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DATE: May 13, 1959

SUBJECT: AEC Symposium on Particle-Fluid Mechanics

TO: R. N. Lyon

FROM: D. G. Thomas

SUMMARY

The agenda for the symposium was divided into three broad categories: Research Associated with Current Reactor Programs, General Studies Related to Nuclear Technology and Basic Studies.

The Martin Company reported liquid-solid fluidization tests with cylindrical UO_2 pellets of 92 to 96% of theoretical density. The attrition rate of 0.080 and 0.250 inch diameter particles was found to be 3.5 and 7 wt % per week, respectively, after an initial period of rapid weight loss. Later tests using UO_2 particles whose method of preparation was considered to be proprietary information indicated that as much as a 25-fold reduction in attrition rate might be achieved.

The problem of fluidized bed stability was covered by several speakers, both from the theoretical as well as from the experimental standpoint. Local density fluctuations of 24% have been observed in gas-solid studies with -60 and -200 mesh particles with the magnitude of the fluctuation increasing with height measured from the bottom of the bed. Theoretical studies indicate a maximum disturbance corresponding to a particular wave length. (This would be of importance in the design of support plates.) Other studies indicate that the e-folding distance for the growth of a disturbance is much larger

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for liquid-solid fluidization systems that for gas-solid systems, typical values being 10^6 and 5.6 cm for glass beads in water and air, respectively. This means that liquid-solid systems are significantly more stable than gas-solid systems.

There was considerable discussion on the effect of density fluctuations on the stability of fluidized bed nuclear reactors and the consensus of opinion seemed to be that known density fluctuations did not present an insurmountable problem. However, no calculations were presented to prove this conclusively.

Argonne National Laboratory presented a brief description of their proposed boiling slurry reactor experiment (See Appendix A). The core would be 2 ft in diameter, fabricated of low carbon steel. Design power is to be 5 Mw with sufficient condenser capacity to operate at three times that power level. Operating pressure would be 150 psi and the initial loading would be of UO_3-ThO_2 , about 500 g/liter, containing 8% fully enriched uranium.

Experimental studies (T. J. Hanratty) of the effect of 0.075 volume fraction glass beads on the turbulent diffusion of injected KCl show that the beads have essentially no effect until appreciable slip velocities are attained.

Theoretical studies (John Happel) of hindered settling show that up to a particle Reynolds number of about 40, the study of inertial and wall effects can be separated and the solutions then combined additively.

The agenda, together with more detailed comments follow. A report of the proceedings is expected to be published by the New York Operations Office.

Symposium on Particle-Fluid Interactions

AGENDA

May 4, 1959

9:15 a.m.

Introductory
Merril Eisenbed, Manager, NYOO
Leonard Topper, NYOO

9:30 a.m.

Research Associated with Current Reactor Programs

1. Fluidized Bed Reactor
Martin Scheve, The Martin Company
2. Pebble-Bed Reactor
Robert Benenati, Sanderson and Porter Company
3. Gas-suspension Coolant
Donald R. Schluderberg, Babcock and Wilcox Company
4. Process-heat Reactor
James Magee, U. S. Bureau of Mines
5. Slurry Studies
D. G. Thomas, Oak Ridge National Laboratory

12:30 p.m.

LUNCH

2:00 p.m.

General Studies Related to Nuclear Technology

1. L. P. Hatch, Brookhaven National Laboratory
2. David Miller, Argonne National Laboratory
3. Ralph Levy, Oak Ridge National Laboratory

3:30 p.m.

Basic Studies

1. "Behavior of a Dilute Turbulent Suspension"
S. K. Friedlander, The Johns Hopkins University
2. "Perturbation of a Turbulent Field by Fine Particles"
T. J. Hanratty, University of Illinois
3. "Creeping Viscous Flow Around Assemblies of Particles"
John Happel, New York University
4. "Stability of Vapor - Solid Bubbles in Fluidized Beds"
R. H. Wilhelm, Princeton University

AGENDA - contd.

May 5, 1959

9:30 a.m.

General Studies

5. "Diagnosis of Fluidized Beds"
E. H. Grohse, Knolls Atomic Power Laboratory
6. "General Discussion"
R. C. Vener, M. W. Kellogg Co.

12:00 p.m.

LUNCHEON

Fluidized Bed Reactor - (Martin Scheve, Martin Company)

The latest report on the Martin Company studies is MND-FBR-1696 available about June 1959. The proposed reactor is to operate at 400 Mw thermal with a single region core 7 ft in diameter. Maximum temperature is 595°F with an average temperature of 575°F, and operating pressure of 2000 psia.

Principal experimental studies were made by fluiding lead shot and UO₂ with water in a 4-in. diameter x 2-ft tall column. The results of previous experimental studies

$$\epsilon = 1.15 (U_o/U_t)^{1.15}$$

where

ϵ = porosity

U_o = Fluidization velocity

U_t = Particle terminal velocity

was verified and UO₂-particle attrition rates were measured. The UO₂ particles were prepared by pressing and sintering to 92 to 96% of theoretical density. Two sizes were manufactured, 0.080 in. and 0.250 in. in diameter. The smaller particles had hemispherical ends and the larger particle was a right circular cylinder. The attrition rate was quite high at the beginning of the experiment (presumably due to rounding of corners). After the initial period the attrition rate was 3.5 and 7 wt per cent loss per week with the larger particle having the higher rate. At the conclusion of the AEC contract, the Martin Company continued study of methods of UO₂ fabrication and used a ball mill to obtain accelerated attrition rate data. A proprietary manufacturing method has been developed that gives a particle having 1/25 the attrition rate of the 0.25-inch particle described above.

Pebble-Bed Reactor - (Robert Benenati, Sanderson and Porter Company)

The reactor is to be batch loaded with 1½-in. diameter fuel moderator balls contained in a graphite core having seven cylindrical cavities, 20 ball diameters across. The reactor is to be cooled with helium gas. A total of 2 kw will be removed from each ball in a 150-day cycle. The balls are UO₂ + graphite coated with a 3-mill layer of SiC. Balls have been irradiated to a burnup of about half the expected power production and no leakage of f.p. (1 part in 10⁶) was observed after holding 6 hrs at 1500°F. Without SiC skin the rate of fission product leakage is about 4% of the rate of production. Experimental studies have shown a maximum voidage (1.0) at container walls with a minimum voidage (0.32) one-half ball diameter from wall, a secondary maximum voidage (0.55) one ball diameter from the wall and a damped oscillation of voidage out to about 4 to 5 ball diameters from the wall where the voidage became essentially constant at about 0.45. Similar results have been reported by Baird and Roblee in the January 1959 A.I.Ch.E. Journal. The high voidage adjacent to the wall means that the temperature profile peaks away from the wall, thus maintaining the wall at a lower temperature than would be expected with homogeneous fuel distribution.

Gas-Suspension Coolant --- D. R. Schluderberg was unable to attend, however there was some enthusiasm for Babcock and Wilcox's idea of improving the heat transfer characteristics of helium by adding sufficient graphite of 5-micron particle size to give a suspension density of 5 to 10 lb/cu ft. No further details were given.

Process Heat Reactor - (James Magee, U. S. Bureau of Mines)

The Bureau of Mines is not doing any reactor design work but is interested in reactors producing high temperature (up to 2700°F) gas for use in gasification of coal. To equal the present oil consumption rate of 10^7 bbl/day, 1000 coal gasification plants of 10,000 bbl capacity each one using 750 thermal Mw of heat would be required. Present studies are of a process development nature. The present small scale pilot plant involves a single stage blower developing 12,000 ft of head (5 lb rise in 250 lb at 1000°F). The blower is driven at 23,000 rpm with a 400 ~ motor and has given the most trouble to date. Other difficulties have been associated with loss of high temperature strength to rupture of high alloy steels when maintained at elevated temperatures in helium. Similar observations have been reported for high alloy steels heated in a vacuum. In pumping the coal-gas suspensions, the attack has been observed to be proportional to the fifth power of the velocity.

General Studies - (L. P. Hatch, Brookhaven)

In studies of the hydro-chlorination and fluorination of fuel elements in fluidized beds, reaction rates of about 6000 mg/cm² hr at 460°C were observed. This is apparently about 10 times the rate observed in present processes.

Brookhaven is also proposing a fluidized solids nuclear reactor in which UO₂ would be fluidized with sodium. Present concepts are for a reactor containing 50 tubular fuel elements about 8-in. OD and 7-in. ID and 12 ft long. The UO₂ would be fluidized in the annular gap and the gap would be cooled on both sides. The metal tube walls would be about 30 mills thick and would be fabricated from stainless steel or zirconium. The outlet temperature is to be 1050°F and it is believed necessary to operate the fluidized bed in the laminar region to ensure nuclear stability of the reactor (See BNL 516, p 61-63).

General Studies - (David Miller, Argonne National Laboratory)

Two reactor concepts were described: the packed bed gas cooled reactor and the aqueous boiling slurry reactor. The latter is described in detail in Appendix A. The packed bed gas cooled reactor would consist of multiple porous trays supporting 1/4-in.-thick beds of 50-micron unclad UO₂ particles. The system operates at 15 atmospheres pressure with helium gas flowing downward. The core volume would be 450 liters and would contain 250 kg of U-235. The reactor power would be 133 kw/liter compared with the 1000 kw/liter expected with EBR-II. The gas flow rate would not be particularly fast since the specific surface area of the powder is 100 sq meters/gram compared with the 10 sq meters/gram required from the heat transfer standpoint. The temperature rise would be 1200°F with an inlet temperature of 500°F. The pressure drop through the bed is expected to be less than 10 psi.

Argonne's work with Nak-UO₂ slurries is summarized in Geneva - 1958 paper 457, and their work with fluidized beds in chemical processing is reported in Geneva - 1958 paper 542.

General Studies - (Ralph Levy, Union Carbide Nuclear Company)

Processing of cold enriched uranium is classically carried out in 100- to 500-gram lots. However, the use of standard fluidization columns 5 inches in diameter and 5-ft long permit production to be carried out in 40-lb batches. Tapering the bed 1/2 to 1 degree stabilizes the bed sufficiently to allow production of up to 100-lb batches.

Basic Studies

This part of the program consisted largely of a review of the following papers, with the review being presented by the authors themselves.

1. (a) S. K. Friedlander, "Behavior of Suspended Particles in a Turbulent Fluid," A.I.Ch.E. Journal, 3, p 381-385 (1957).
(b) S. K. Friedlander, "Deposition of Suspended Particles from Turbulent Gas Streams," Ind. Eng. Chem., 49, p 1151-1156 (1957).
2. T. J. Hanratty, "Perturbation of a Turbulent Fluid by Fine Particles," Illinois University, Eng. Exp. Station, Tech. Report No. 7, March 1959.

The principal conclusion of this study (conducted in vertically tubes) was that appreciable slip velocities between the particle and the flowing fluid were required to produce noticeable effects on the eddy diffusivity as determined in KCl injection experiments.

3. John Happel, N.Y.U., "Creeping Viscous Flow Around Assemblies of Particles."
  - a) John Happel and Howard Brenner, "Viscous Flow in Multiparticle Systems: Motion of Spheres and a Fluid in a Cylindrical Tube," A.I.Ch.E. Journal, 3, p 506 - 513, (1957). This paper contains additional references to other reports by Dr. Happel on similar subjects.
4. R. H. Wilhelm, Princeton University, "Stability of Vapor-Solid Bubbles in Fluidized Beds," (see A.I.Ch.E. Journal, 4, p 423-430 (1958)).

The theoretical analysis predicts that there is a particular disturbance wave length whose amplitude grows more rapidly than all others. This has particular significance in the design of perforated plate distributor plate since the perforations might represent source of disturbance. Dr. Wilhelm also reported results obtained by Tom Baron (which are to be published in the A.I.Ch.E. Journal) which predict that the e-folding distance for the growth in amplitude of a disturbance in a gas solid system might be 5.6 cm, whereas for the same solid fluidized in water the e-folding distance would be 10⁶ cm.

5. E. H. Grohse, Knolls Atomic Power Laboratory, "Diagnosis of Fluidized Beds."

Dr. Grohse was unable to attend, however reprints of his paper in the A.I.Ch.E. Journal, 1, p 358-365, (1955) were available.

Dr. Grohse studied density variations in a gas-solid fluidized bed using an X-ray absorption technique. The particulate matter was silicon metal powder with a mean particle diameter of 45 microns. Three distributor plates were used: a multiorifice plate, a screen distributor and a porous plate distributor. Bed density measurements were made of velocities of 0.05, 0.15 and 0.25 ft/sec. During start-up incipient fluidization was observed at 0.030 to 0.035 ft/sec. The porous plate distributor was the only one giving even approximately the same average bed density from top to bottom of the bed and the maximum and minimum fluctuations appeared to be somewhat smaller with the porous plate distributor.

6. Dr. Dodson of the General Electric Company gave a resume of his work on gas-solid fluidized bed diagnostics to be published in the June A.I.Ch.E. Journal. The studies were made using a capacitance probe connected to a fast recorder. Results of tests in a 4-in.-dia column are shown in Fig. 1.

Fig. 1. Effect of Operating Conditions of 4-in Diameter Gas-Solid Fluidized Bed on Fluctuations in Bed Density.

The data show that fluctuations were slightly greater with the larger diameter particles and in qualitative agreement with Dr. Baron's prediction the variation in bed density was appreciably greater at the 48-in. level than at the 18-in. level.

APPENDIX A

BOILING HOMOGENEOUS SLURRY REACTOR EXPERIMENT PROPOSAL

PREPARED BY MICHAEL PETRICK AND JOHN F. MARCHATERRE
OF THE ARGONNE NATIONAL LABORATORY

The design power of the experiment is 5 Mw thermal (although the condenser will be sufficiently large to allow operation at 15 Mw thermal) and will be operated at 150 psi. The initial loading of fuel would be 500 g/liter of ThO_2 containing 8% enriched uranium. The reactor system would be fabricated from ASTM-A-106 carbon steel and would be contained in a tank 15 x 25 ft and the auxillary components, condenser, recombiner, etc., would be contained in a 15 x 17 ft tank. The core would be a section of 2-ft-dia sch 40 steel pipe with a 24 x 8-in std reducer at the bottom and a 24 x 12 std reducer at the top, and would have an active core section height of 24-in. A schematic drawing of the equipment contained in the 15 x 25-ft tank is shown in Fig. 1, and a sketch of a possible high power density, large total power reactor is shown in Fig. 2.

The purpose of the experiment would be:

1. a parametric study to investigate the relation between power, concentration, recirculation rate and pressure,
2. investigate the rate of radioactive gas evolution as a function of power,
3. study slurry behavior,
4. study the over-all stability problem,
5. study the rate of water decomposition,
6. as a physics test for the determination of critical concentration, void coefficient and the temperature coefficient,
7. study of vapor transport and separation problems associated with boiling and slurry,
8. study of system hydrodynamics,
9. study response and control characteristics,
10. study erosion and corrosion rates.

Fig. 1. Schematic Diagram of Boiling Slurry Homogeneous Reactor Experiment.

Fig. 2. Schematic Diagram of One Possible Configuration of High Power Density Large Total Power Boiling Slurry Homogeneous Reactor.

Estimated performance characteristics are shown in Figs. 3 and 4, and the power distribution would be expected to be

	<u>% Total Power</u>
8-in. pipe below core	8
core	91
1-ft pipe above core	1

For the case $(\text{Area Down Comer}/\text{Area Core}) < 1$, approx. 80% of the Δp from the upper plenum to the down comer is irrecoverable unless a high efficiency diffuser is used. With the use of a high efficiency diffuser upwards of 75% of the pressure drop can be recovered. The acceleration pressure drop occurring in the core and riser are considered as completely irrecoverable. The acceleration pressure drop can be virtually eliminated by designing a system in which the area ratios $(\text{Area Down Comer}/\text{Area Core})$ and $(\text{Area Riser}/\text{Area Core})$ are ≥ 1 . With a void coefficient of 0.9, as long as the mean voids do not fluctuate more than $\Delta\alpha = 0.008$, the instantaneous reactivity will not exceed prompt critical.

The cost of the experiment is expected to be \$400,000 with a breakdown approximately as given in Table 1.

Table 1. Experimental Boiling Slurry Reactor Costs for Location at Arco, Idaho

Reactor vessel	\$ 9,000
Equipment (pump, evap., cond., etc)	58,000
Piping and equipment installation cost	28,000
Remote maintenance tools	30,000
Excavation and grading	900
Earth shields	7,200
Concrete work	5,500
Armco buildings and heaters	12,850
Water storage and shield tanks (includes installing existing tank from Borax)	25,500
Air tanks	2,000
Installed instrumentation	208,700
Electrical equipment	<u>10,500</u>
	398,150
20% contingency	<u>79,000</u>
	477,150
Recoverable equipment available at Laboratory	<u>90,000</u>
	\$ 387,150

Fig. 3. Effect of Reactor Power on Operating Characteristics of Boiling Slurry Homogeneous Reactor Experiment.

Fig. 4. Effect of Core Recirculation Velocity on Operating Characteristics of Boiling Slurry Homogeneous Reactor.

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