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Correlation of Physical Coal Separations—Part I

E. C. Hise

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CORRELATION OF PHYSICAL COAL SEPARATIONS — PART I

E. C. Hise

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CORRELATION OF PHYSICAL COAL SEPARATIONS — PART I*

E. C. Hise

ABSTRACT

Experimental separations of the inorganic material from a coal by the specific-gravity (wet), high-gradient magnetic (dry), and open-gradient magnetic (dry) processes were performed and analyzed to compare for Btu recovery vs efficiency of removal of pyrite and ash and to determine the degree of liberation of the inorganics by the crushing. It is shown that the liberated minerals can be separated from dry crushed coal by both the high-gradient magnetic separation (HGMS) and the open-gradient magnetic separation (OGMS) processes with an efficiency comparable to the specific-gravity (float-sink) process. Coal feed through the HGMS was by gravity with low-velocity transport air and through the OGMS by vibrating tray and by gravity free fall. The degree of liberation of the minerals was assayed by a set of specific-gravity separations. These separations were performed with size fractions in the range of −14 +100 mesh of Western Kentucky seam No. 9 coal in the laboratories of the Bureau of Mines (specific gravity), the Oak Ridge National Laboratory (ORNL) (open-gradient magnetic and specific gravity), and of a magnetic separator manufacturer (high-gradient magnetic).

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1. INTRODUCTION AND SUMMARY

In the interest of brevity, this report presumes some reader familiarity with the physical separation processes discussed and with the nature of the inorganic contaminants in coal. A bibliography is given as a source for more detailed information.

A series of experimental tests of the separation of inorganic contaminants from crushed coals by different physical separation methods was performed. The purposes of these tests were:

1. to measure the degree of liberation of the inorganics from the coal as a function of the coal, the grind, and the size fraction;

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*Research sponsored by the Division of Fossil Fuel Extraction, U.S. Department of Energy, under contract W-7405-eng-26 with the Union Carbide Corporation.

2. to measure the efficiency of a physical separation process as a function of the fraction of the liberated inorganics that are actually removed and the Btus recovered by that process;
3. to compare the efficiency of separation achieved by the several physical separation processes;
4. to devise a simple laboratory assay to determine, for a coal, the grind and process parameters for economical production separation.

The results of the tests on one coal, Western Kentucky No. 9 from Muhlenberg County, Kentucky, are presented. The separation methods used are specific-gravity or float-sink, high-gradient magnetic separation (HGMS), and two variations of open-gradient magnetic separation (OGMS). Successful separation was achieved by one or more of these methods with particles ranging from 1 mm to 10 μm in size; however, the correlation reported herein is for the size fraction of ~600 to 150 μm (—30 +100 mesh) that was common to all separation methods. All feed materials and products were chemically analyzed to determine the efficiency of separation and Btu recovery.

The results of these first tests of the planned series follow.

1. The degree of liberation of inorganics can be measured by a set of laboratory specific-gravity separations or OGMSs and chemical analyses.

2. HGMS efficiently removes the liberated inorganics from dry crushed coal fed downward through the separator with low-velocity transport air.

3. OGMS efficiently separates the liberated inorganics from dry crushed coal fed through the magnetic field on a vibratory tray or by vertical free fall.

4. Liberation of the finely dispersed inorganics in coal requires crushing. The test series is being extended to other size fractions and other coals to more clearly define the optimum degree of crushing. From these results, we can conclude that the dry magnetic process offers the potential for the separation of dry crushed coal at high production rates and high Btu recovery without the difficulty of a later dewatering step.

2. EXPERIMENTAL PROCEDURE

2.1 Specific-Gravity Separation

The specific-gravity or float-sink separation depends on the difference in specific gravity between the organic and inorganic fractions of coal. The specific gravity of the organic coal is around 1.3, that of the various ash-forming materials is around 2.5, and that of the iron pyrite is about 5. The separations performed at Oak Ridge National Laboratory (ORNL) were done in flasks, shown in Fig. 1, using zinc chloride solutions of specific gravity ranging from 1.3 to 1.7. A 100-g sample of the −30 +100 mesh size fraction was used for each test, and the floats and sinks from each test were dried, weighed, and analyzed. To achieve the best possible approach to complete separation, the wetted sample was added gradually in increments, the material was agitated to disperse agglomerates, the process was observed for completion of the slow settling of the near-gravity particles, and the floats were removed between additions.

Results are compared with specific-gravity separation data from the Bureau of Mines Report of Investigation 8118, *Sulfur Reduction Potential of the Coals of the United States*. The chosen data were for particle sizes of 14 mesh by 0 separated in an organic liquid at specific gravities of 1.3, 1.4, 1.6, and 1.9.

2.2 High-Gradient Magnetic Separation (HGMS)

The HGMS data used in these correlations are a portion of the data obtained in a parametric test program carried out at Sala Magnetics, Inc., under the direction of ORNL and reported in toto.[1] The separations were accomplished in a conventionally conducting, iron-flux return frame solenoid having a 3 1/2-in.-diam by 6-in.-long cavity magnetized to a uniform flux of up to 20 kilogauss (kG). Matrices formed by stacking disks of martensitic stainless steel expanded mesh alternately with spacers are placed in the magnetized cavity. The ferromagnetic mesh is placed so that the filaments are normal to the field, and extremely high magnetic gradients are generated around each filament. The iron pyrite

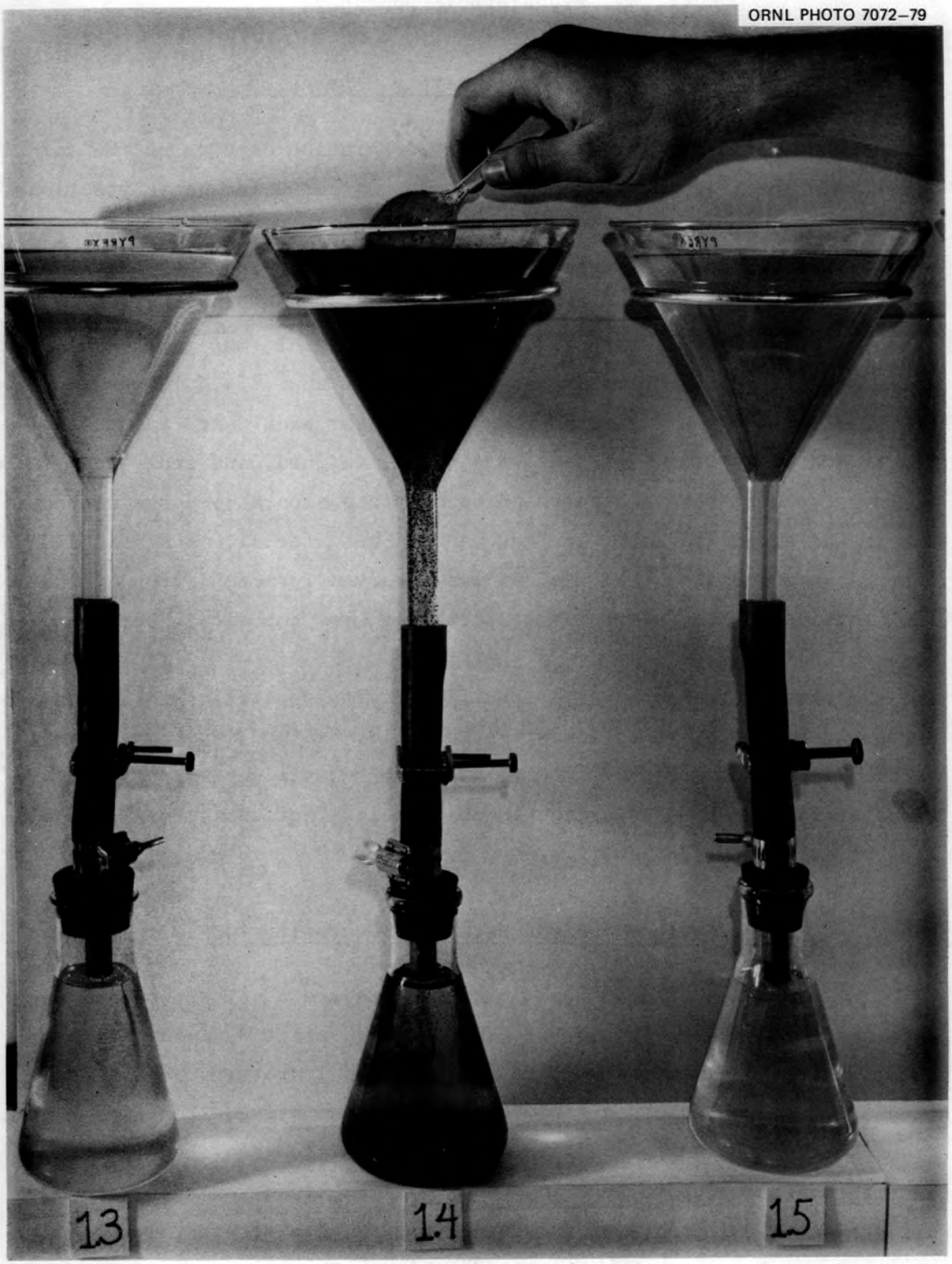

Fig. 1. Specific-gravity separation flasks.

and some of the other inorganic contaminants are attracted into the magnetic gradient and adhere to the filaments. These particles are released when the magnet is turned off and fall or are flushed or shaken from the matrix. Figure 2 is a cross-sectional drawing of an HGMS, and Fig. 3 is a photograph of a typical mesh disk. Various patterns of mesh and spacer thicknesses were assembled to form matrix configurations suited to the particle size fractions to be separated. Tests were conducted with pneumatic feed upward and downward, in pneumatic fluidized beds, and with water transport. Only the data for the 150- to 600-μm fraction of Kentucky No. 9 processed in the downflow mode with superficial air velocities of 50 to 300 ft/min are presented here.

Figure 4 shows the test arrangement for downward transport of the crushed coal. The vibrating tray at the top feeds the sample into the transport air stream, which carries the coal through the matrix where the magnetics are retained; the nonmagnetic fraction passes through the matrix and is collected in the filter box below. The clean coal sample is then removed from the filter box, and, with a fresh piece of paper placed

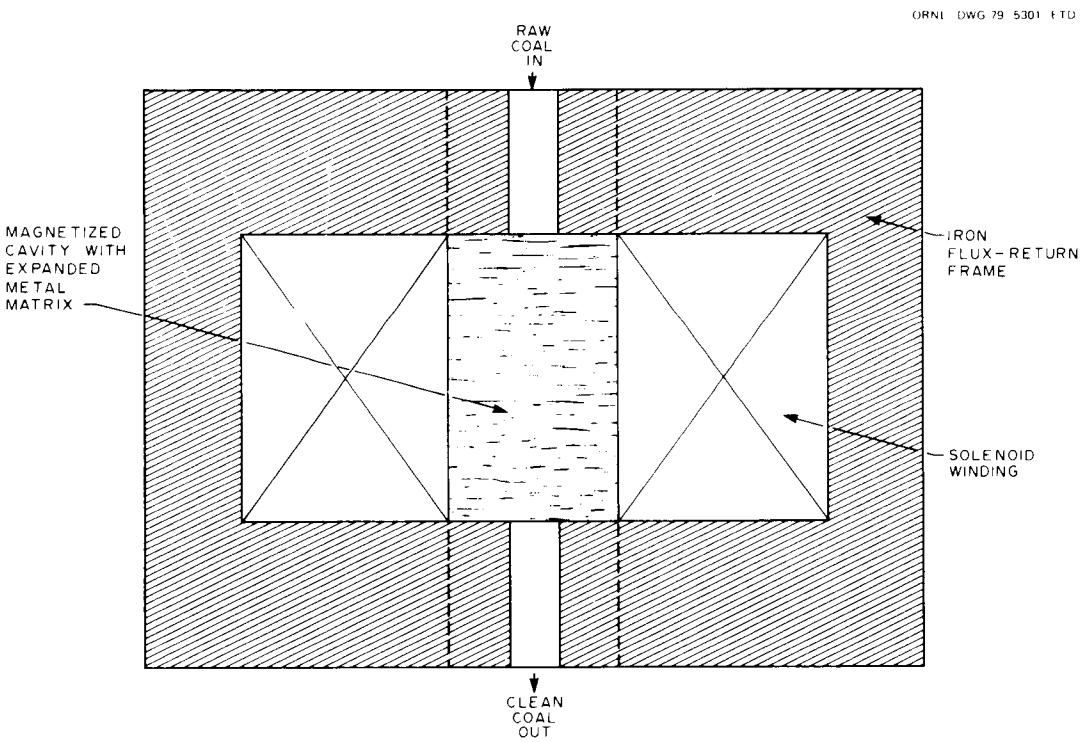

Fig. 2. High-gradient magnetic separator.

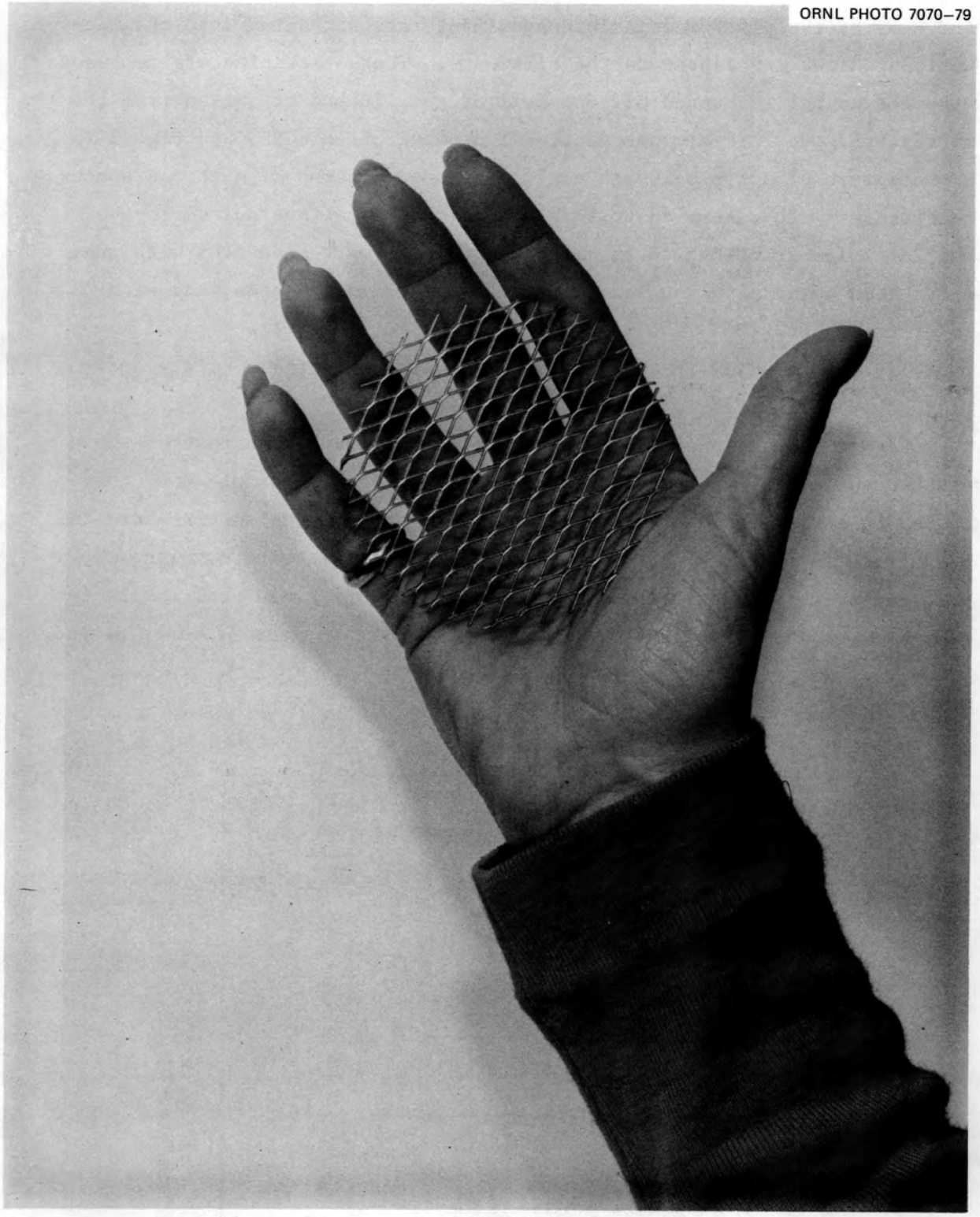

Fig. 3. Expanded metal mesh disk.

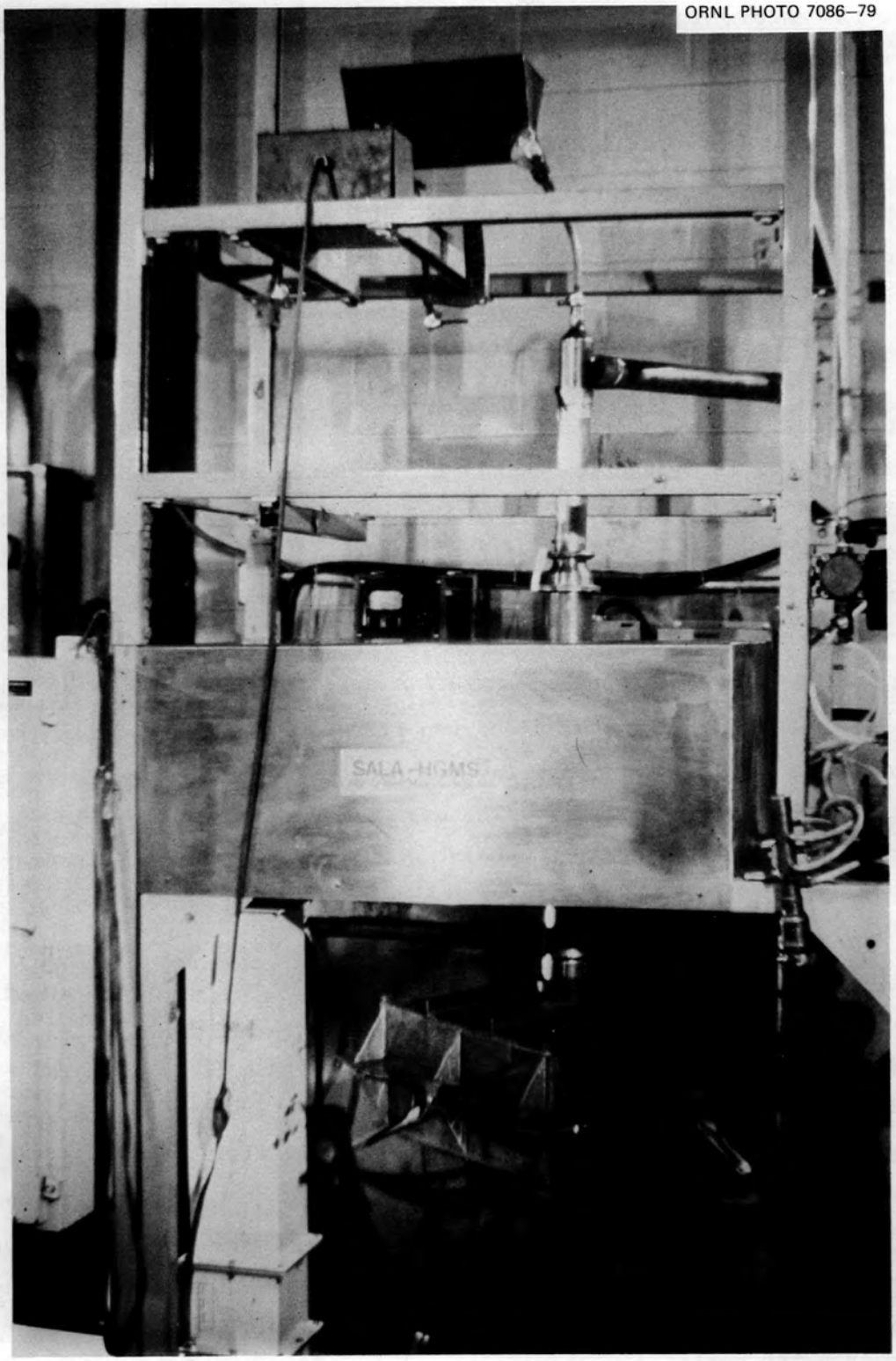

Fig. 4. HGMS test setup.

under the matrix exit, the magnet is de-energized, and the magnetics fall out as shown in Fig. 5.

2.3 Open-Gradient Magnetic Separation (OGMS)

If particles are transported through a cavity having a magnetic field that exhibits a gradient normal to their line of travel, those particles having a negative magnetic susceptibility will be deflected down gradient (toward the lower field strength), the nonmagnetic particles will be unaffected, and those particles having a positive magnetic susceptibility will be deflected up gradient. The magnitude of the deflecting force is a function of (1) the magnetic field strength, (2) the magnitude of the gradient, (3) the mass of the particle, and (4) the magnetic susceptibility of the particle. This principle can be applied to the separation of dry crushed coal, because the pyrite and much of the ash-forming minerals exhibit a positive magnetic susceptibility, while the organic fraction exhibits a negative susceptibility.

The open-gradient separations reported were performed in an Isodynamic Separator* shown in vibrating-tray transport mode in Fig. 6 and in free-fall transport mode in Fig. 7. The magnetized cavity is 25 cm long by 23 mm wide by 5 mm thick at the point of narrowest air gap. The maximum field is 20 kG, and the gradient is about 5 kG/cm.

For the test series with vibrating-tray transport, the longitudinal angle was set to give a suitable feed rate (20° for 150 to 600 μm particles) and separations were performed at transverse angles of +2, +1, 0, −1, and −2°. As used here, a positive transverse angle causes the tray to slope upward toward maximum field, and a negative transverse angle causes the tray to slope downward toward maximum field. For the test series in free-fall transport, the center line of the feed funnel was placed −6 mm from the line of maximum flux (minimum air gap), and separations were performed with the splitter located at +1.5, +0.5, −0.5, −2.5, and −3.5 mm with respect to the center line of the feed. Displacements from the center line toward maximum field are referred to as positive and those away from maximum field as negative.

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*Manufactured by S. G. Frantz Company; Registered Trademark.

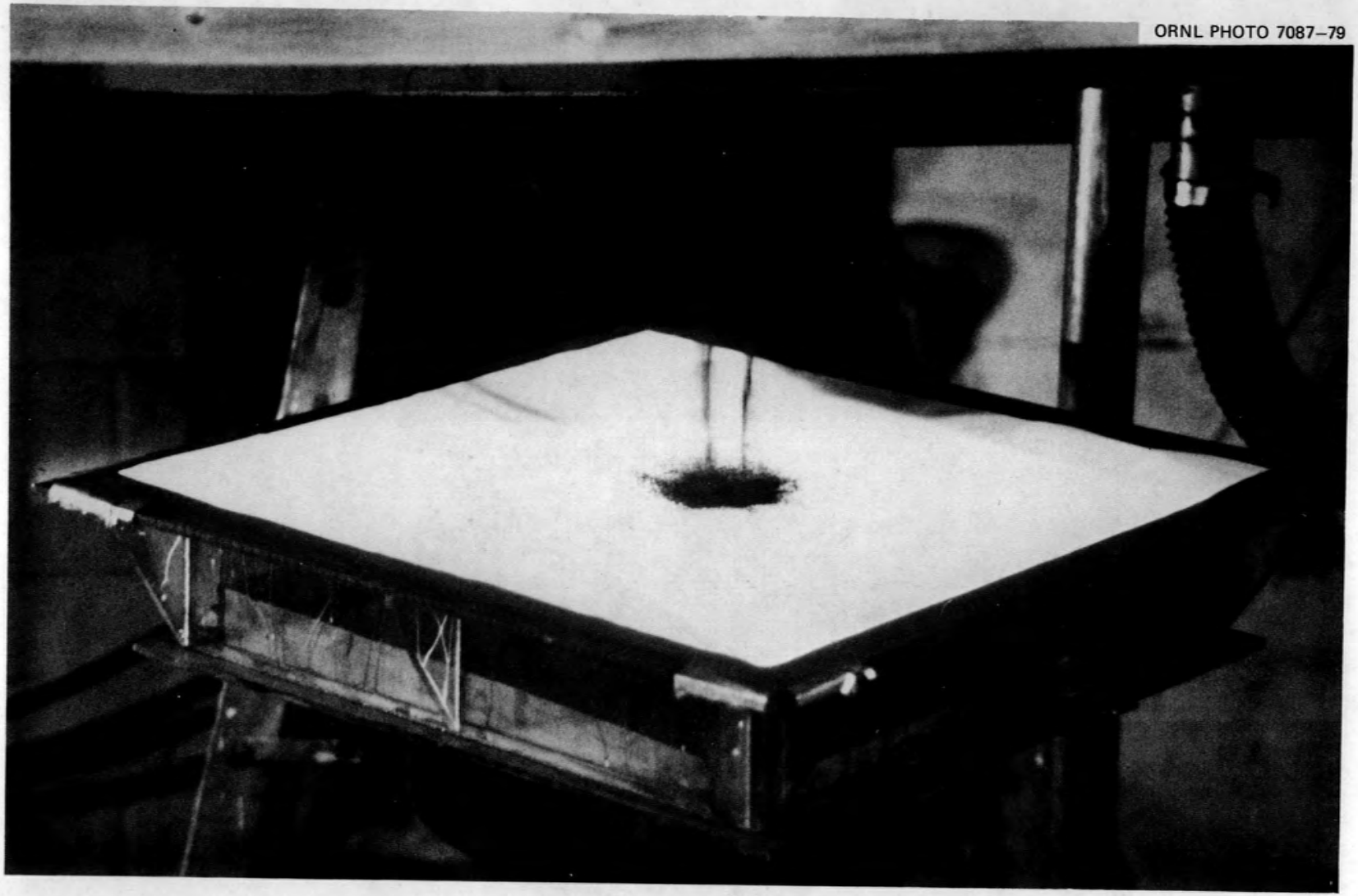

Fig. 5. Release of inorganics.

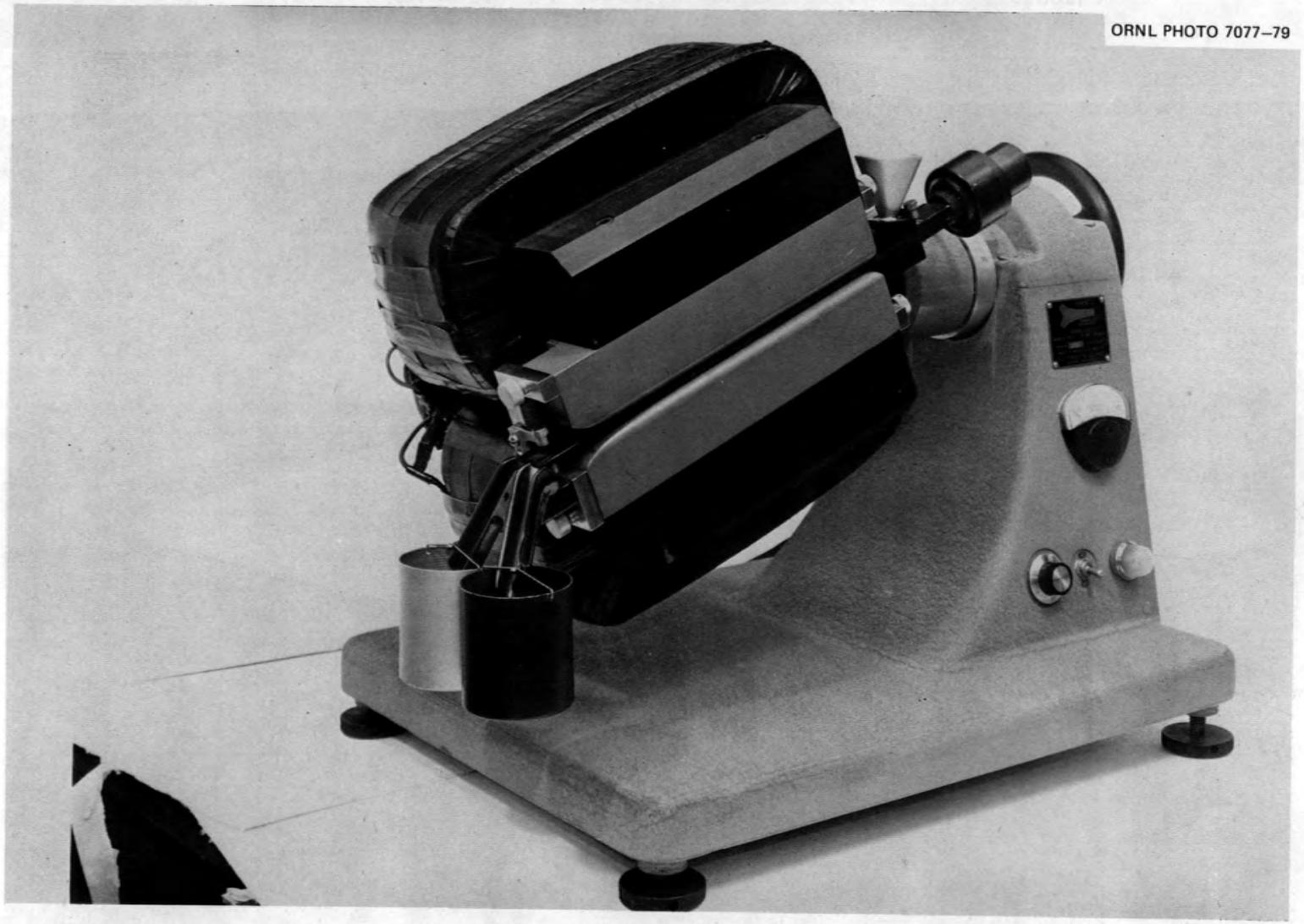

Fig. 6. Open-gradient magnetic separator vibrating-tray transport.

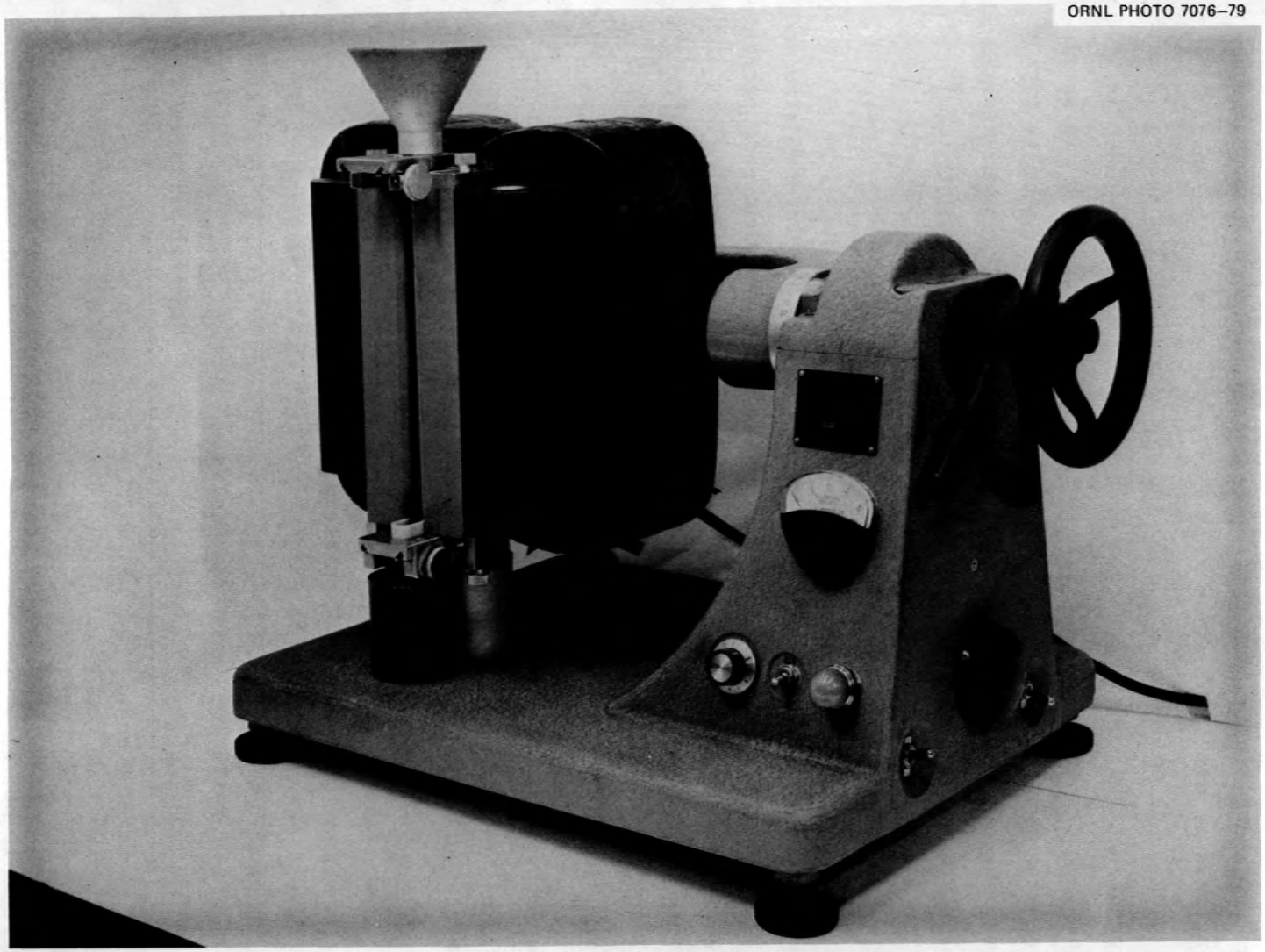

Fig. 7. Open-gradient magnetic separator free-fall transport.

2.4 Coal Sampling

The coal used in all reported tests is Western Kentucky seam No. 9 from Muhlenberg County, Kentucky. The samples were collected in different ways at different times from different parts of the seam. The Bureau of Mines collected a 600-lb channel sample by a standard face sample procedure that ensures no contamination of the coal by material from the roof and floor. The Sala tests were performed on a 1000-lb sample of run-of-mine coal as delivered to the Tennessee Valley Authority (TVA) steam plant at Paradise, Kentucky. ORNL used a 300-lb run-of-mine sample similarly supplied from the TVA Paradise plant.

2.5 The Coal Preparation

The Bureau of Mines sample was jaw-crushed to 3/8-in. top size and then hammer-milled to a 14-mesh top size. The separations were performed on the entire 14 mesh × 0 size fraction.

The coal prepared by Sala was jaw-crushed and roller-milled to a 24-mesh top size. This 24 mesh × 0 material was classified in a centrifugal air separator into five size fractions. The weight distribution between those five fractions is given in Table 1; standard sizes are given in Table 2 for reader convenience. The magnetic separations performed on the −24 +100 mesh fraction are reported.

Table 1. Particle size distribution of Kentucky No. 9 ground at −24 mesh

Particle size	Analysis (wt %)	Weight percent obtained in classification
−24 +100 mesh	76.9	76.9
−100 +200 mesh	11.9	11.9
−200 +325 mesh	5.1	5.1
−325 mesh + 10 μm	4.0	4.1
−10 μm	2.1	2.0

Table 2. U.S. sieve series and Tyler equivalents (A.S.T.M. E-11-61)

Sieve designation		Sieve opening		Nominal wire diam.		Tyler equivalent designation
Standard	Alternate	mm.	in. (approx. equivalents)	mm.	in. (approx. equivalents)	
107.6 mm.	4.24 in.	107.6	4.24	6.40	0.2520	
101.6 mm.	4 in.†	101.6	4.00	6.30	.2480	
90.5 mm.	3½ in.	90.5	3.50	6.08	.2394	
76.1 mm.	3 in.	76.1	3.00	5.80	.2283	
64.0 mm.	2½ in.	64.0	2.50	5.50	.2165	
53.8 mm.	2.12 in.	53.8	2.12	5.15	.2028	
50.8 mm.	2 in.†	50.8	2.00	5.05	.1988	
45.3 mm.	1¾ in.	45.3	1.75	4.85	.1909	
38.1 mm.	1½ in.	38.1	1.50	4.59	.1807	
32.0 mm.	1¼ in.	32.0	1.25	4.23	.1665	
26.9 mm.	1.06 in.	26.9	1.06	3.90	.1535	1.050 in.
25.4 mm.	1 in.†	25.4	1.00	3.80	.1496	
22.6 mm.*	⅞ in.	22.6	0.875	3.50	.1378	0.883 in.
19.0 mm.	¾ in.	19.0	.750	3.30	.1299	.742 in.
16.0 mm.*	⅝ in.	16.0	.625	3.00	.1181	.624 in.
13.5 mm.	0.530 in.	13.5	.530	2.75	.1083	.525 in.
12.7 mm.	½ in.†	12.7	.500	2.67	.1051	
11.2 mm.*	7/16 in.	11.2	.438	2.45	.0965	.441 in.
9.51 mm.	⅜ in.	9.51	.375	2.27	.0894	.371 in.
8.00 mm.*	5/16 in.	8.00	.312	2.07	.0815	2½ mesh
6.73 mm.	0.265 in.	6.73	.265	1.87	.0736	3 mesh
6.35 mm.	¼ in.†	6.35	.250	1.82	.0717	
5.66 mm.*	No. 3½	5.66	.223	1.68	.0661	3½ mesh
4.76 mm.	No. 4	4.76	.187	1.54	.0606	4 mesh
4.00 mm.*	No. 5	4.00	.157	1.37	.0539	5 mesh
3.36 mm.	No. 6	3.36	.132	1.23	.0484	6 mesh
2.83 mm.*	No. 7	2.83	.111	1.10	.0430	7 mesh
2.38 mm.	No. 8	2.38	.0937	1.00	.0394	8 mesh
2.00 mm.*	No. 10	2.00	.0787	0.900	.0354	9 mesh
1.68 mm.	No. 12	1.68	.0661	.810	.0319	10 mesh
1.41 mm.*	No. 14	1.41	.0555	.725	.0285	12 mesh
1.19 mm.	No. 16	1.19	.0469	.650	.0256	14 mesh
1.00 mm.*	No. 18	1.00	.0394	.580	.0228	16 mesh
841 micron	No. 20	0.841	.0331	.510	.0201	20 mesh
707 micron*	No. 25	.707	.0278	.450	.0177	24 mesh
595 micron	No. 30	.595	.0234	.390	.0154	28 mesh
500 micron*	No. 35	.500	.0197	.340	.0134	32 mesh
420 micron	No. 40	.420	.0165	.290	.0114	35 mesh
354 micron*	No. 45	.354	.0139	.247	.0097	42 mesh
297 micron	No. 50	.297	.0117	.215	.0085	48 mesh
250 micron*	No. 60	.250	.0098	.180	.0071	60 mesh
210 micron	No. 70	.210	.0083	.152	.0060	65 mesh
177 micron*	No. 80	.177	.0070	.131	.0052	80 mesh
149 micron	No. 100	.149	.0059	.110	.0043	100 mesh
125 micron*	No. 120	.125	.0049	.091	.0036	115 mesh
105 micron	No. 140	.105	.0041	.076	.0030	150 mesh
88 micron*	No. 170	.088	.0035	.064	.0025	170 mesh
74 micron	No. 200	.074	.0029	.053	.0021	200 mesh
63 micron*	No. 230	.063	.0025	.044	.0017	250 mesh
53 micron	No. 270	.053	.0021	.037	.0015	270 mesh
44 micron*	No. 325	.044	.0017	.030	.0012	325 mesh
37 micron	No. 400	.037	.0015	.025	.0010	400 mesh

*These sieves correspond to those proposed as an international (I.S.O.) standard. It is recommended that wherever possible these sieves be included in all sieve analysis data or reports intended for international publication.

†These sieves are not in the fourth-root-of-2 series, but they have been included because they are in common usage.

The coal prepared by ORNL was jaw-crushed to a 16-mesh top size and classified into size fractions by sieving. The specific gravity and the magnetic separations performed on the −30 +100 fraction are reported.

For both the Sala and ORNL coal samples, separations were performed on the remaining size fractions down to 10 μm and are reported elsewhere.[1] For all magnetic separations, the <10-μm fraction had to be removed to obtain a satisfactory separation.

3. DATA SOURCES AND SELECTION

This correlation draws on the data from experiments and measurements performed by several experimenters using different types of equipment.

3.1 Specific-Gravity Separation by the Bureau of Mines

The Bureau of Mines RI 8118 (Ref. 2) reports on the specific-gravity separations of three size fractions (1 1/2 in. × 100 mesh, 3/8 in. × 100 mesh, and 14 mesh × 0) of various coals. This comprehensive test program is being conducted to determine the sulfur reduction potential of the coals of the United States. A typical data summary from that report is presented in Table 3. The data for the 14 mesh × 0 fraction of the Western Kentucky seam No. 9, Muhlenberg County, are extracted from that report as appropriate data for correlation with the other experiments.

3.2 HGMS by Sala

The test series performed by Sala Magnetics under contract to ORNL tested a Lower Freeport and the Kentucky No. 9 in a high-gradient magnetic separator over a broad range of the parameters of superficial velocity, transport mode, matrix configuration, magnetic field strength, and size fraction, using both air and water as the transport media. The objectives of these tests were to determine if acceptable separations of dry pulverized coal could be achieved by HGMS and, if so, at what specific conditions. A typical data summary from that test series is presented in Table 4. The data for the −24 +100 mesh size fraction of the Kentucky No. 9 were selected as appropriate data for correlation with the other experiments, and the satisfactory points were chosen from that data (shown in Table 4) because the purpose of those exploratory tests was to identify successful operating conditions.

3.3 Specific-Gravity and Open-Gradient Separation by ORNL

The ORNL test program has separated various size fractions of several coals by specific gravity and by OGMS in two transport modes to

Table 3. Data sheet from Bureau of Mines RI 8118 (Ref. 2)

STATE: KENTUCKY (WEST)
COUNTY: MUHLENBURG

COALBED: NO. 9
RAW COAL MOISTURE: 6.4 %

CUMULATIVE WASHABILITY DATA

SAMPLE CRUSHED TO PASS 1-1/2 INCHES

PRODUCT	RECOVERY,% WEIGHT	RECOVERY,% BTU	BTU/LB	ASH,%	SULFUR,% PYRITIC	SULFUR,% TOTAL	LB SO2/M BTU
FLOAT-1.30	45.8	48.3	13732	4.1	.68	2.73	4.0
FLOAT-1.40	88.7	91.5	13446	6.1	1.00	3.07	4.6
FLOAT-1.60	94.7	97.0	13345	6.8	1.27	3.41	5.1
FLOAT-1.90	96.0	98.0	13302	7.1	1.41	3.57	5.4
TOTAL	100.0	100.0	13030	9.0	2.19	4.33	6.6
EPA STANDARD	*****	*****	*****	*****	*****	*****	1.20

SAMPLE CRUSHED TO PASS 3/8 INCH

PRODUCT	RECOVERY,% WEIGHT	RECOVERY,% BTU	BTU/LB	ASH,%	SULFUR,% PYRITIC	SULFUR,% TOTAL	LB SO2/M BTU
FLOAT-1.30	50.2	53.4	13889	3.0	.42	2.45	3.5
FLOAT-1.40	86.4	89.9	13589	5.1	.77	2.81	4.1
FLOAT-1.60	93.7	96.6	13460	6.0	1.05	3.13	4.7
FLOAT-1.90	95.2	97.7	13403	6.4	1.19	3.30	4.9
TOTAL	100.0	100.0	13059	8.8	2.21	4.36	6.7
EPA STANDARD	*****	*****	*****	*****	*****	*****	1.20

SAMPLE CRUSHED TO PASS 14 MESH

PRODUCT	RECOVERY,% WEIGHT	RECOVERY,% BTU	BTU/LB	ASH,%	SULFUR,% PYRITIC	SULFUR,% TOTAL	LB SO2/M BTU
FLOAT-1.30	43.4	46.4	13904	2.9	.40	2.40	3.5
FLOAT-1.40	84.4	88.3	13603	5.0	.73	2.75	4.0
FLOAT-1.60	93.3	96.5	13446	6.1	.99	3.03	4.5
FLOAT-1.90	95.1	97.8	13374	6.6	1.15	3.22	4.8
TOTAL	100.0	100.0	13002	9.2	2.21	4.34	6.7
EPA STANDARD	*****	*****	*****	*****	*****	*****	1.20

STATE: KENTUCKY (WEST)
COUNTY: OHIO

COALBED: NO. 9
RAW COAL MOISTURE: 5.3 %

CUMULATIVE WASHABILITY DATA

SAMPLE CRUSHED TO PASS 1-1/2 INCHES

PRODUCT	RECOVERY,% WEIGHT	RECOVERY,% BTU	BTU/LB	ASH,%	SULFUR,% PYRITIC	SULFUR,% TOTAL	LB SO2/M BTU
FLOAT-1.30	57.4	60.0	13697	4.2	.58	2.65	3.9
FLOAT-1.40	89.8	91.5	13342	6.5	1.03	3.07	4.6
FLOAT-1.60	98.2	98.8	13172	7.6	1.40	3.44	5.2
TOTAL	100.0	100.0	13095	8.1	1.60	3.63	5.5
EPA STANDARD	*****	*****	*****	*****	*****	*****	1.20

SAMPLE CRUSHED TO PASS 3/8 INCH

PRODUCT	RECOVERY,% WEIGHT	RECOVERY,% BTU	BTU/LB	ASH,%	SULFUR,% PYRITIC	SULFUR,% TOTAL	LB SO2/M BTU
FLOAT-1.30	61.2	64.4	13728	4.0	.56	2.68	3.9
FLOAT-1.40	87.4	90.0	13434	5.9	.90	3.00	4.5
FLOAT-1.60	96.5	97.8	13218	7.3	1.23	3.31	5.0
TOTAL	100.0	100.0	13049	8.4	1.63	3.72	5.7
EPA STANDARD	*****	*****	*****	*****	*****	*****	1.20

SAMPLE CRUSHED TO PASS 14 MESH

PRODUCT	RECOVERY,% WEIGHT	RECOVERY,% BTU	BTU/LB	ASH,%	SULFUR,% PYRITIC	SULFUR,% TOTAL	LB SO2/M BTU
FLOAT-1.30	49.7	52.5	13805	3.5	.71	2.73	4.0
FLOAT-1.40	85.1	87.9	13512	5.4	.82	2.87	4.2
FLOAT-1.60	95.8	97.4	13296	6.8	1.11	3.11	4.7
TOTAL	100.0	100.0	13080	8.2	1.61	3.60	5.5
EPA STANDARD	*****	*****	*****	*****	*****	*****	1.20

Table 4. Typical data summary from Sala test series

HIGH GRADIENT MAGNETIC SEPARATIONS

MATRIX #	FLOW TYPE	FIELD STRENGTH	TRANSPORT VELOCITY	% WEIGHT MAGNETICS	% SULFUR MAGNETICS	% SULFUR PRODUCTS	% ASH MAGNETICS	% ASH PRODUCTS	% BTU RECOVERY	% SULFUR REDUCTION	% ASH REDUCTION	SAMPLE WEIGHT
31	W	20.0	30	25.9	5.4	2.9	45.1	8.1	87.2	27.4	59.3	47.1
31	W	20.0	20	32.4	4.5	2.7	38.8	7.8	81.6	26.7	61.4	47.1
31	W	20.0	50	18.0	5.9	2.9	51.7	9.3	92.4	23.8	50.3	47.0
31	W	20.0	40	22.0	5.0	2.9	48.6	9.1	89.8	22.6	54.1	47.4
31	W	9.0	40	17.8	5.8	3.0	53.5	9.8	92.8	22.3	49.6	47.7
59	W	20.0	40	26.8	4.7	2.9	35.4	7.7	84.0	22.0	53.5	46.5
59	D	20.0	50	16.2	5.7	3.0	51.0	8.6	93.0	19.9	49.1	190.9
31	W	13.8	20	26.7	4.4	3.1	40.9	8.6	85.4	19.8	55.1	47.2
59	D	20.0	92	14.4	5.7	3.0	52.3	10.6	93.9	18.4	40.8	191.1
31	W	9.0	20	23.7	4.9	3.3	41.9	9.2	87.4	18.2	50.6	47.8
59	W	20.0	60	21.2	4.7	3.1	41.8	8.2	88.7	17.6	50.9	47.1
31	W	13.8	40	19.1	4.6	3.3	51.7	9.1	91.6	16.0	52.3	47.6
31	W	9.0	30	20.3	4.3	3.3	48.9	9.3	90.5	15.0	51.5	47.4
59	D	20.0	150	12.2	5.2	3.2	59.2	11.6	95.6	13.7	38.0	190.1
59	W	20.0	80	17.8	4.5	3.3	45.6	8.6	91.1	13.3	47.6	47.3
59	D	20.0	200	10.9	4.7	3.2	63.1	10.3	96.5	11.5	40.1	190.0
31	W	13.8	30	22.3	3.8	3.5	46.6	8.7	88.9	11.2	54.0	47.4
31	D	20.0	50	13.6	4.1	3.7	54.2	10.6	94.3	8.4	40.5	192.5
31	D	20.0	92	13.7	3.9	3.5	53.2	10.4	94.1	8.4	40.4	191.7
31	D	13.8	92	12.3	3.2	3.5	53.4	10.0	94.7	4.5	38.6	190.8
31	D	13.8	50	13.1	3.2	3.8	50.6	8.4	93.9	4.3	43.6	190.8
31	D	20.0	300	9.8	3.1	3.8	59.2	12.6	96.3	3.8	30.4	194.5
31	D	9.0	50	7.3	3.0	3.5	64.6	11.7	97.6	3.4	28.2	193.4
31	D	13.8	300	7.2	2.8	3.9	52.3	14.9	96.8	1.3	17.9	193.9

COAL - NAME: KENTUCKY #9
GRIND: 24 SIZE: 24-100
FEED ANALYSIS - TS: 3.62% PS: 1.37% ASH: 16.99%

(1) examine the separability of coals, (2) quantify the influence of particle size, and (3) establish the separation potential of OGMS. From these tests, the −30 +100 mesh size fraction of the Kentucky No. 9 coal was chosen for correlation with the other experiments.

4. DATA PRESENTATION AND DISCUSSION

The data obtained are examined in two ways. First, the results for each separation method are plotted as a function of the controlling independent variable for that method to show the response of the separation to the independent variable. Second, the results from all methods are normalized to the common dependent variable of Btu recovery, and the product sulfur and product ash are each plotted against Btu recovery to correlate the several methods on a common basis.

4.1 Independent-Variable Plots

4.1.1 Specific-gravity separation

The specific-gravity separations performed at the Bureau of Mines and at ORNL are both displayed in Fig. 8, with the weight percent of sinks, the product sulfur, and the product ash each plotted separately against the independent variable of the specific gravity of the separating media. Clearly, for this size fraction of this specific coal, the inorganics are not completely liberated; otherwise, the weight percent of sinks would be nearly constant over the range of specific gravity of 1.4 to 1.9.

4.1.2 HGMS

Data from the HGMSs performed at Sala are graphed in Fig. 9 as the weight percent of material trapped in the magnetic matrix, the product sulfur, and the product ash vs the independent variable of the superficial transport velocity with the other independent variables being constant. The response to the competing forces of fluid drag and magnetic attraction and, at very low velocities, of the third factor of mechanical entrapment can be seen.

4.1.3 OGMS with vibrating-tray transport

The OGMSs with vibrating-tray transport are displayed in Fig. 10, with the weight percent reporting to the magnetic fraction, the product

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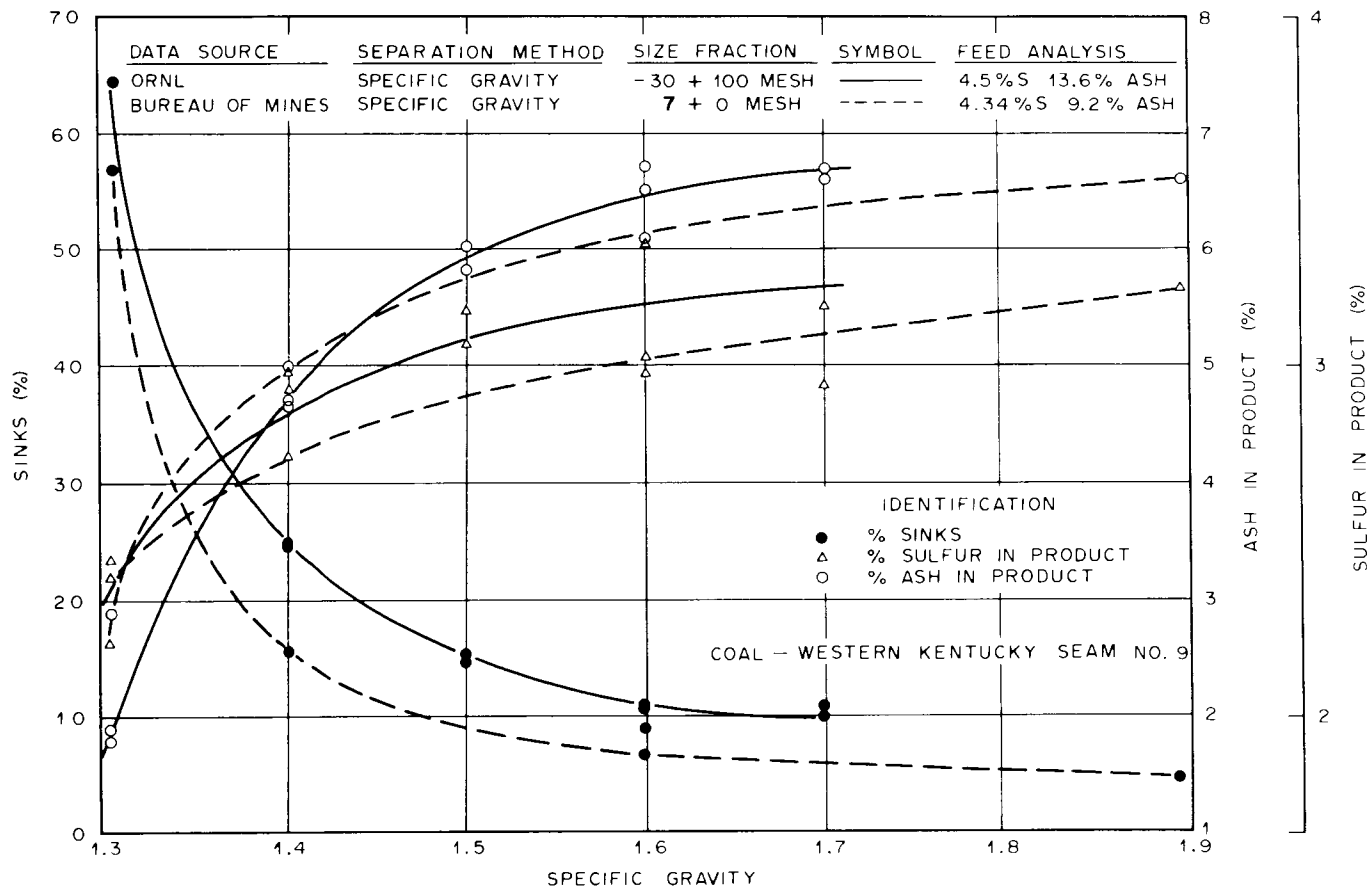

Fig. 8. Specific-gravity separations.

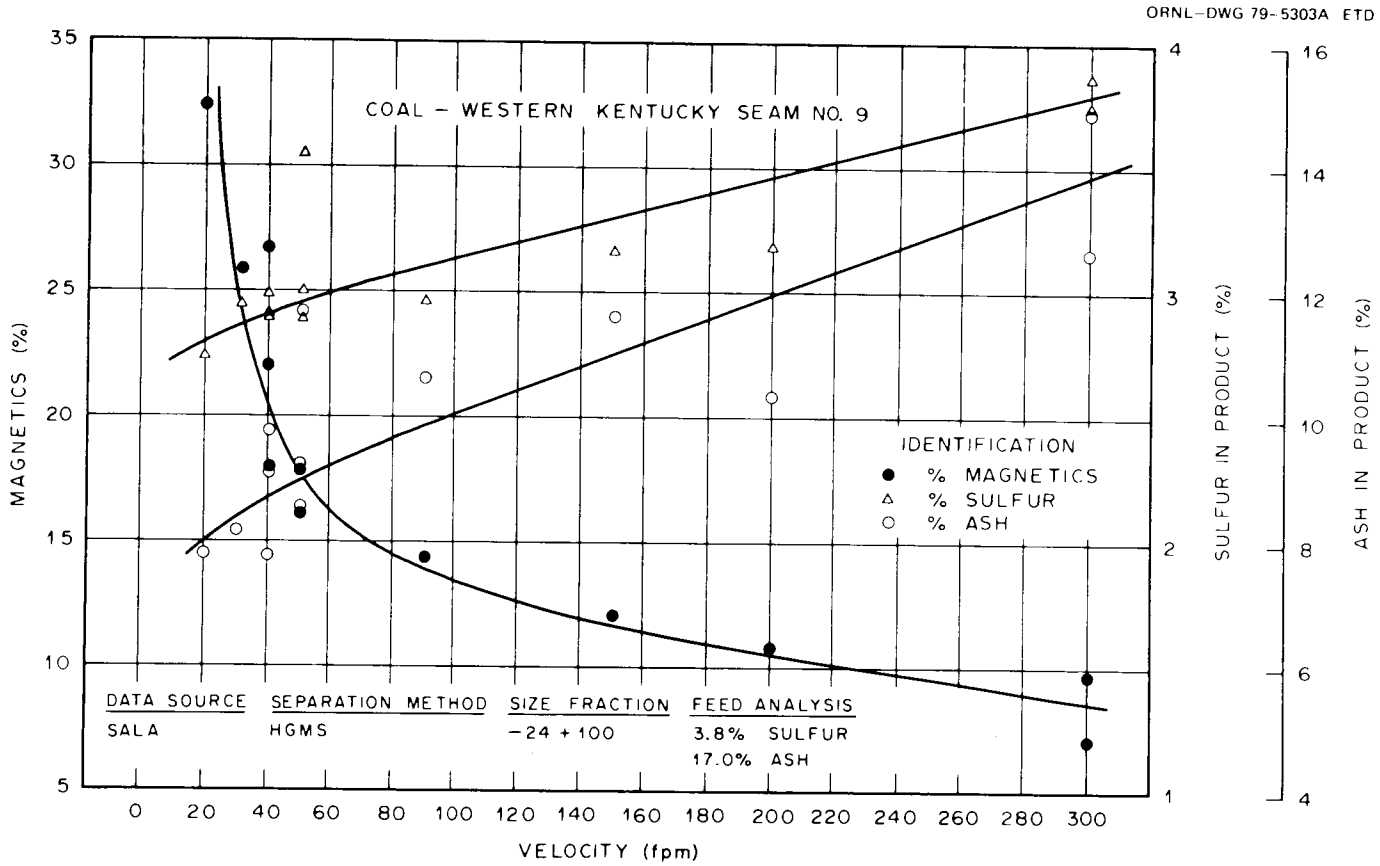

Fig. 9. High-gradient magnetic separations (HGMSs).

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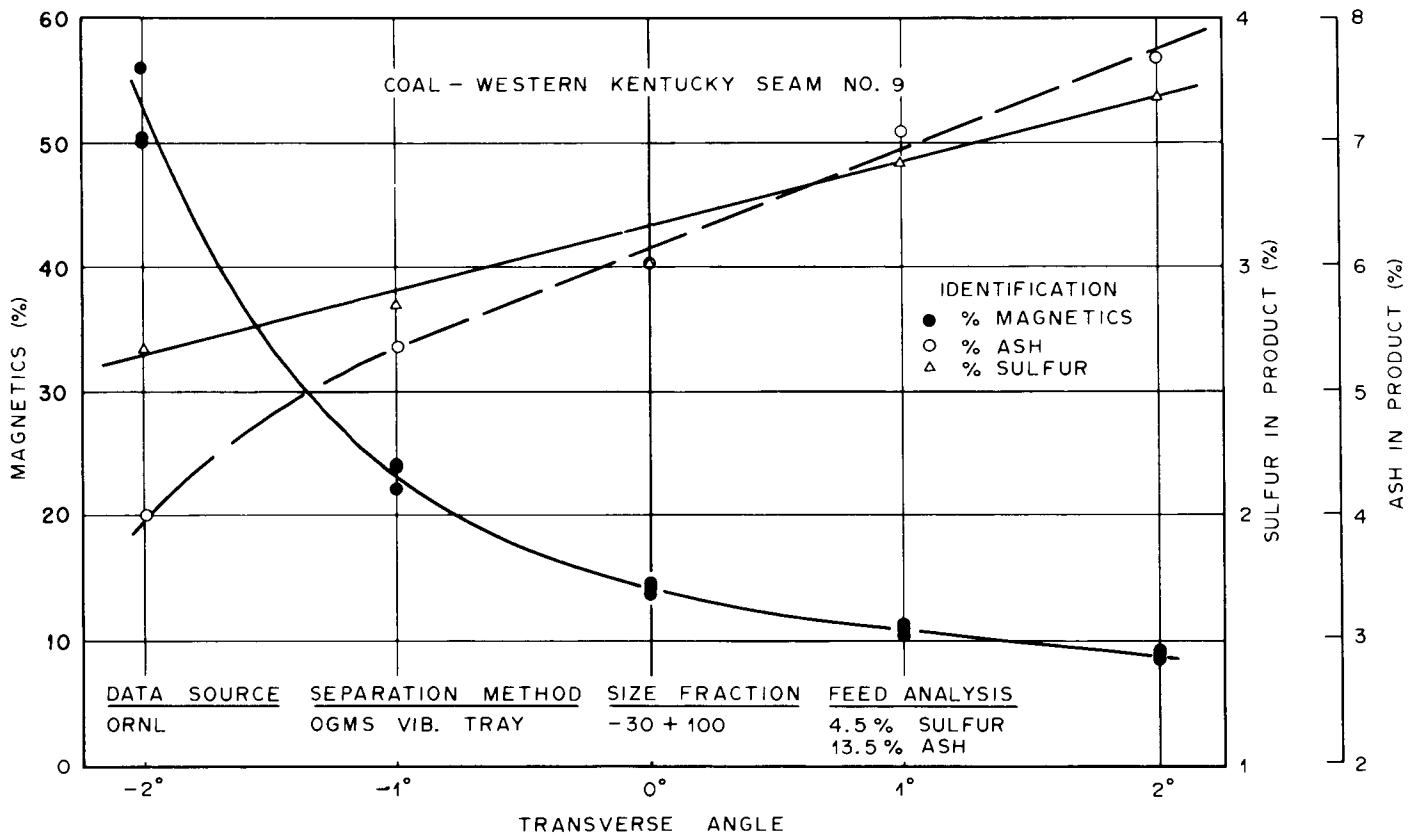

Fig. 10. Open-gradient separations with vibrating-tray transport.

sulfur, and the product ash plotted against the independent variable of the transverse angle.

Note that positive transverse angle separation requires that the paramagnetic material be deflected against gravity, while the nonmagnetic and diamagnetic fractions are deflected with gravity. A zero transverse angle separation requires that the paramagnetic material be deflected toward increasing field strength and the diamagnetic material be deflected away from increasing field strength with no influence by gravity, while the nonmagnetic fraction randomly distributes itself across the tray. In a negative transverse angle separation, the paramagnetic and nonmagnetic fractions are deflected with gravity, while the diamagnetic material is deflected against gravity.

The remarkably repeatable separations at a zero transverse angle support the argument that there is very little random effect and, therefore, very little truly nonmagnetic material. Rather, there appears to be a continuous spectrum of magnetic susceptibility from some positive to some negative value. Further, the repeatable separations accomplished at a negative transverse angle indicate that those separations are being accomplished on the basis of the negative susceptibility of the coal, as opposed to the positive susceptibility of the inorganics. The literature values for the susceptibilities of the coal and the inorganic constituents indicate that the forces exerted on coal and pyrites are approximately equal in magnitude but opposite in direction.

In these open-gradient separations, it is again evident that the inorganics are not fully liberated from this particular coal crushed to this size. For instance, of the material having an adequate negative susceptibility to be displaced against gravity up to a 1° slope, only about half was displaced up to a 2° slope. The other half presumably contains enough positive susceptibility and/or higher-specific-gravity material to prevent its being displaced against the 2° slope. The sulfur and ash content of the product coal from the separations at −1 and −2° bear the same testimony. One of the more easily observed forms of coal containing dispersed inorganics is the fusinite, a charcoal-like fraction that clearly shows the residual cell wall structure. Frequently, the voids in these vestigial cells contain inorganic deposits. Figure 11 pictures such a

Fig. 11. Fusinite with pyrite deposits, magnification = 100.

particle, and it is shown in Fig. 12 at a higher magnification, revealing the cell wall structure and the deposited pyrite crystals ranging from about 5 μm down in size. Fusinite particles such as these will appear in either the product or magnetic fraction as a function of their relative inorganic content and the separation process parameters.

4.1.4 OGMS with free-fall transport

If the crushed coal is permitted to fall freely through an appropriate magnetic field, the various constituents should be deflected in a direction and amount related to the susceptibility of each, and the falling stream should be spread into a susceptibility spectrum. If the buckets and flow splitters are removed from the bottom of the machine pictured in Fig. 7, one can look in from the left side and view the falling stream of coal exiting the magnet pole pieces, as shown in Figs. 13 and 14. The falling coal stream is continuous, but only the illuminated portion is visible. The grid divisions are 0.1 in. In Fig. 13, the magnet is off, and the stream is falling vertically with some scatter because of air drag and particle collisions. In Fig. 14, the magnet is on, and the force exerted by the shaped magnetic field deflects the particles from vertical fall as a function of their positive or negative magnetic susceptibility, thus spreading the stream into a band about 1.4 in. wide. The bulk of the stream is relatively clean coal with a negative susceptibility, and it is deflected down gradient (to the left) 0.2 to 0.3 in.

The results of some open-gradient separations performed in free-fall transport are given in Fig. 15, with the weight percent of the fraction reporting to the magnetic collection, the product sulfur, and the product ash being plotted against the independent variable of the linear displacement (in mm) of the flow splitter on either side of the center line of an undeflected fall. The center line was determined by physical measurement and confirmed by observing the collection of equal fractions of "magnetic" and "nonmagnetic" particles when feeding a sample with the magnet off. The data argue that the falling stream is, indeed, spread into a spectrum from strongest negative susceptibility to strongest positive susceptibility and that the stream can be split at any point by the location of the splitter. These separations have been made only recently, and too few of

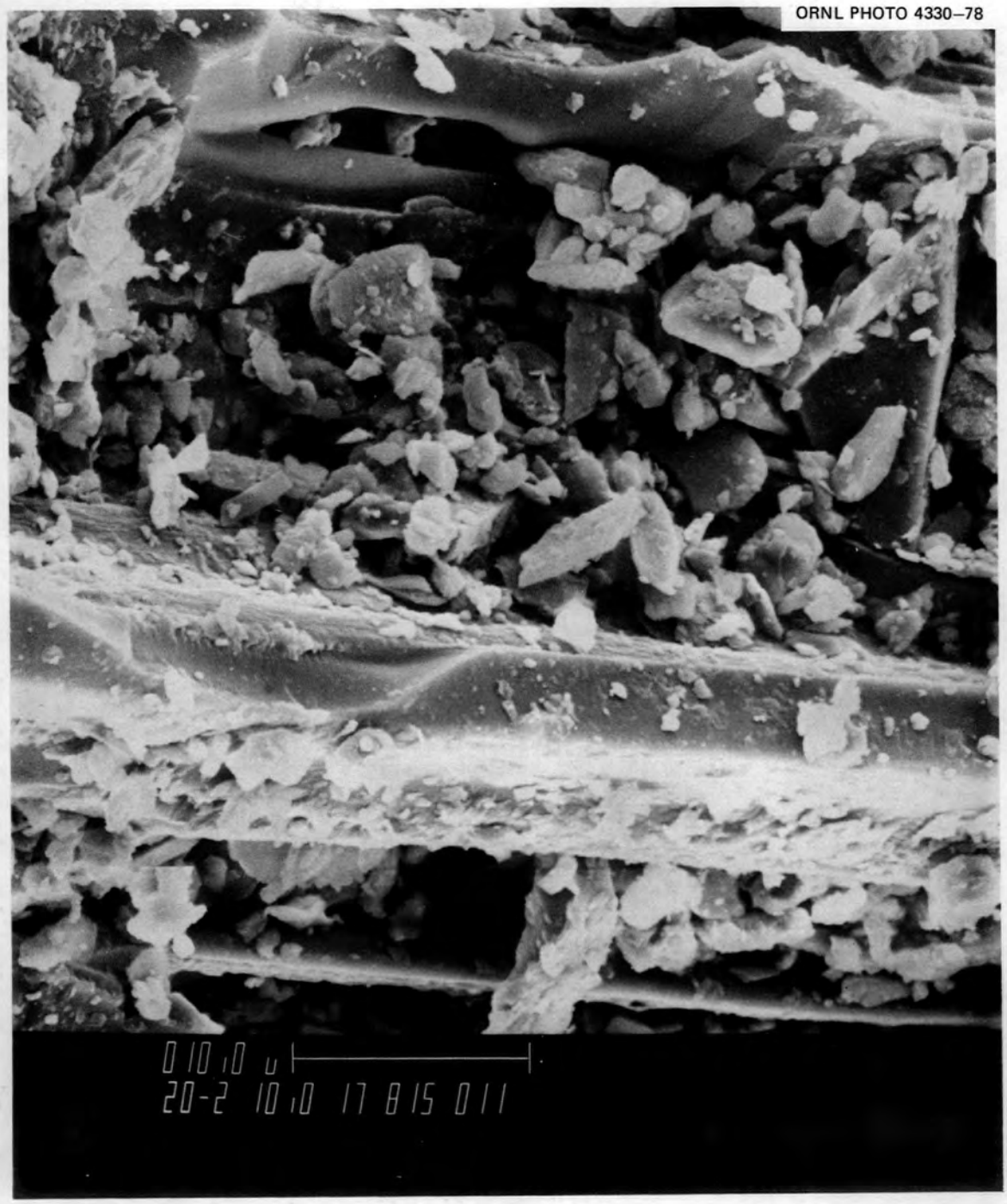

Fig. 12. Fusinite with pyrite deposits, magnification = 2000.

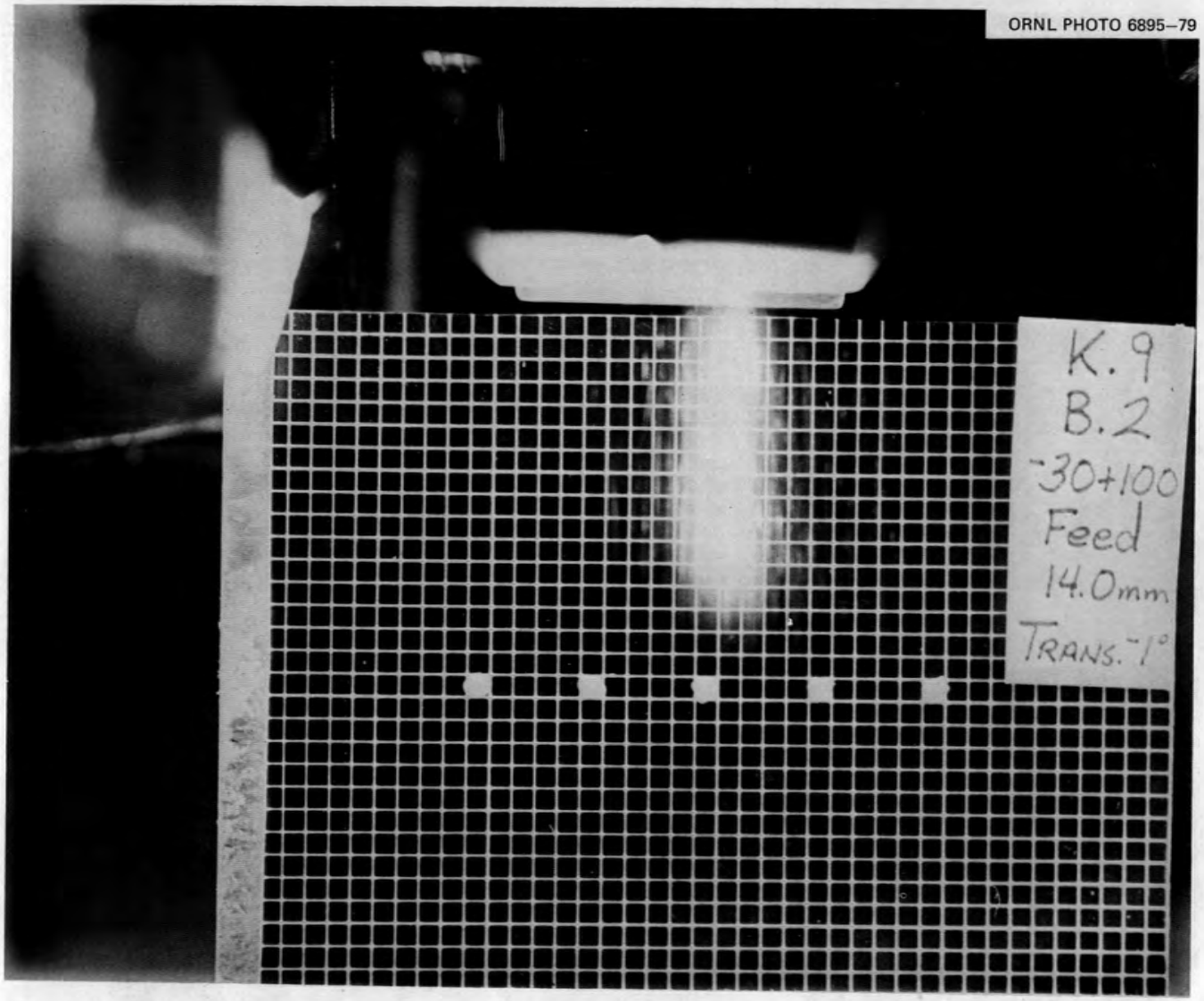

Fig. 13. Free-fall OGMS (magnet off).

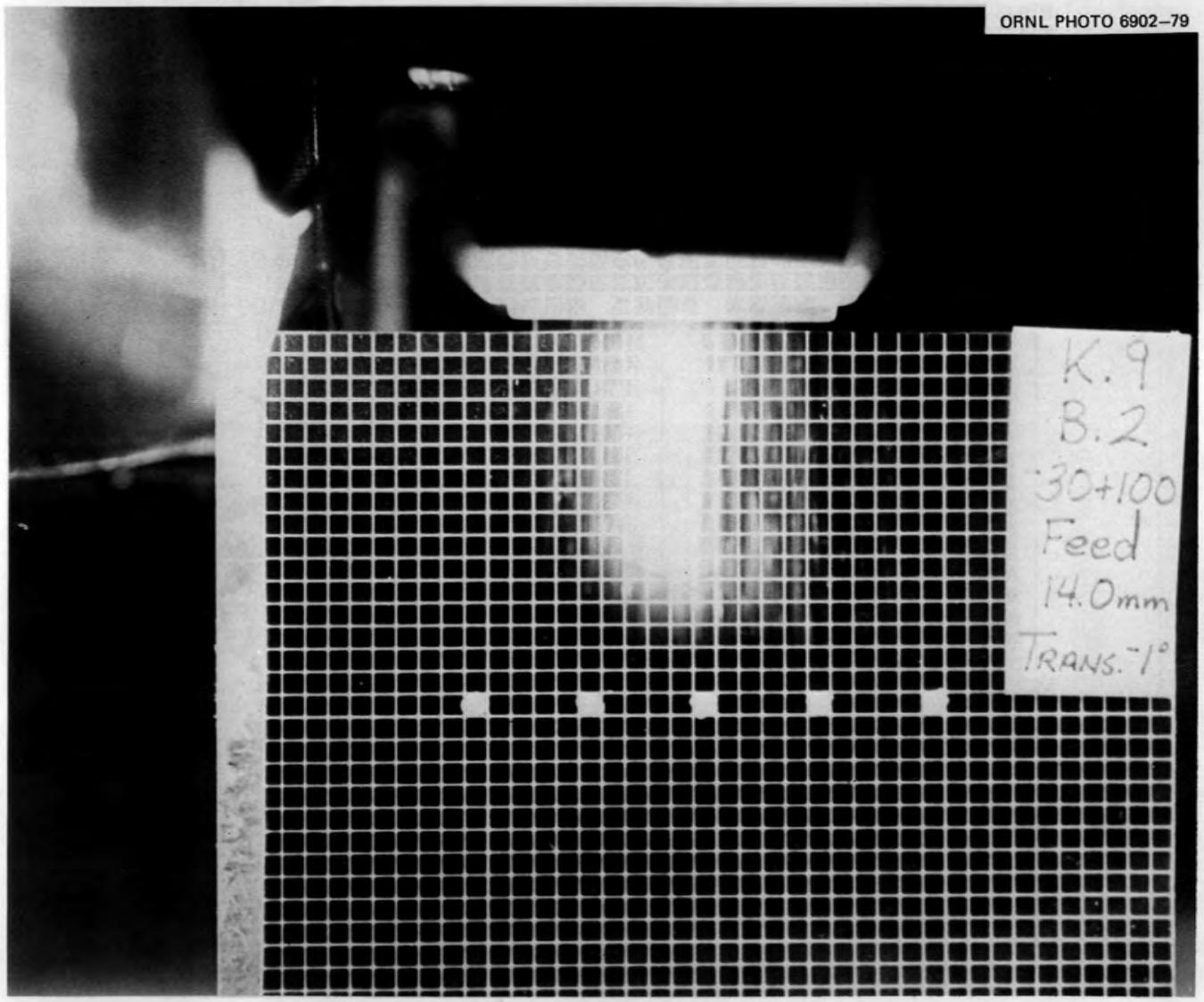

Fig. 14. Free-fall OGMS (magnet on).

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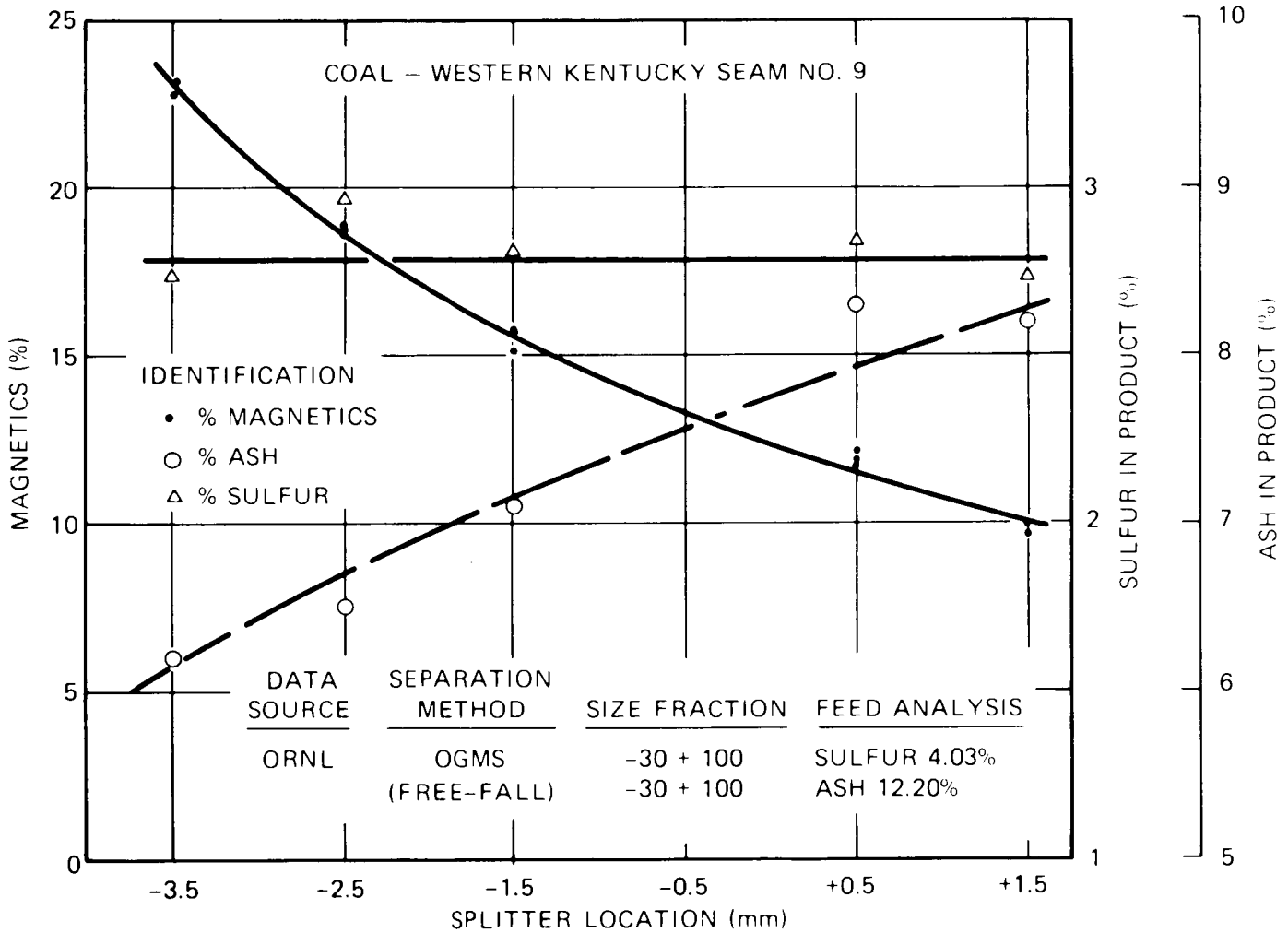

Fig. 15. Open-gradient separation free-fall transport.

them have been performed to completely explore the whole range of the spectrum. It does appear, however, that over the range of splitter locations from 3.5 mm down gradient to 1.5 mm up gradient from the vertical free-fall line, the pyrite removal is constant. Thus, it appears that all liberated pyrite is being deflected further up gradient than 1.5 mm and that, therefore, it all has a positive susceptibility greater than the value required for this deflection. Conversely, the ash shows an almost linear spectrum of susceptibility over the range of deflections tested. A comparison of the magnetic separation in Fig. 15 and the ORNL specific-gravity separation in Fig. 8 shows an interesting difference in the selectivity of the two separations. The magnetic separation achieved a product sulfur of about 2.75% at about a 10% weight removal, while the specific-gravity separation achieves the 2.75% product sulfur at about a 27% weight removal. Conversely, the specific gravity achieved about a 6.5% product ash at about an 11% weight removal, while the magnetic achieved the 6.5% product ash at a 20% weight removal.

4.2 Dependent Variable Plots

The product sulfur content is plotted against the common dependent variable of Btu recovery in Fig. 16, and product ash is plotted against Btu recovery in Fig. 17 for all of the separations. From these two plots, a number of observations can be made.

4.2.1 Coal sampling

The samples for the several tests were obtained at different times, by different methods, and from different locations in the seam, resulting in slightly different sulfur content and widely different ash content of the raw sample; however, the shapes of the curves for all processes are virtually identical. Most notably, the curves for ash, which start at quite different values, rapidly converge to essentially the same value (with the exception of HGMS, which is discussed later). This rapid convergence probably occurs because the higher ash content of the run-of-mine samples, as opposed to the carefully removed face sample, was not inherent

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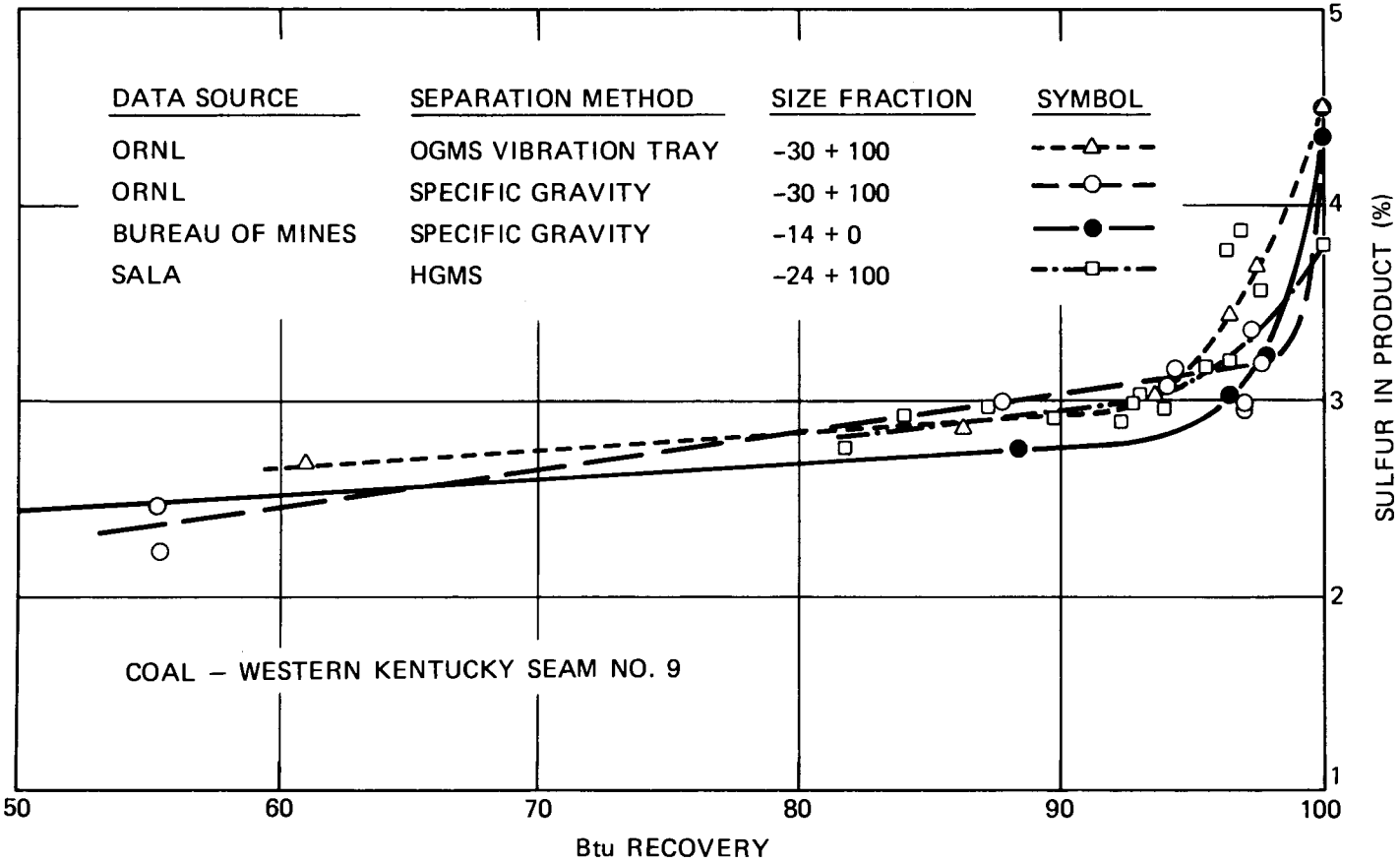

Fig. 16. Product sulfur vs Btu recovery.

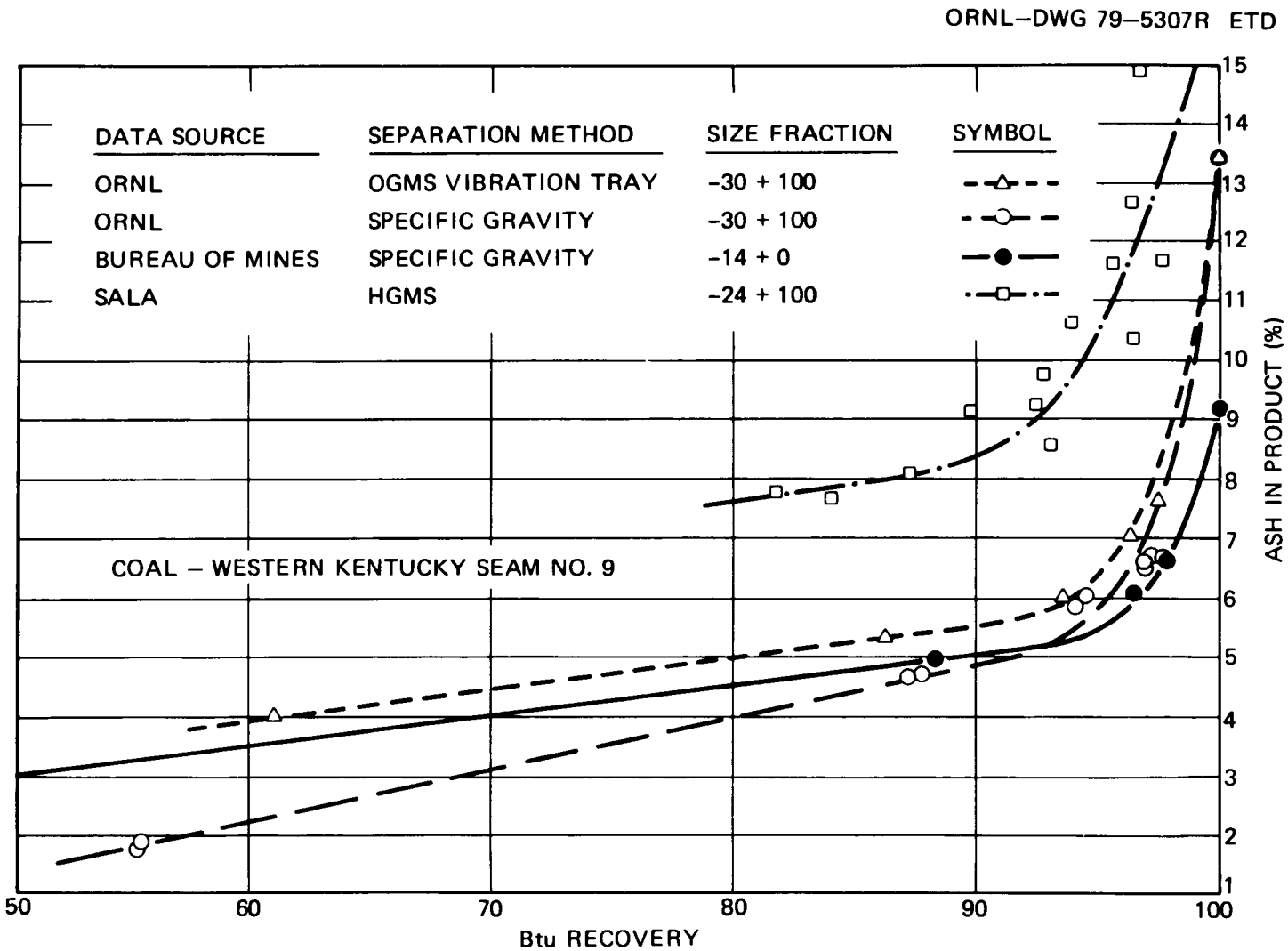

Fig. 17. Product ash vs Btu recovery.

to the seam, was already liberated from the coal, and separated immediately. While a precise correlation of the several separation methods would be best achieved using a single, uniform sample, it does not appear that the validity of the correlation is appreciably marred by the divergent samples.

4.2.2 Size fraction

Both the sulfur and ash content curves are quite steep between 100 and 95% Btu recovery, break abruptly between about 95 and 93% Btu recovery, and exhibit a very flat slope past that. The inorganics removed in that steep slope from 100% down to about 93% Btu recovery were almost fully liberated and carried very little coal attached to them. The inorganics removed below 93% were not liberated and carried significant coal with them. Thus, it would appear that the nearly coincident curves for specific gravity and OGMS represent the limit of separation for this grind of this coal.

The inherent ash in the Bureau of Mines face sample was 9.2%; the ash remaining at 93% Btu recovery was about 5.3%. Thus, for the 14 × 0 sample, about 42% of the ash was liberated. The pyritic sulfur content of the Bureau of Mines face sample was 2.21% (with a total sulfur content of 4.34%). At 93% Btu recovery, the remaining pyritic sulfur was 0.88, indicating that about 60% of the pyritic sulfur had been liberated.

Extending these ORNL separation tests to size fractions larger and smaller than this −30 +100 mesh fraction is required to establish the limits of achievable separation as a function of the grind and/or particle size and to thereby obtain some of the information required for the design of an optimum coal-preparation plant flowsheet.

4.2.3 Separation methods

With respect to separation methods, it appears that either of the magnetic methods is able to achieve, for a given size fraction of dry coal, essentially the same sulfur reduction and Btu recovery as the specific-gravity separation method. Further, the OGMS can achieve essentially the same ash reduction and Btu recovery, while the HGMS may be

unable to achieve ash reductions comparable to the specific-gravity separation. The OGMS is capable of using (1) the magnetic attractive force exerted on particles having a positive susceptibility, (2) the magnetic repulsive force exerted on particles having a negative susceptibility, and (3) the gravitational force exerted on all particles to separate a stream of particles into a spectrum that can then be split at any desired point or points. The HGMS, however, is capable only of capturing those particles having an adequate positive susceptibility. Thus, it may be that the OGMS has the potential capability of performing more precise separations; Figs. 16 and 17 apparently confirm this speculation. The sulfur reduction vs Btu recovery is virtually identical to specific gravity for both HGMS and OGMS, but the ash reduction vs Btu recovery is virtually identical to specific gravity only for OGMS. The poorer performance of HGMS in ash reduction could occur because the separated sulfur compounds all exhibit approximately the same positive susceptibility, while the much wider variety of ash-forming inorganic compounds exhibits a spectrum of susceptibility from zero to some positive value.

The separations achieved in the batch-operation HGMS are expected to extrapolate directly to the continuous separation HGMS machine. A test of continuous separation at 1 ton per hour will be performed in the summer of 1979. HGMS machines capable of continuous processing at several hundred tons per hour are commercially available.

The author is unaware of any OGMS machine suited to production separation of dry crushed coal. Since OGMS is simpler in concept, more versatile in principle, and more successful in practice (at least in these tests) than HGMS, there is a strong incentive to develop a production OGMS machine.

5. CONCLUSIONS

As stated initially, only the first tests of a planned series are reported here; therefore, the conclusions are drawn from one size fraction of one coal. However, the internal consistency of the data and the degree of separation achieved by the several magnetic processes do warrant tentative conclusions.

1. The most meaningful measure of the efficiency of a separation process is the percentage of liberated minerals removed, as opposed to simply the percentage of minerals removed. The degree of liberation of minerals for a grind of a coal can be determined from the plots of the Btu recovery vs the sulfur and ash remaining in the product (Figs. 16 and 17) obtained by laboratory separations at specific gravities of 1.3, 1.4, 1.5, 1.6, and 1.7, or at transverse angles of +2, +1, 0, −1, and −2° in vibrating-tray feed OGMS. The efficiency of any other process can then be determined by comparing the plots obtained over the appropriate range of the controlling independent variable for that process with the specific gravity or OGMS.

2. Several magnetic processes have been shown to separate efficiently the liberated minerals from dry crushed coal.

The high-gradient magnetic separator can attract and retain the paramagnetic particles on the magnetized mesh. Production-scale machines suited for HGMS of dry crushed coal are commercially available.

The open-gradient magnetic separator can deflect both the diamagnetic and the paramagnetic particles in a freely falling stream of coal into a spectrum that can be split to separate the minerals from the clean coal. The process, as demonstrated on a laboratory scale, appears to be simple and efficient and, therefore, merits further development.

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