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GRAVITY FLOW RATE OF SOLIDS THROUGH ORIFICES AND PIPES

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ABSTRACT

Lock-hopper systems are the most common means for feeding solids to and from coal conversion reactor vessels. The rate at which crushed solids flow by gravity through the vertical pipes and valves in lock-hopper systems affects the size of pipes and valves needed to meet the solids-handling requirements of the coal conversion process. Methods used to predict flow rates are described and compared with experimental data. Preliminary indications are that solids-handling systems for coal conversion processes are over-designed by a factor of 2 or 3.

Gravity Flow Rate of Solids Through Orifices and Pipes

by

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Lockhopper systems are the most common means for feeding solids to and from coal conversion reactor vessels. The required rates at which these solids must flow affects the size of piping and valves used in the lockhopper systems.

The Morgantown Energy Research Center conducted a literature review on solids feeding to analyze valve size requirements for solids handling service in coal conversion plants. From this literature review, it is apparent that limited investigations have been performed to determine the rate at which crushed solids fl⌐ by gravity from hoppers, pipes and valves.

Most experimental work on gravity flow of solids occurred during the post-WWII years of 1945-1955.[1-6] Gregory[7] in 1952 appraised the problem of gravity flow of solids and drew the following conclusions:

1. The internal pipe diameter should be at least 5 to 7 times as large as the largest particle size encountered in the charge.

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2. Materials of narrow size range tend to flow more readily. Materials with wide size spectra may exhibit sticking tendencies, as do comparitively small particles (on the order of D_p <0.003 in.).

3. Mild steel encourages particle sticking whereas smoother surfaces of stainless steel and glass are more amendable to unimpeded flow.

4. Flow may be severely affected by surface moisture. Thus a solids surface moisture content in excess of 1 to 2 percent should be avoided.

Gregory's work was a good start on determining the variables which affect gravity flow of solids. Other investigations have determined that the following factors also affect solids flow.

1. Solids Density.

2. Surface properties of the solid.

3. Size and shape of storage reservoir.

4. Length and shape of the standpipe.

5. Temperature of the solids.

6. Velocity effects (transonic effects or Reynolds Number effects.)

7. Electrostatic influences.

Rausch in 1948[5] investigated a wide variety of solids falling through tubes of 3" to 8" diameter. His experimental equipment consisted of a simple hopper with orifices and discharge tubes. He varied the orifice diameters from 1/16" to 2" while varying D_o/D_p from 2.5 to 250. Rausch observed the following effects:

1. Solids head had little effect.

2. The diameter of the discharge duct had little effect on solids flowrate.

3. Particle size had little impact except when considered in combination with orifice diameter.

4. With D_O/D_p <25 the bulk density of the solids passing through the ofifice appeared to be reduced.

5. The angle of approach in the bottom of a delivery hopper (as shown in figure 1) had an influence on flow rate.
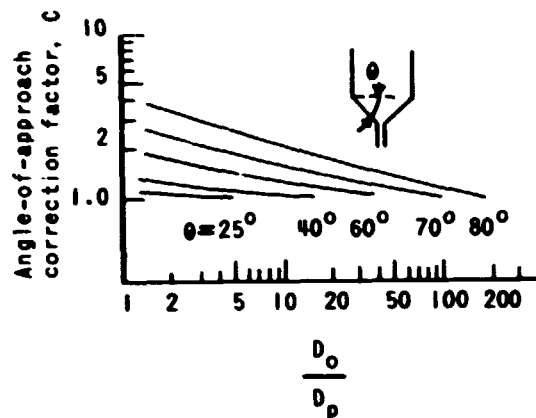

FIGURE 1[5] - Angle of Approach Correction Factor for Gravity Feed Systems

Rausch also developed a correction factor to take into account the pipe wall effect. This is given in Figure 2.
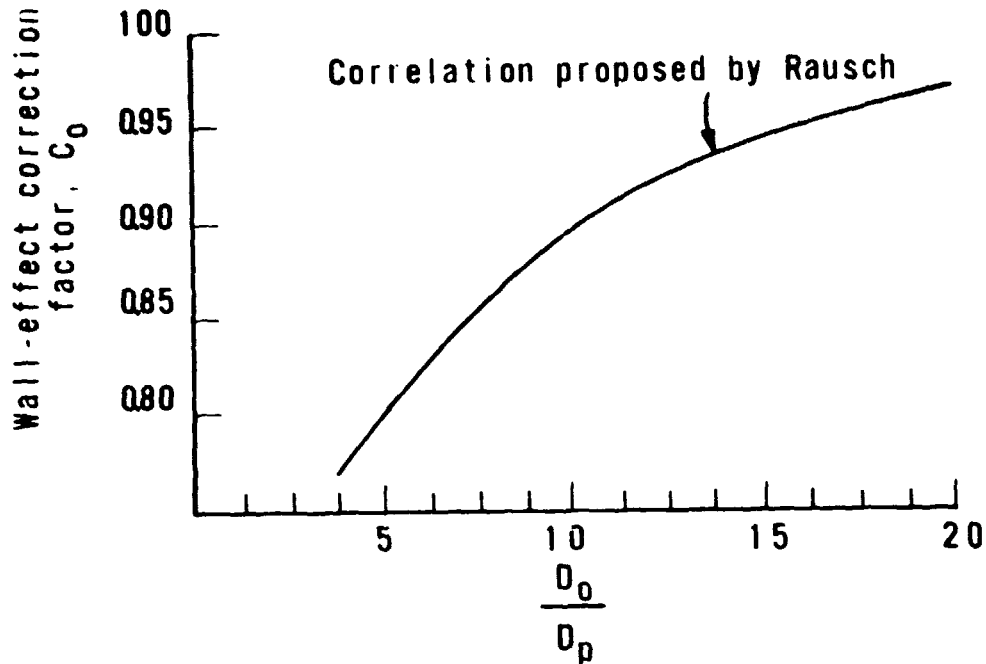
FIGURE 2[5] - Wall Effect Correction Factor for Gravity Flow of Solids

The experimental data of Rausch[5] was correlated and used to develop the following equation:

$$Wa = C\ C_0\ \frac{(D_0/D_p)^{2.70}\ g_c^{0.5}\ \rho_b}{\tan \beta_a^{0.5}}\ D_p^{2.50}.\qquad(1)$$

When rearranged this equation yields:

$$Wa = C\ C_0\ \frac{\rho_b}{D_p^{0.2}}\ \left[\frac{g_c}{\tan \beta_a}\right]^{0.5}\ D_0^{2.70} = C_s D_0^{2.70}.\qquad(2)$$

C_s is a constant that is characteristic of the solids involved.

A similar form of this equation has been proposed by a variety of experimenters. These equations differ in the values of C_s and in the exponent of the orifice diameter.[2-8] These differences are listed in Table 1.

Zenz[10] concluded that the Rausch[5] correlation is relatively accurate for a wide range of solids flow conditions. Zenz felt that further tests should be performed to verify and correct the correction factors used in equation 2.

A series of solids flow experiments were performed at the Morgantown Energy Research Center. Limestone solids with the character-istics given in Table 2 flowed from a solids storage bin through a pipe or orifice plate for a specified time into a receiving hopper. The solids were then weighed and a flowrate calculated.

The discharge configurations used in the experiments consisted of 7-foot lengths of 1-1/2, 2, 4, 6, and 8-inch diameter, Schedule 40 carbon steel pipes, and 4, 6, and 8-inch diameter flat plate orifices. For each individual test, the pipe or plate was attached to the bottom of a 25-ton capacity storage hopper having an inverted-frustrum bottom. Additional experiments were also conducted using a variety of types of reducer sections (both conical and concentric in shape) located be-tween the hopper bottom and the discharge orifice.

The results of these experiments are given in Table 3. Photo-graphs of the tests and a typical experimental configuration are shown in Figures 4, 5, and 6.

Observations from these experiments were:

1. A uniform flow of the solids occurred in all tests. The observed flow of the solids (as photographed through a plexi-glass tube) indicated an acceleration of particles and a nearly full tube of solids at the start. The flow stream then tapered with increasing distance from the beginning of the tube.

2. The flow of solids was uniform during the entire period of
    the tests.

3. A "choked" flow condition did not occur during the tests.
    A "choked" flow condition, however, could be induced by
    restricting a small amount of the flow area.

Table 4 compares predicted flowrates with the actual flow rates
found in the MERC tests.

From Table 4 it is apparent that flow rates calculated from the
equations developed by previous experimenters correlate poorly with
the results obtained at MERC. This indicates that good correlations
are not available for designing gravity-flow systems for handling
crushed solids in coal conversion processes. Further investigation
into this problem area thus needs to be done. With accurate pre-
diction methods for solids flow, valves and piping for coal conversion
process plants could be accurately sized. For example, the MERC data
show that 3885 tons/day of drushed solids can flow under gravity head
through an 8" vertical pipeline. This indicates that relatively small
valves and piping could be sufficient for commercial-scale coal conver-
sion plants. This would lower costs, and lessen design, fabrication, and
operating problems with valves.

The experiments conducted at MERC were not sufficient to fully
investigate the effects of pipe and valve size on gravity flow rates
of crushed solids. The results indicate the need for further studies.
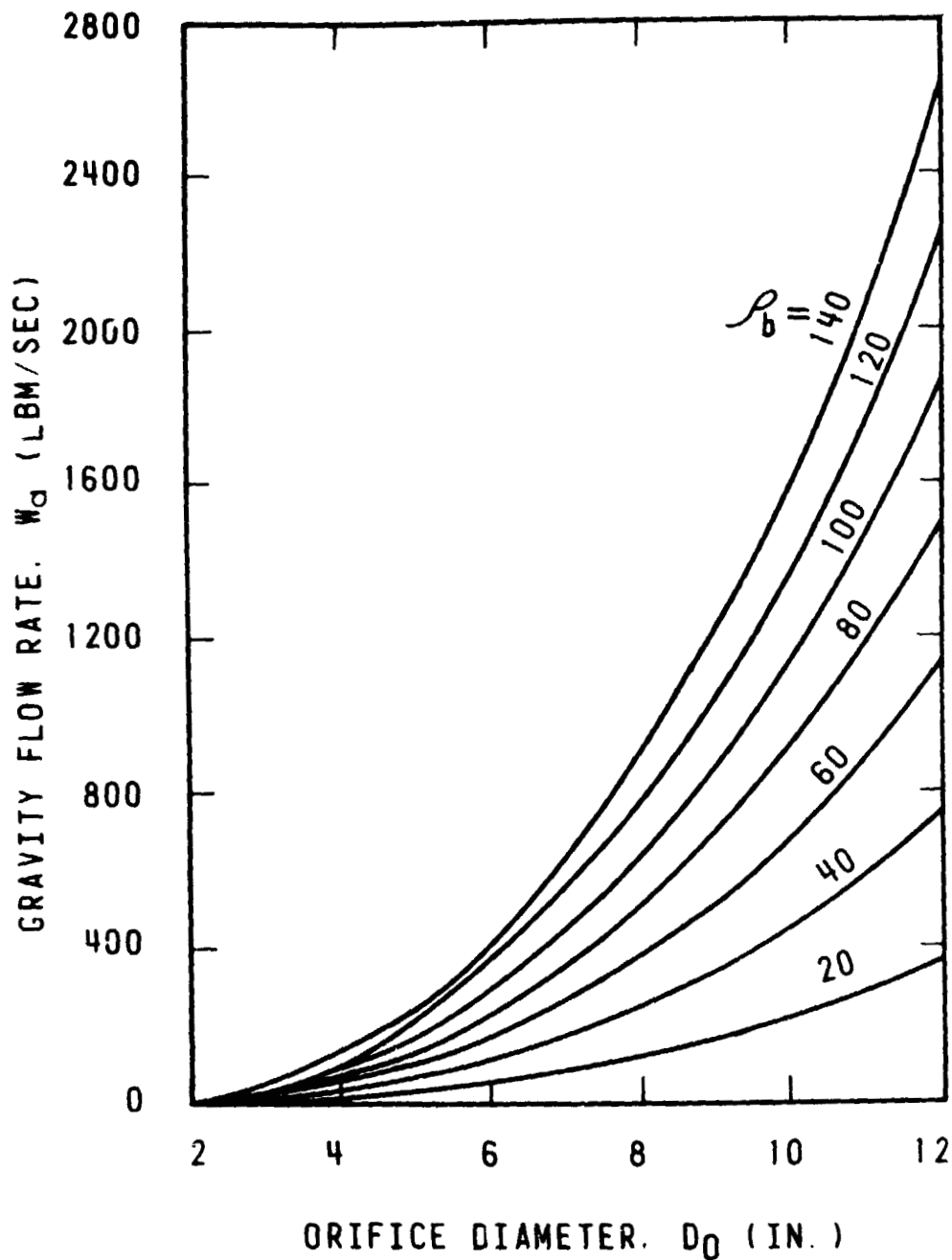MERC has proposed such studie' to Fossil Energy, ERDA.

FIGURE 3 - VALUES OF FLOW RATES FOR VARYING BULK
DENSITIES AND ORIFICE DIAMETERS.
BASED ON RAUSCH'S EQUATION [5]
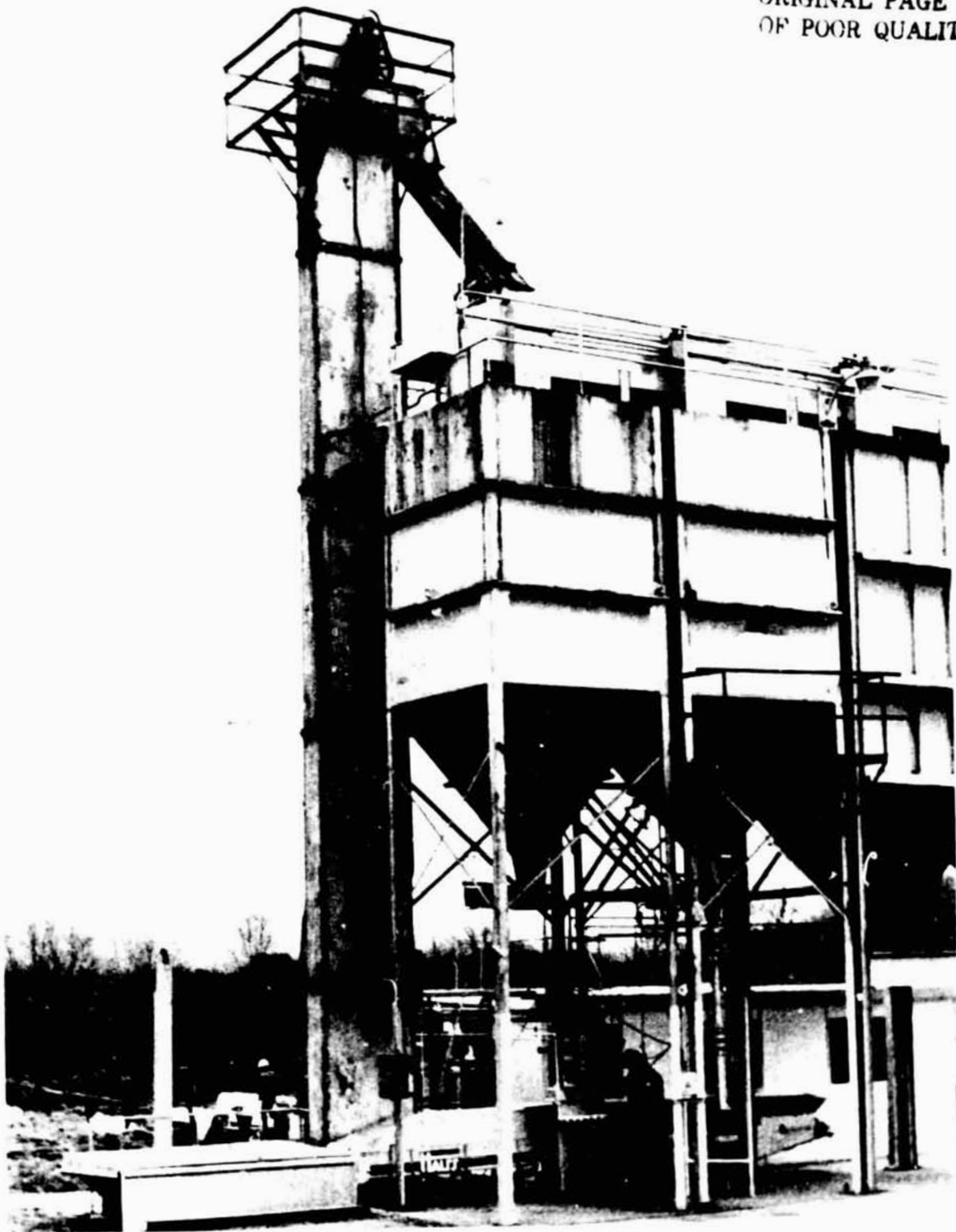
FIGURE 4 - VIEW OF STORAGE HOPPER
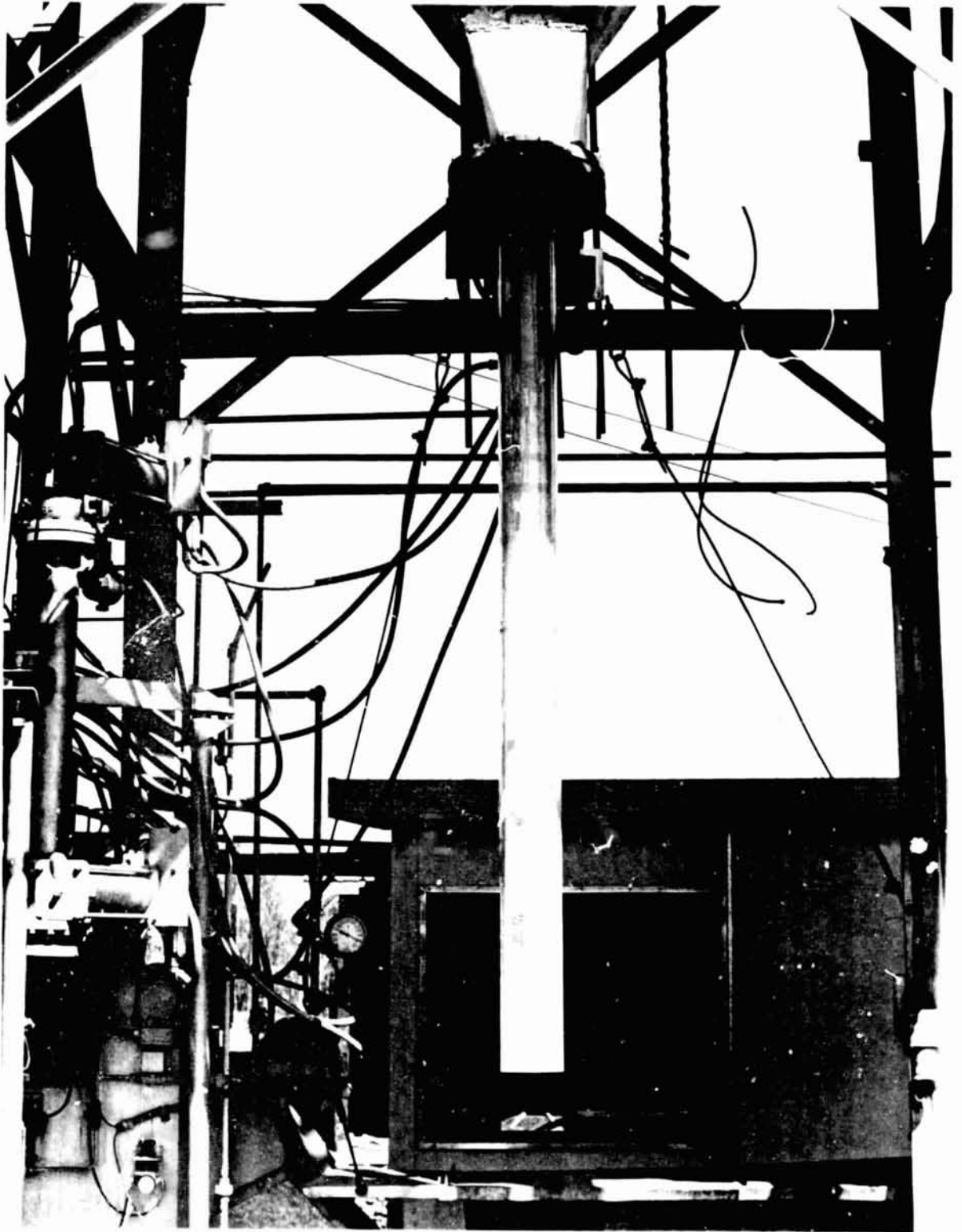USED IN MERC SOLIDS FLOWRATE TESTS

FIGURE 5 - TYPICAL CONFIGURATION
USED IN SOLIDS FLOWRATE TESTS

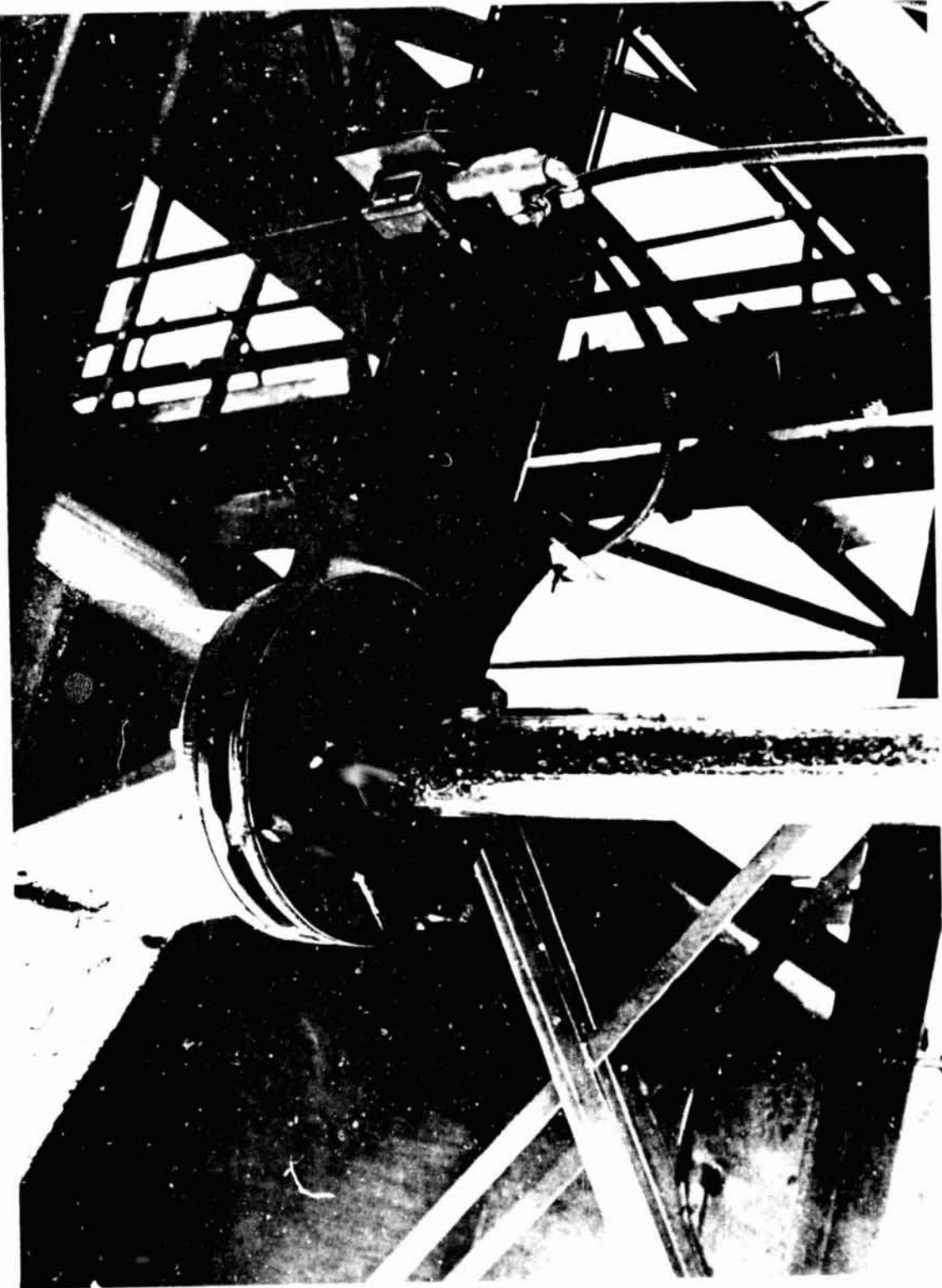FIGURE 6. - View of Solids Flow During Test

TABLE I. - Reference Values of C_s and the

Orifice Diameter Exponent of Various Experimenters

Reference	C_s	Exponent
Gregory (7)	0.28	2.50
Newton et al. (4)	0.14	2.96
Kelly (3)	0.16	2.84
Franklin & Johanson (2)	0.05	2.93
Rausch (5)	0.65	2.70
Kuwai (8)	0.82	2.75
Shirai (6)	0.18	2.50

Table 2 – Properties of Limestone Solids Used in Solids Gravity Flow Tests at MERC

Material   –   Limestone

ρ_b = Bulk Density = 88.17 lb_m/ft^3

β_a = Angle of Repose = 38°

D_p = Average Particle diameter = 0.172 in.

Size Analysis:

Screen Size	Weight Percent, %
5/16" x 1/4"	⌐.9
1/4" x 1/8"	82.7
1/8" x 1/16"	7.3
1/16" x 16 mesh	3.0
16 mesh x 30 mesh	0.5
30 mesh x 50 mesh	0.2
50 mesh x 100 mesh	0.3
100 mesh x 200 mesh	0.4
minus 200 mesh	2.7

TABLE 3. - Results of Solids Flowrate Tests
Conducted at MERC

Test Configuration No.	Orifice Size, D_o, in.	Pipe Length L, Ft.	Av. Solid Flowrate W_a lbm/sec	Av. Solids Flowrate* WA, lb/hr $(x10^3)$
PIPES				
1	1.5	7.0	1.01	3.64
2	2.0	7.0	2.28	8.21
3	4.0	7.0	13.99	50.36
4	6.0	7.0	43.12	155.23
5	8.0	7.0	89.93	323.75
PLATES				
6	4.0	---	13.78	49.61
7	6.0	---	41.74	150.26
8	8.0	---	82.65	297.54

* Solids used as Described in TABLE 2

TABLE 4.- Calculated Flow Rate of Solids W_a (lbm/sec)
Predicted by Various Researchers.

	D_o, in		
	4	6	8
1 M.E.R.C. '*	13.99	43.12	89.93
2 GREGORY (7)	8.96	24.69	50.69
3 NEWTON et al. (4)	8.48	28.15	65.96
4 KELLEY (3)	8.20	25.95	58.73
5 FRANKLIN & JOHANSON (2)	2.90	9.53	22.13
6 RAUSCH (5)	27.45	82.02	178.34
7 KUWAI (8)	37.11	113.17	249.64
8 SHIRAI (6)	5.76	15.87	32.58

** Actual flow rates observed experimentally at MERC, as shown in
Table 3. All other values are calculated.

Nomenclature

D_O = diameter orifice (in.)
D_p = diameter particle (in.)
WA = flowrate (lbs/hr)
C = correction factor (angle of approach)
Co = correction factor (wall effect)
g_c = gravity (386.5 lbm in/lb$_f$ sec^2)
ρ_b = bulk density (lbs/in^3)
β_a = angle of repose of poured solids (degrees)
L = fluid column height (ft.)
C_s = constant characteristic of the solids involved
Wa = flowrate, lb/sec
De = effective orifice diameter (in.)
h = height of reservoir (ft.)
d = diameter of reservoir (ft.)

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