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STABILITY OF RANDOMLY PACKED BEDS OF FUEL SPHERES: A BASIC PROBLEM IN THE DESIGN OF THE SETTLED BED FAST REACTOR*

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Summary

The Settled Bed Fast Reactor concept (SBFR) features a packed bed of fuel, directly cooled with sodium, which must be highly resistant to consolidation during power operation to avoid reactivity excursions resulting from sudden increases in bed solid fraction. This paper presents the results of an experimental study to determine bed stability. In the experimental program, the stability of a packed bed was considered acceptable if a 12-g lateral shock produced a change in bed solid fraction of less than 0.002 (e.g., 0.630 to 0.632), equivalent to a 10¢ reactivity change in the SBFR. The experimental results show that beds settled from fluidization can be remotely compacted to exhibit 1/6 of this change when shock tested. The particle interlocking effect of simulated coolant downflow gives a substantial extra measure of stability.

The Settled Bed Fast Reactor

The Nuclear Engineering Department of Brookhaven National Laboratory has long maintained an active interest in the development of large power reactor systems utilizing mobile fuel. Present emphasis centers on reactor concepts which use packed beds of fuel particles to combine advantages offered by the solid and the liquid fuel systems.

In the reference design of a sodium cooled 1000 MWe fast breeder, designated as the Settled Bed Fast Reactor (SBFR),[1] the fuel is featured as 1/8 in. spherical particles in the form of a randomly packed settled bed. The fuel bed is directly cooled with sodium downflow during periods of reactor operation. Fuel reloading or transfer is facilitated by fluidization, with coolant upflow, during periods of reactor shutdown. A number of special problems are introduced with this concept; however, the potential advantages offered by this type of reactor appear to warrant an agressive approach to the inherent development problems. In addition to the advantages of a high breeding ratio (1.7) and short doubling time (4.7 years) provided by the SBFR, the economic significance of reactor availability of about 95%, made possible through the use of mobile fuel, should be of considerable importance.

Fuel Bed Stability

In the SBFR concept, a high degree of stability of the packed fuel bed, as distinguished by its resistance to consolidation, is required to prevent abnormal reactivity excursions which would accompany an excessive increase in solid fraction.

First of all, to establish a meaningful point of reference for the study, stability was considered to be adequate if a 12-g lateral shock on the bed container produced an increase in bed solid fraction of less than 0.002 (for example, from 0.630 to 0.632). This magnitude of shock is four times greater than has been used to date in the design calculations for power plants - nuclear or non-nuclear - in earthquake areas.[2] An increase

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(1) Green, L., et al., The Settled Bed Fast Reactor - 1000 MW(e) Reactor Design, Nuc. Appl. (April 1965).

(2) Nucleonics, Vol. 23, No. 5, May 1965, p. 21.

in solid fraction of 0.002 (corresponding to an average decrease in bed depth of only 1/32 in. for a 1-ft deep bed) would result in a reactivity increase of about 10¢. Such an increase would be within the correction capability of the reactor control and protection systems.

Bed Compaction Method

In the SBFR, the reference design features the fuel bed, randomly packed, settled from a state of fluidization. It was found that beds settled from a state of fluidization always required some initial compaction in order to achieve stability according to the above criterion. Consequently, it was necessary to develop a practical means for initially compacting the bed before a test of stability would be meaningful. For this purpose, hydraulic pulsing was used to impart very small up-and-down motions to the bed, permitting some local repositioning of particles. Only short periods of pulsing are necessary to obtain an appreciable degree of bed compaction.

Pulsing was accomplished by means of a motor-driven ball valve suitably modified for continuous ball rotation. The time for the valve to move from a closed position to successive open and closed positions was 0.5 seconds, and the valve remained closed for 0.2 seconds. Under the pulsing conditions, for the drag forces to be sufficient to lift the bed, the upward flow through the bed had to exceed that required for incipient fluidization by about 50%. Acceptable pulsing could be achieved for a range of valve and flow conditions. In the course of the study it is found that the compaction effect of pulsing was enhanced by the action of a gas cushion established above the bed. The gas was compressed during the upflow period and served to accelerate bed motion during the downflow period. The particular piping arrangement used in the investigation is schematically presented in Fig. 1. The pulsing equipment used in the laboratory is shown in Fig. 2. Alternatively, the down-pulse might be induced by means of a four-way rotating valve without a gas cushion, schematically shown in Fig. 3.

Solid Fraction Measurement

Of prime importance in this study was the development of a means of measuring very small changes in over-all packed bed solid fraction resulting from a disturbance. For this purpose, a volumetric displacement method was used to measure small changes in over-all volume of the packed bed. The measurement apparatus, called a membrane cap, is shown in Fig. 4.

The membrane cap assembly, which is handled as a unit, was machined from a thick Lucite disc to provide a shallow dome-shaped cavity bounded on the bottom by a rubber membrane and terminating at the apex in a burette tube. With the cap in place on top of the test section, the cavity is filled with a measured quantity of water and a partial vacuum is established in the bed below (after draining the water from the bed), thus causing the rubber membrane to conform to the top of the bed (shown in Fig. 5). Changes in bed volume are given directly by changes in volume of water in the burette tube. The membrane cap, as a unit, can be readily interchanged with a column extension section as required for the fluidization and pulsing operations.

Membrane Cap Calibration

The membrane cap was largely used in determining very small changes in bed volume, or solid fraction, of a 6-in. diameter by

15-in. deep bed of 1/8-in. steel spheres. The volumes of the empty container, the membrane cap, and the 1/8-in. stainless steel spheres making up the bed were measured to an accuracy which permitted determinations of the over-all bed solid fraction to ±.003, e.g., .6300 ±.003.* By way of calibration, the effect of varying the differential pressure across the membrane was determined over the range of 10 to 30 in. of Hg. The effect of differential pressure was approximately linear between 20 and 30 in. of Hg and produced changes in liquid volume readings on the burette of about 0.2 ml per in. Hg. This effect translates, for a bed of 6500 ml volume, to potential errors in solid fraction determination due to inconstancies in differential pressure of only 2 parts in 100,000 per in. Hg. Since the membrane under differential pressure applies a compressive force on the bed, it was important to determine the effect of that force in causing any progressive increase in solid fraction as a result of removing and returning the membrane cap a number of times. The maximum increase in solid fraction for one replacement cycle was 1 part in 10,000 and such changes were found only in the case of wholly unconsolidated beds.

Bed Stability Determination

The determinations of bed stability were made on beds of 1/8-in. polished stainless steel spheres, 6 in. in diameter x 15 in. deep, with a 12-g lateral shock generated by a brass hammer which struck the bed container horizontally at the end of a swing. The 12-g shock was measured with a piezoelectric pickup.

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* A measurement technique of this accuracy would be valuable in pressure drop experiments across packed beds since the voidage is an important parameter. A difference of 0.01 in solid fraction could account for about 20% scatter in existing pressure drop correlations.

The experimental results given in Table I and Fig. 7 show that beds settled from fluidization can be compacted by pulsing so that when subjected to a 12-g lateral shock, the change in solid fraction is only about 1/6 of the value which is considered acceptable for the SBFR. Furthermore, it is shown that the particle interlocking effect with a pressure drop gradient of only 3 psi per in. depth gives a substantial extra margin of stability by a factor of 3 as indicated by a reduction in reactivity response from 1.5 cents to 0.5 cents. For the proposed SBFR the pressure drop gradient would be about 10 psi/in. Consequently, a greater margin of stability would be anticipated. In addition, there is evidence that the response to shock is concentrated in the top 20% of the bed - a region with less than average importance in terms of nuclear reactivity.

As expected, the response to the 12-g shock diminished, for any one bed, as the blow test continued. As shown in Fig. 8, with a bed pulsed to give a solid fraction of 0.629 and zero pressure drop gradient, more than 325 shocks were required to produce a change in solid fraction which exceeded the acceptable change of 0.002. For a bed with 0.635 solid fraction and a pressure drop gradient of 3 psi per in., almost 5000 shocks were required to produce the same change.

Although the experimental program presented in this paper dealt with beds no larger than 6 in. in diameter, no inherently difficult problems are anticipated in demonstrating stability with full-scale beds.

Acknowledgments

The authors gratefully acknowledge the assistance rendered in the experimental program by Theodore Arns, E. H. Jackson, and Michael Stone.

Figure Captions

1. Hydraulic Pulsing Using One 3-Way Rotating Ball Valve.
2. Three-Way Rotating Ball Valve With 44 RPM Driving Motor and Throttle Valve.
3. Hydraulic Pulsing Using a 4-Way Plug Valve.
4. Membrane Cap for Measuring Small Changes in Solid Fraction of Packed Beds.
5. Rubber Membrane Pulled Down on Top of 1/8-in. Spheres by a Partial Vacuum in the Bed.
6. 12-g Shock Test Device With Associated Mechanism for Multiple Blows. (Also Shown is the Lucite Spool Piece Which Allows Observation of the Top of the Bed During Downflow Operation).
7. Response to One 12-g Shock.
8. Cumulative Response to 12-g Shocks.

Table Captions

1. Representative Sensitivity to a 12-g Lateral Shock of Hydraulically Pulsed Beds of 1/8-in. Diameter Polished Stainless Steel Spheres 15-in. Deep in a 6-in. Diameter Steel Container.

Table I

Representative Sensitivity to a 12 g Lateral Shock of Hydraulically Pulsed Beds of 1/8" Diameter Polished Stainless Steel Spheres 15" Deep in a 6" Diameter Steel Container.

Initial Solid Fraction	Zero Downflow: Solid Fraction Increase	Zero Downflow: Equivalent SBFR Reactivity Increase	2.3 psi/in Downflow Pressure Gradient: Solid Fraction Increase	2.3 psi/in Downflow Pressure Gradient: Equivalent SBFR Reactivity Increase	3.0 psi/in Downflow Pressure Gradient: Solid Fraction Increase	3.0 psi/in Downflow Pressure Gradient: Equivalent SBFR Reactivity Increase
0.60 (as settled from fluidization)	0.0047	23.5¢	0.0026	13.0¢	-	-
0.61	0.0030	15.0¢	0.0019	9.5¢	-	-
0.62	0.0017	8.5¢	0.0012	6.0¢	0.00050	2.5¢
0.63	0.0008	4.0¢	0.00050	2.5¢	0.00015	0.75¢
0.635	0.0003	1.5¢	0.00015	0.75¢	0.00010	0.50¢

HYDRAULIC PULSING USING ONE 3-WAY ROTATING BALL VALVE

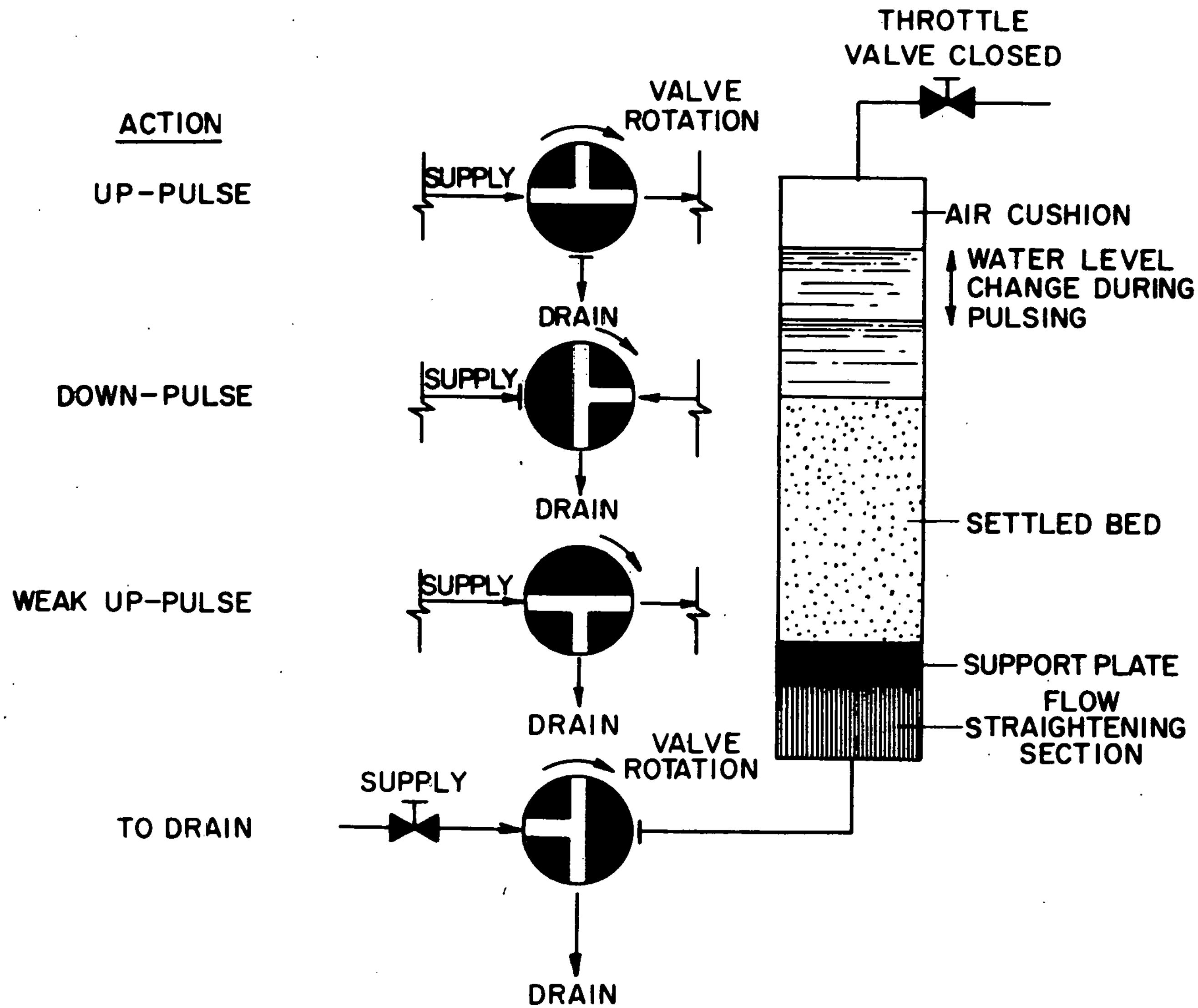

Fig. 1

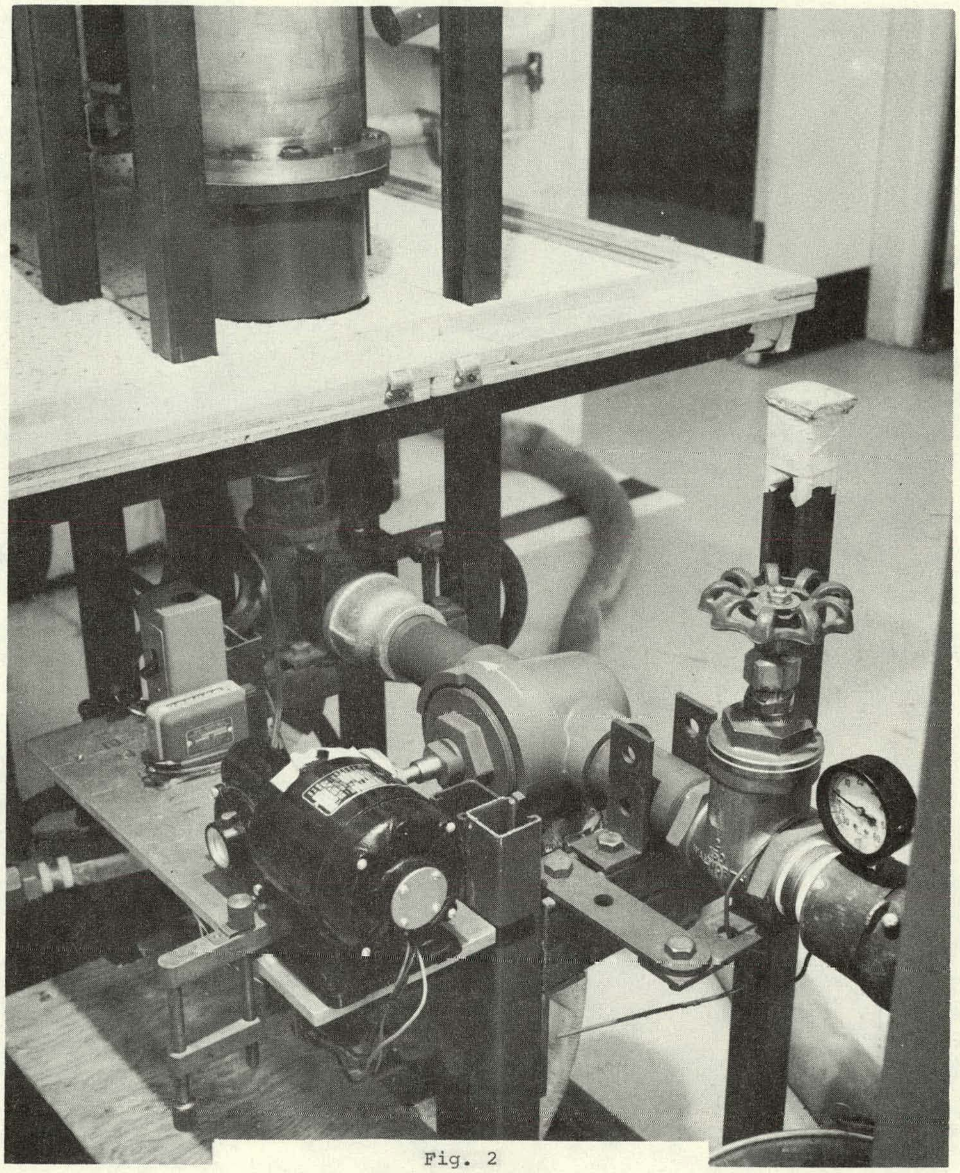

Fig. 2

Three-Way Rotating Ball Valve With
44 RPM Driving Motor and Throttle
Valve.

HYDRAULIC PULSING USING A 4-WAY PLUG VALVE

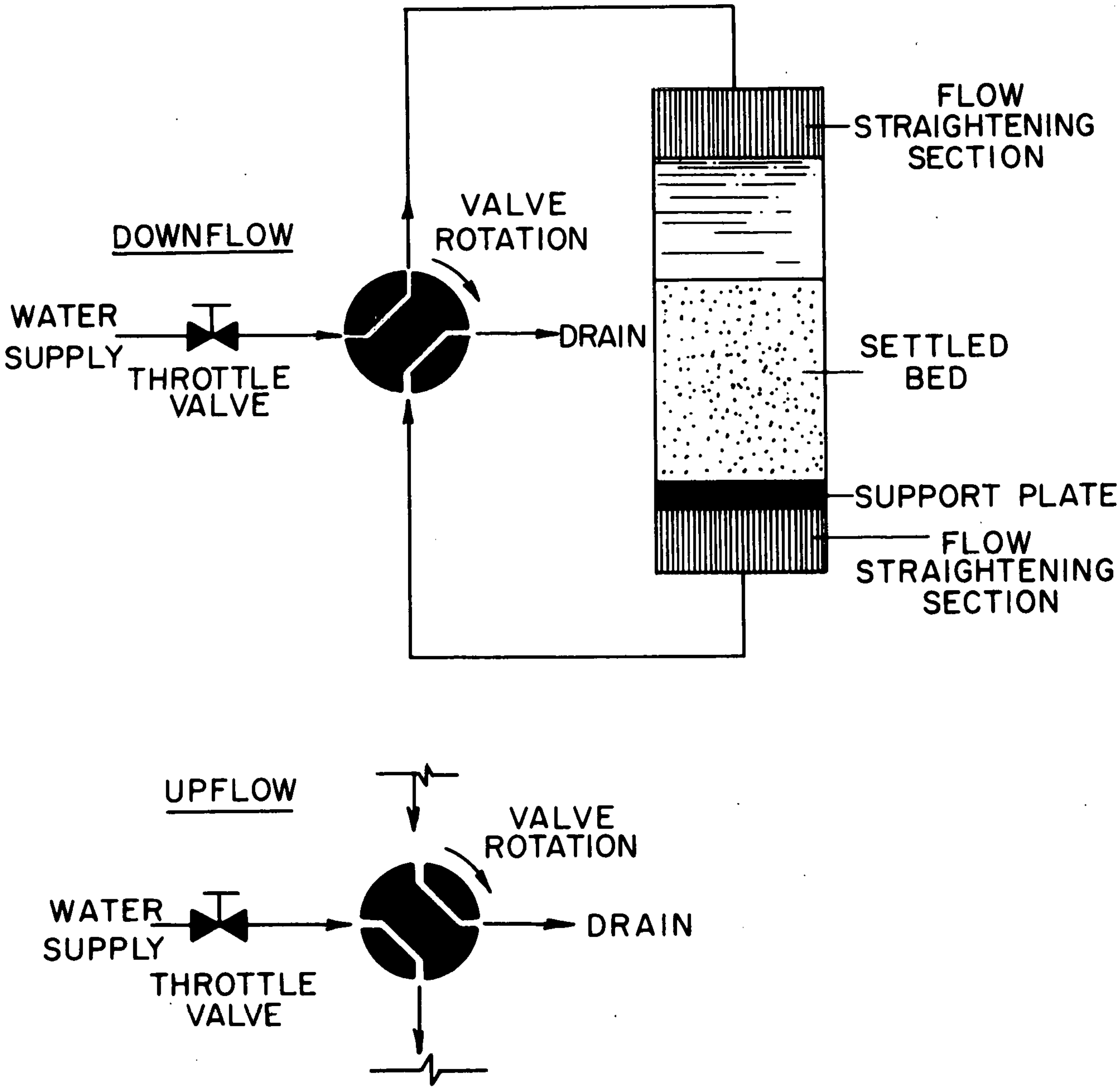

Fig. 3

MEMBRANE CAP FOR MEASURING SMALL CHANGES IN SOLID FRACTION OF PACKED BEDS

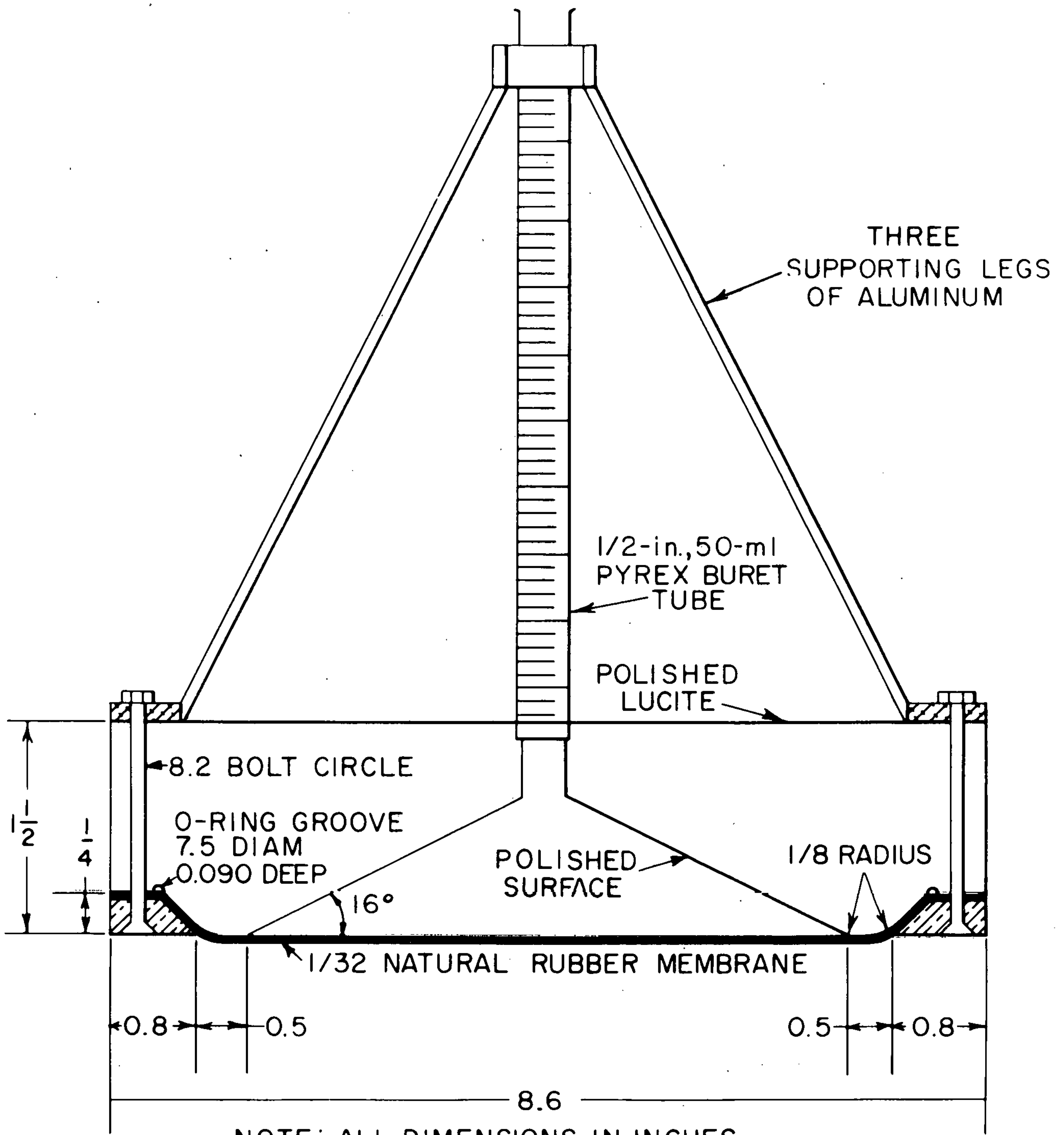

Fig. 4

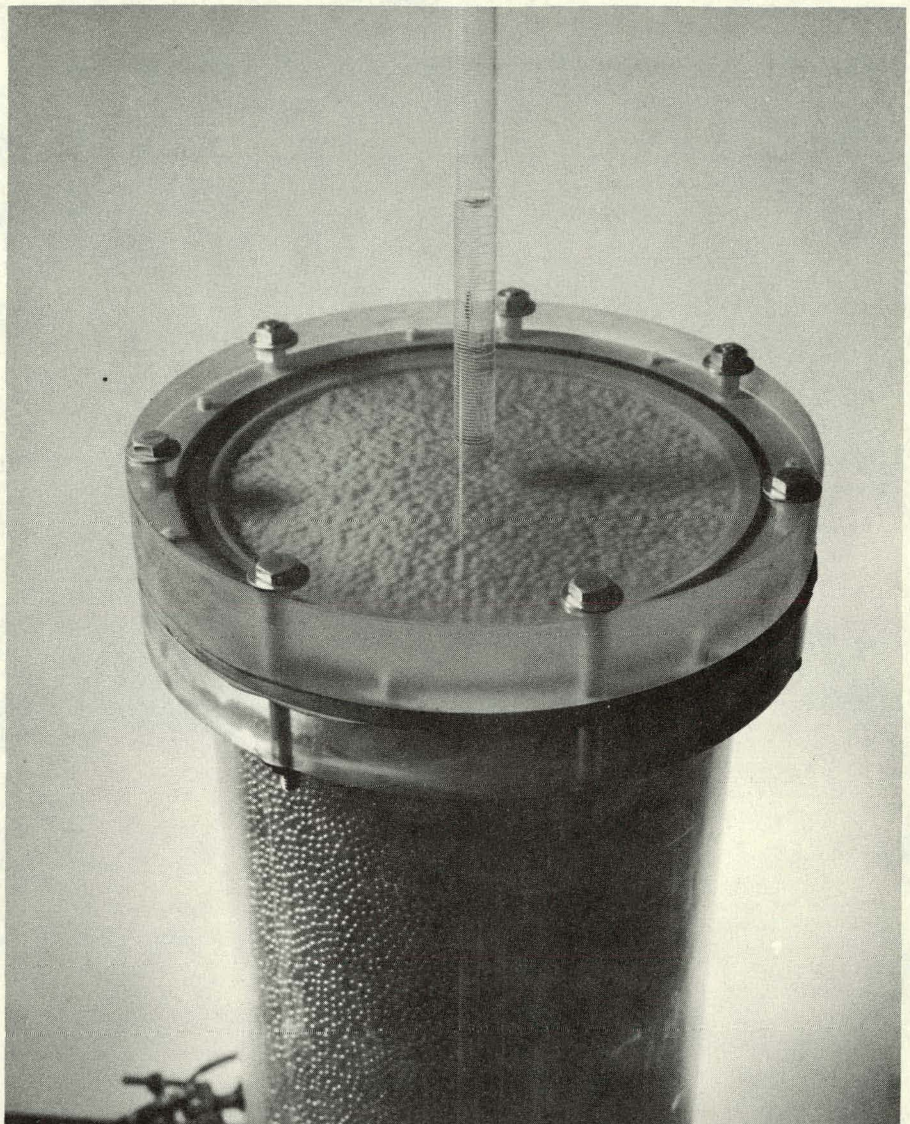

Fig. 5
Rubber Membrane Pulled Down on Top of 1/8-in. Spheres by a Partial Vacuum in the Bed.

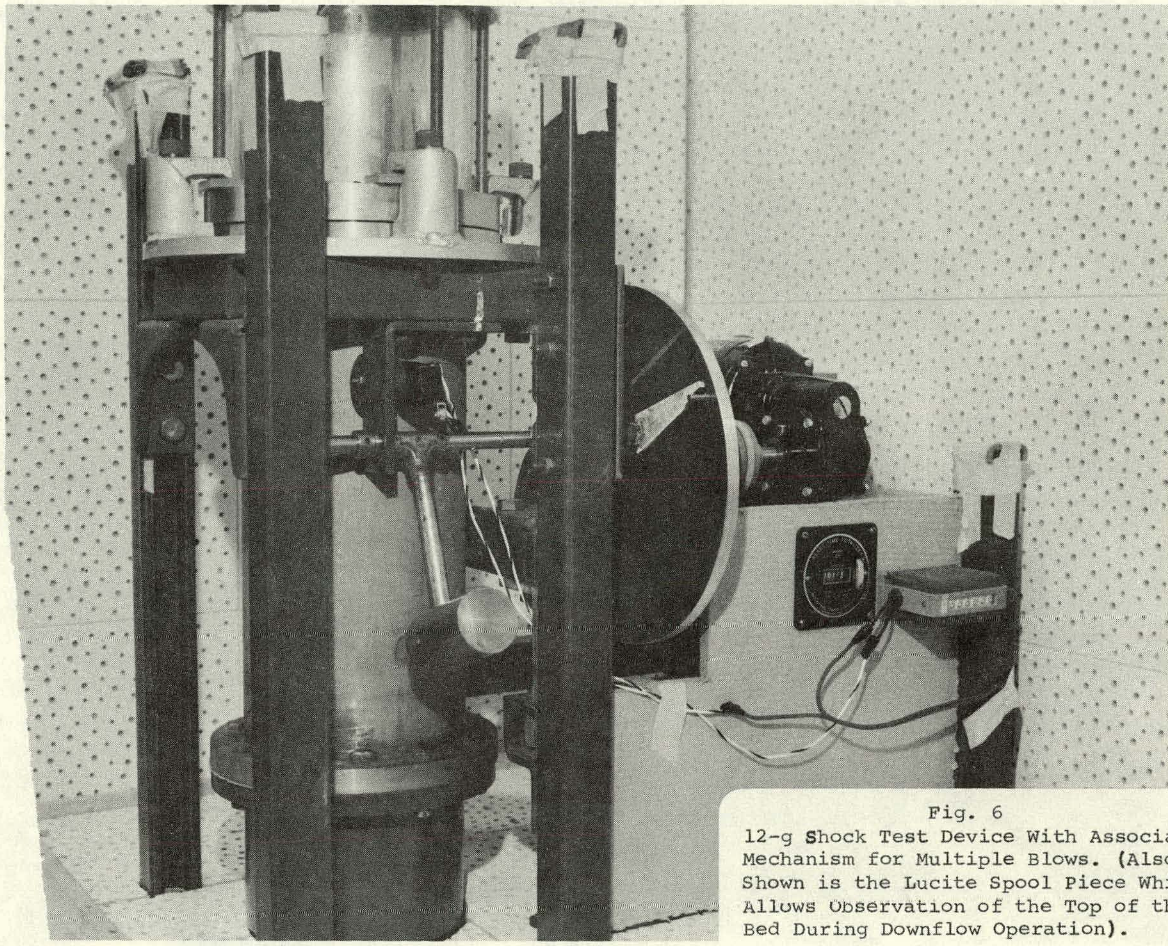

Fig. 6
12-g Shock Test Device With Associated Mechanism for Multiple Blows. (Also Shown is the Lucite Spool Piece Which Allows Observation of the Top of the Bed During Downflow Operation).

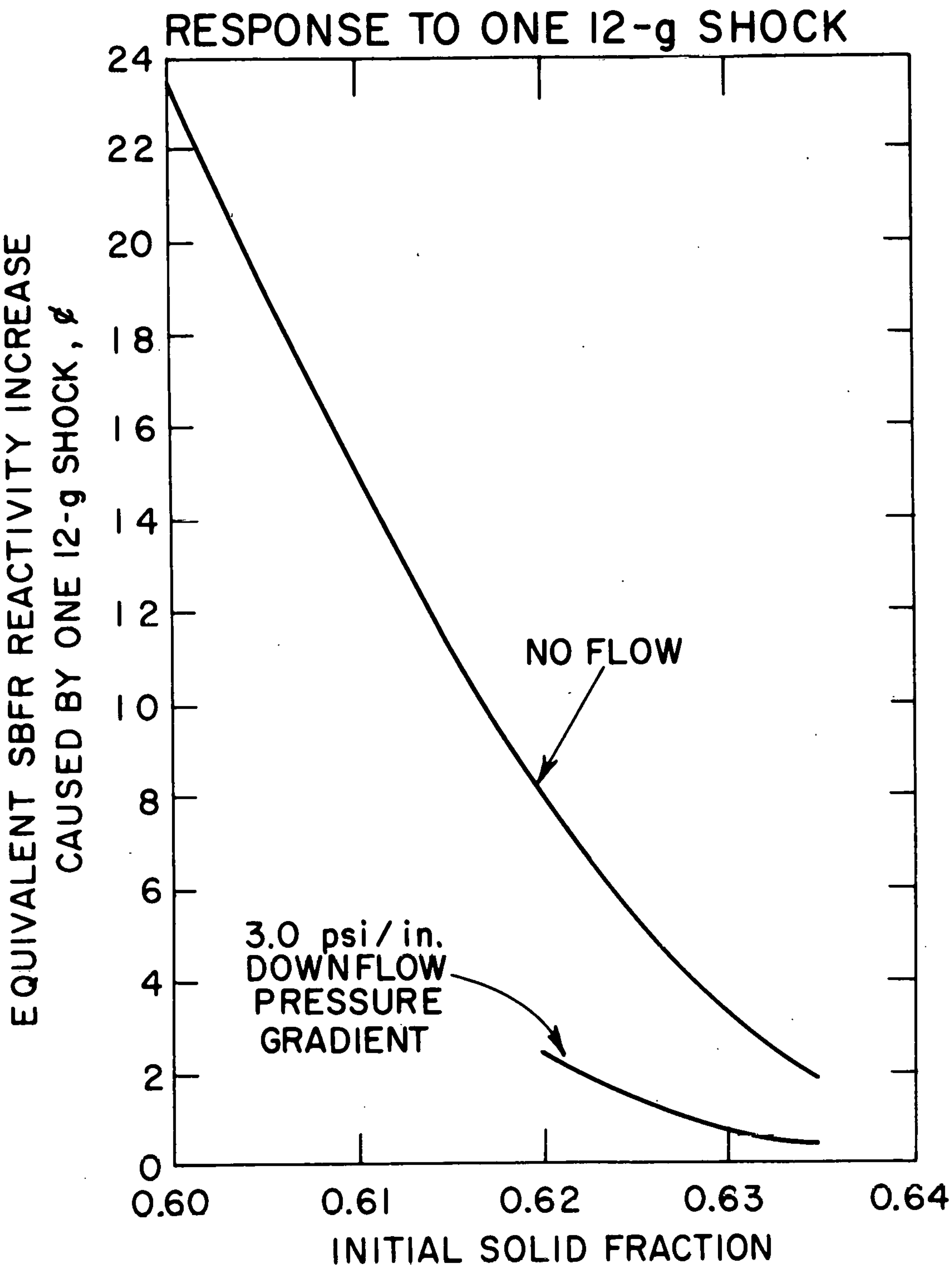
RESPONSE TO ONE 12-g SHOCK
EQUIVALENT SBFR REACTIVITY INCREASE CAUSED BY ONE 12-g SHOCK, ¢
24
22
20
18
16
14
12
10
8
6
4
2
0
0.60
0.61
0.62
0.63
0.64
INITIAL SOLID FRACTION
NO FLOW
3.0 psi/in.
DOWNFLOW
PRESSURE
GRADIENT

Fig. 7

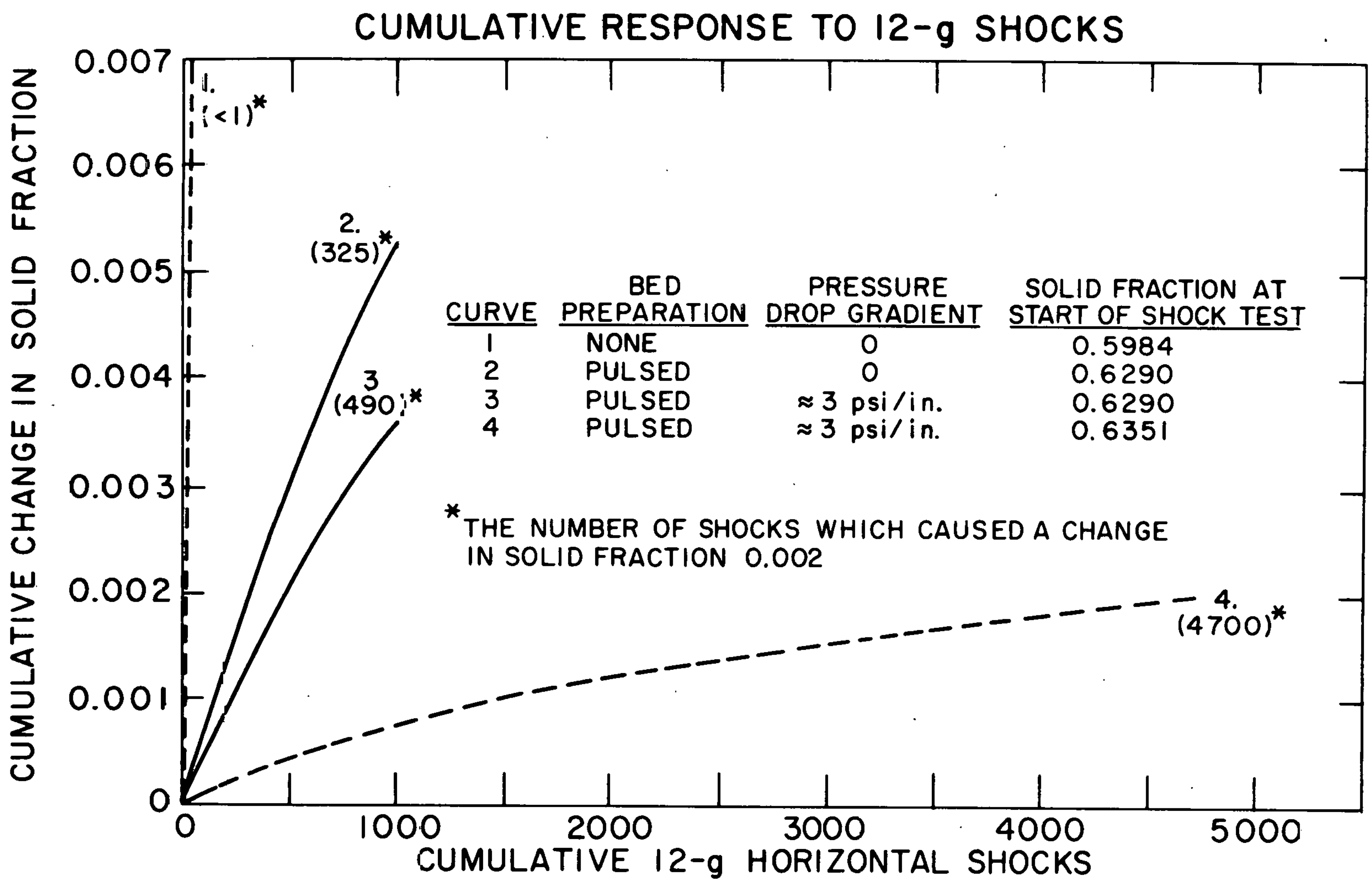
CUMULATIVE RESPONSE TO 12-g SHOCKS
CUMULATIVE CHANGE IN SOLID FRACTION
0.007
0.006
0.005
0.004
0.003
0.002
0.001
0
0
1000
2000
3000
4000
5000
CUMULATIVE 12-g HORIZONTAL SHOCKS
1. (<1)*
2. (325)*
3 (490)*
4. (4700)*
CURVE | BED PREPARATION | PRESSURE DROP GRADIENT | SOLID FRACTION AT START OF SHOCK TEST
1 NONE 0 0.5984
2 PULSED 0 0.6290
3 PULSED ≈ 3 psi/in. 0.6290
4 PULSED ≈ 3 psi/in. 0.6351
*THE NUMBER OF SHOCKS WHICH CAUSED A CHANGE IN SOLID FRACTION 0.002

Fig. 8