C(V_{150})} = \frac{V_{150}}{V} \quad (\text{UNDEVIATING PARTICLES})$$

EUGENE DIETZGEN CO.
MADE IN U. S. A.

$\frac{C(V)}{C_{150}}$

NO. 340 20 DIETZGEN GRAPH PAPER
20 X 20 PER INCH

FIG. 8

When isokinetic sampling is not possible, the spherical sampler may be an alternative. Concentrations determined by such a sampler appear to be somewhat low but tend to be less biased by changes in orientation, slurry and sampling velocity than other samplers tested. It would be informative to test the spherical sampler at 300°C to determine if the slow increase with temperature of the ESD exhibited at a high sample rate (see Fig. 5) is actually the case. If it is, the spherical sampler is especially good at 300°C.

Proper sampling procedure is most imperative at high temperatures and low slurry concentrations. Under the poorest condition, it was found by extrapolation, that sampling errors may be at least as great as 160 g ThO₂/kg H₂O at 300°C.

It may also be important to investigate with thoria slurry the effect on the particle size distribution of a sample as the withdrawal rate and velocity are varied. Griffiths using a coal dust-air system reported that reasonable variation in sampling method can cause charges in observed mean particle sizes of ± 2 microns. With thoria slurry, this effect would be largest at 300°C.

REFERENCES

1. L. F. Parsly et al, Study of Simulated Slurry Reactor Core High Pressure System, ORNL-CF-60-4-92 (April 26, 1960).
2. J. H. Griffiths, Trans. Instn. Min. Eng. 99, 150, Determination of Dust Concentrations in Mine Atmospheres (1940).
3. H. Schlichting, Boundary Layer Theory, Pergamon Press., p 408.
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APPENDIX ASlurry Physical Properties

The ThO₂ charged to the loop was unpumped DT oxide designated by the following batch numbers: 26-29, 34-40, 42, 43, 45, 47, 48, and 57. Though properties of the individual batches are available, only properties of the pumped mixture are given below:

Table IVYield Stress and Coefficient of Rigidity of Slurry Used in Tests

Slurry Conc. g Th/kg H ₂ O	Temp. °C	Combina- tion of Batches No.	Approx. Pumping Time	Viscometer Type	Coefficient of Rigidity Cp.	Yield Stress lb _f /ft ²
500	25	26,27,34	5 hrs.	Capillary	1.51	0.052
1000	25	26,27,34	5 hrs.	tube	2.27	0.165
500	25	(26,27,34)	200 hrs.	Capillary	1.29	0.020
1000	25	(34-36)		tube	2.05	0.150
800	29	(26,27,34)	300 hrs.	1/4 in. D	2.92	0.062
1100	28	(34-36,37)	300 hrs.	tube	4.32	0.173
870	80	(28-30)	300 hrs.		2.05	0.075
870	28		300 hrs.		3.14	0.0562

Particle size distribution of a sample withdrawn during run G is given below:

<u>d(micron)</u>	<u>% Undersize</u>
5	100
3	96
2	78
1.5	47
1.0	13
0.7	6
0.5	4
0.2	2

Hindered settling rate data for this slurry are given in reference (4).

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