Figure 1

PDU H-COAL REACTOR

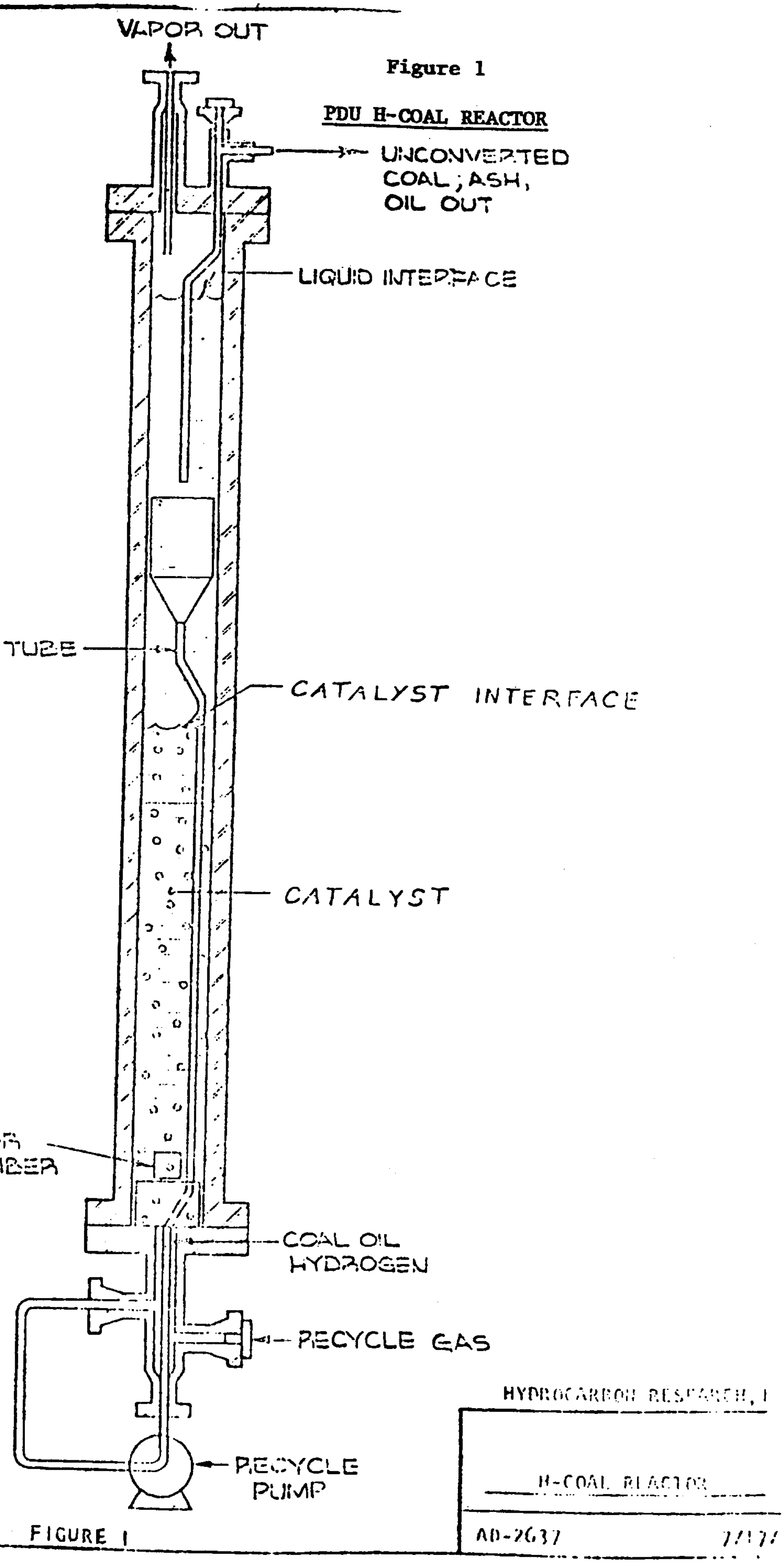


FIGURE 1

Figure 2

H–COAL PROCESS DEVELOPMENT UNIT

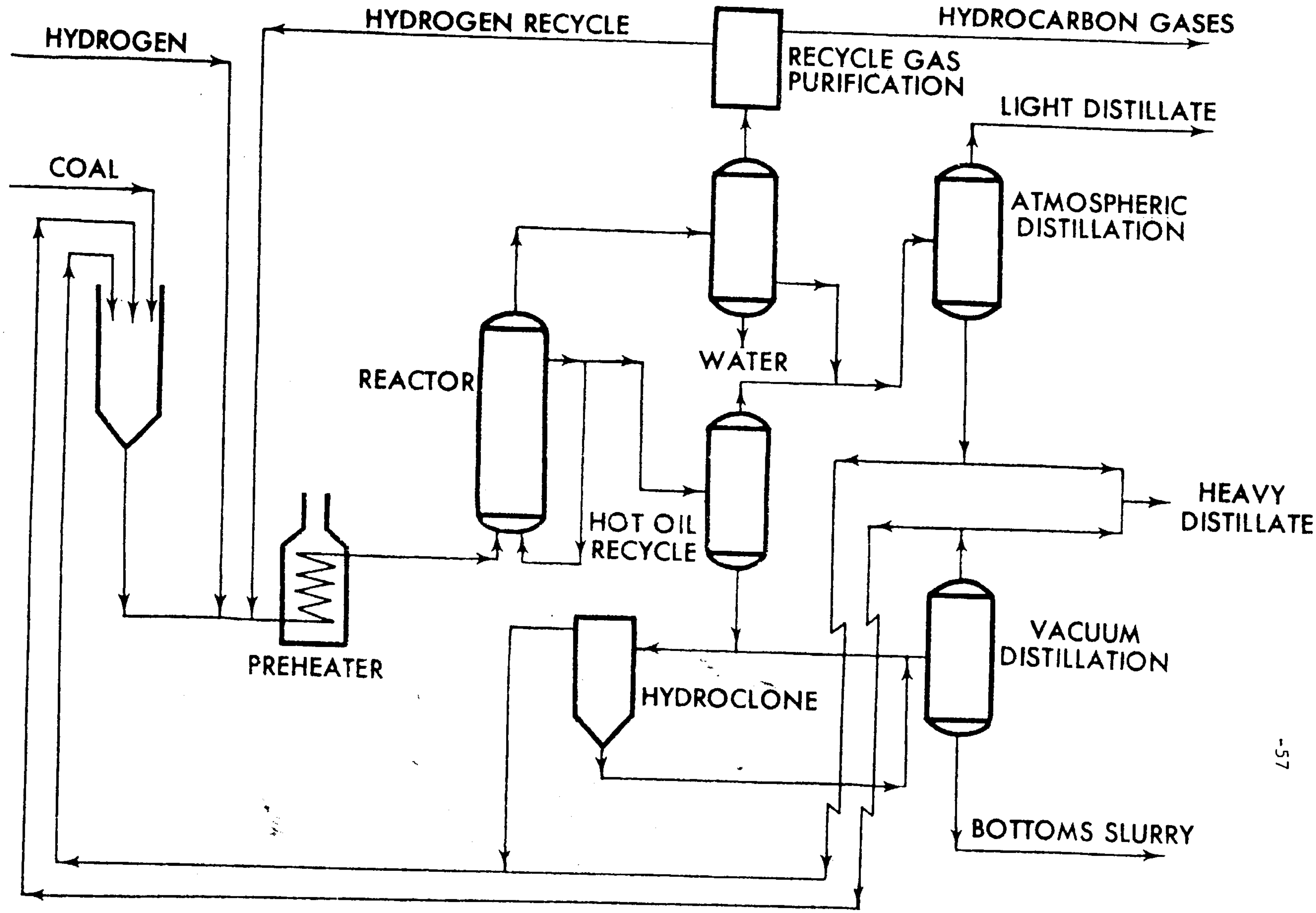


Figure 3

BED VOIDAGE VERSUS SUPERFICIAL LIQUID VELOCITY:
EFFECT OF PARTICLE DIAMETER--HEPTANE

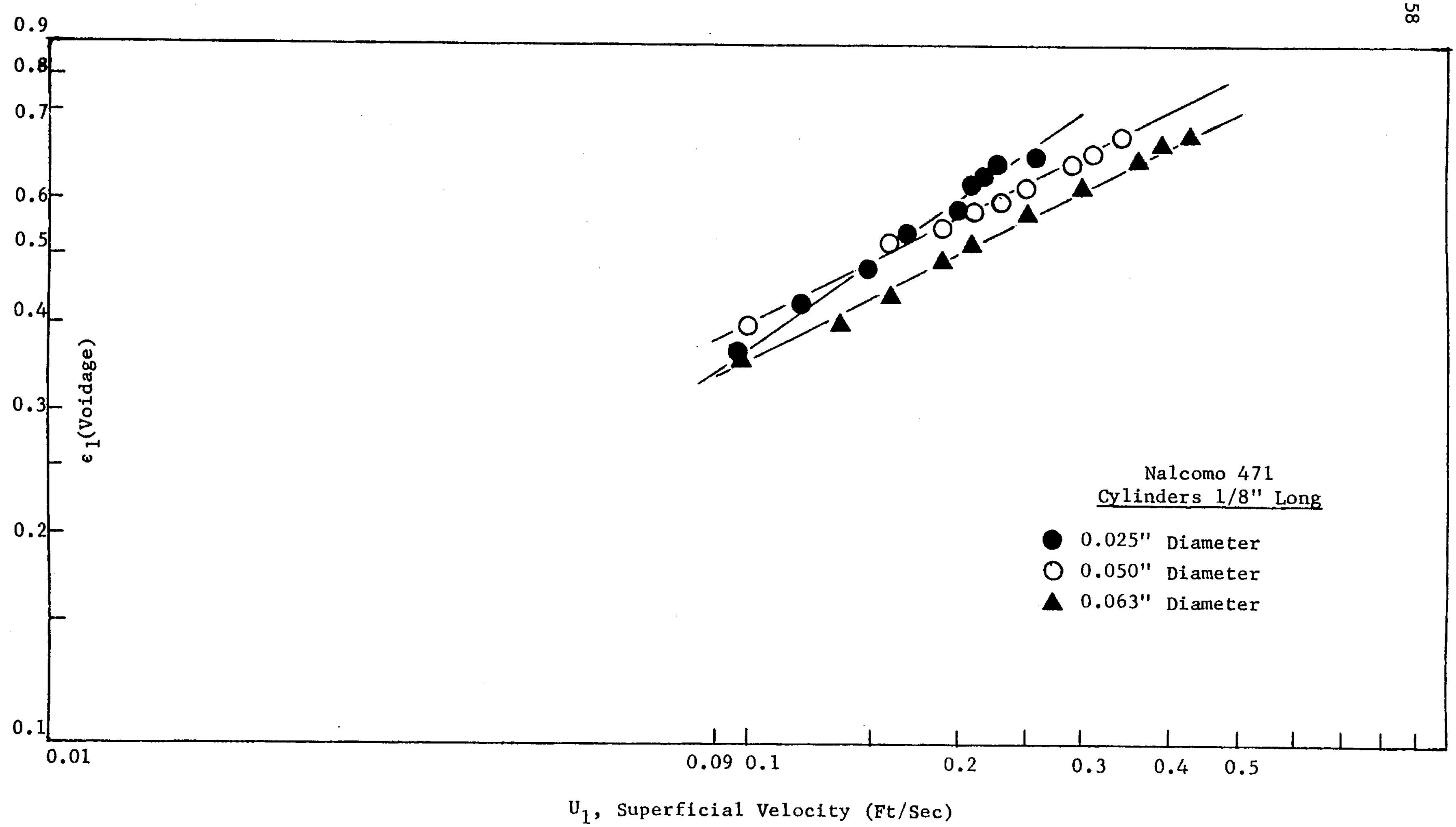


Figure 4

BED VOIDAGE VERSUS SUPERFICIAL LIQUID VELOCITY:
EFFECT OF LIQUID VISCOSITY--NALCOMO 471
0.025" DIAMETER CYLINDER, 1/8" LONG

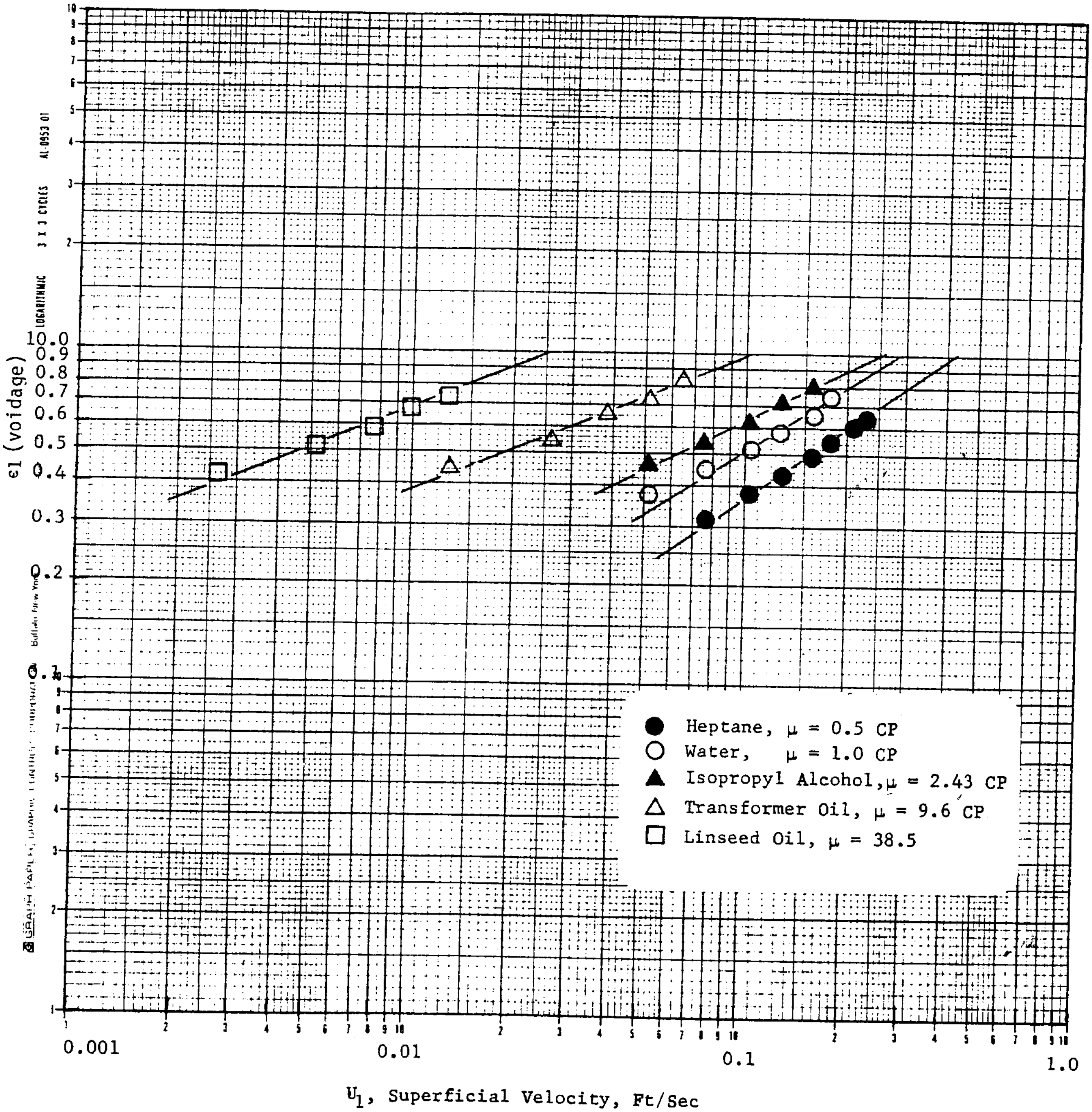


Figure 5

BED VOIDAGE VERSUS U_l/U_t:
EFFECT OF PARTICLE DIAMETER--HEPTANE

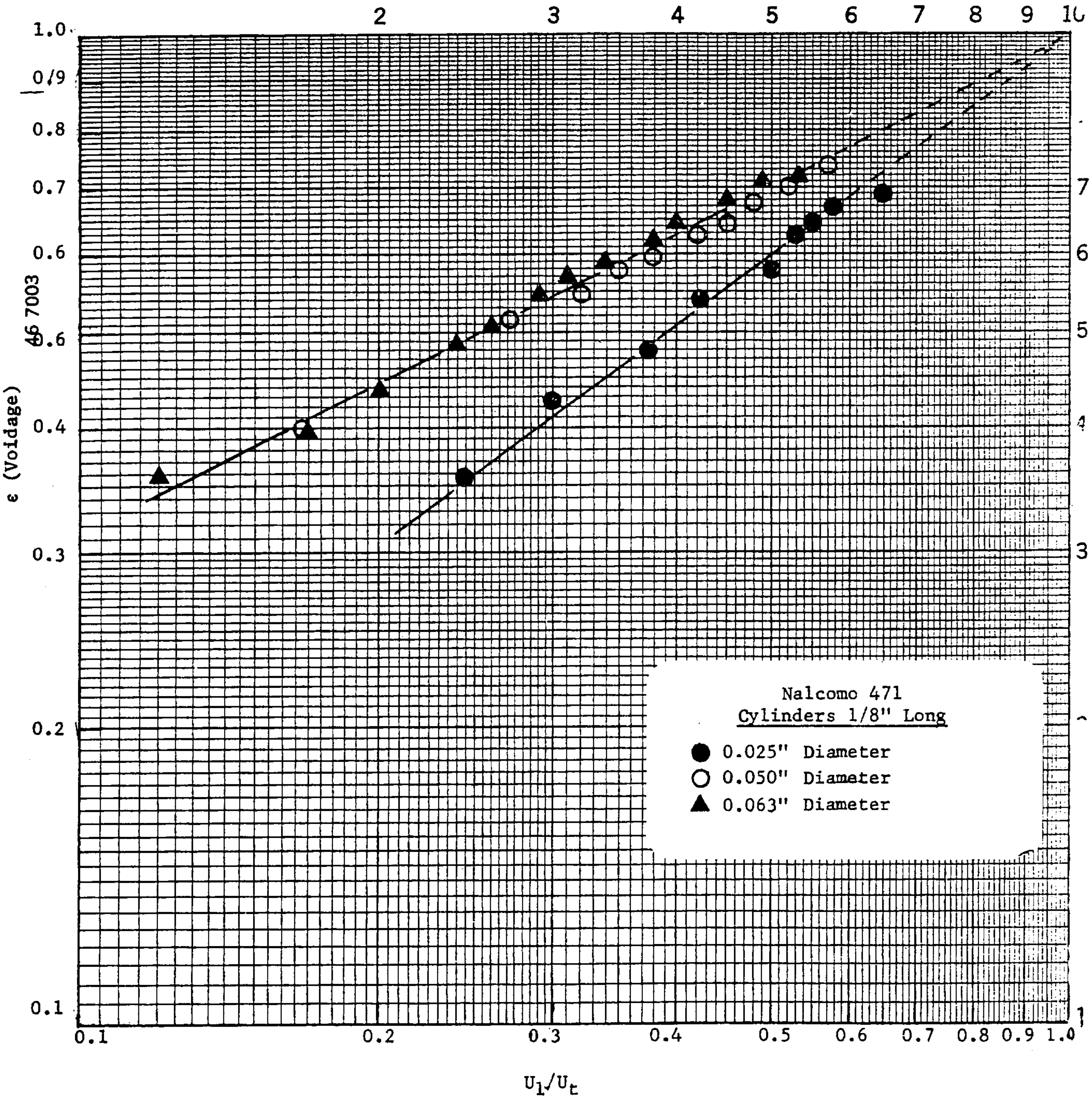


Figure 6

BED VOIDAGE VERSUS U_l/U_t:
EFFECT OF LIQUID VISCOSITY--NALCOMO 471
0.025" DIAMETER CYLINDER, 1/8" LONG

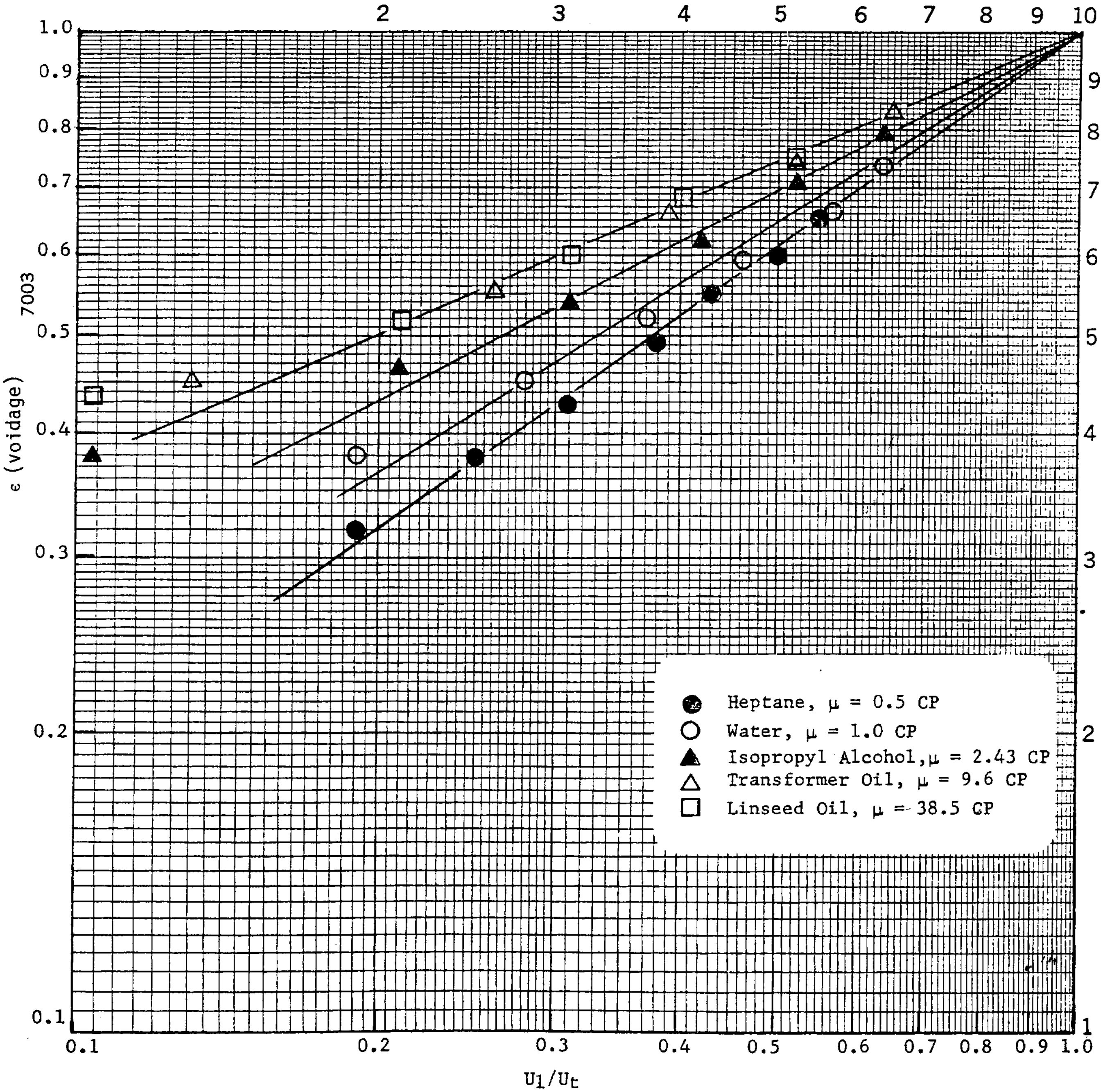
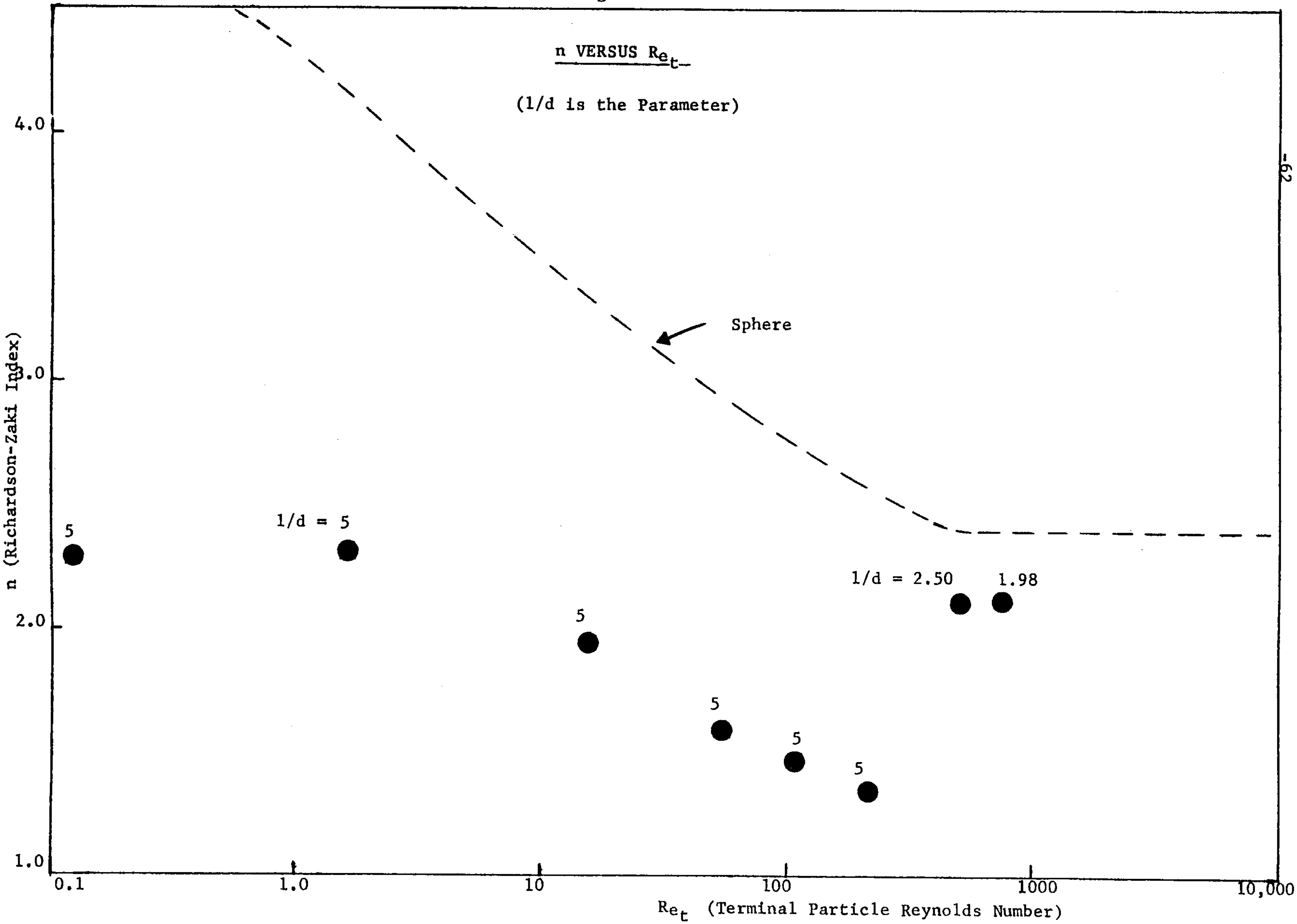


Figure 7



n VERSUS Re_t
(1/d is the Parameter)
Sphere
1/d = 5
5
5
5
5
5
1/d = 2.50
1.98
4.0
3.0
2.0
1.0
n (Richardson-Zaki Index)
0.1
1.0
10
100
1000
10,000
Re_t (Terminal Particle Reynolds Number)

Figure 8

n VERSUS K:
RICHARDSON-ZAKI CORRELATION
$Re_t > 500$

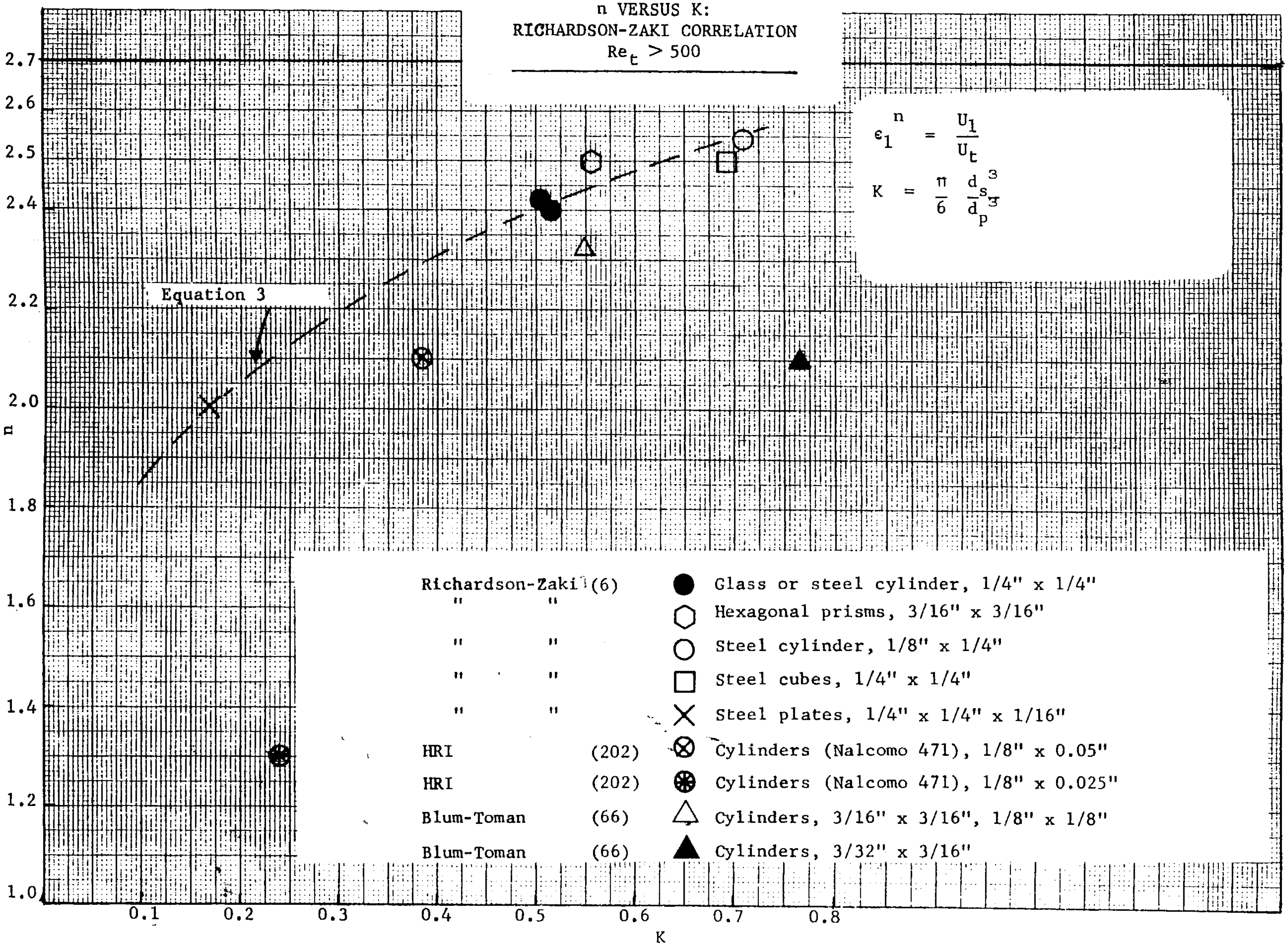


Figure 9

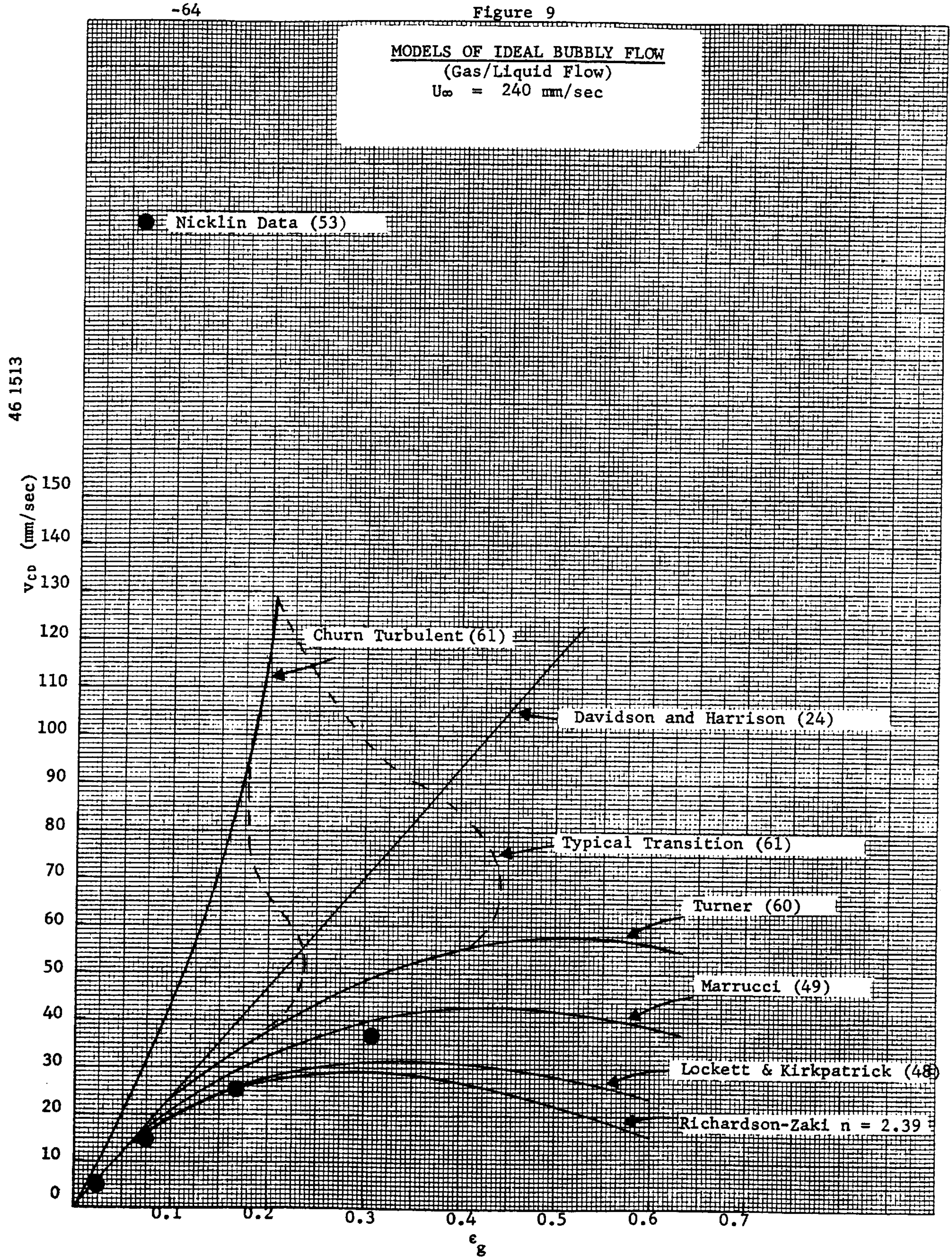
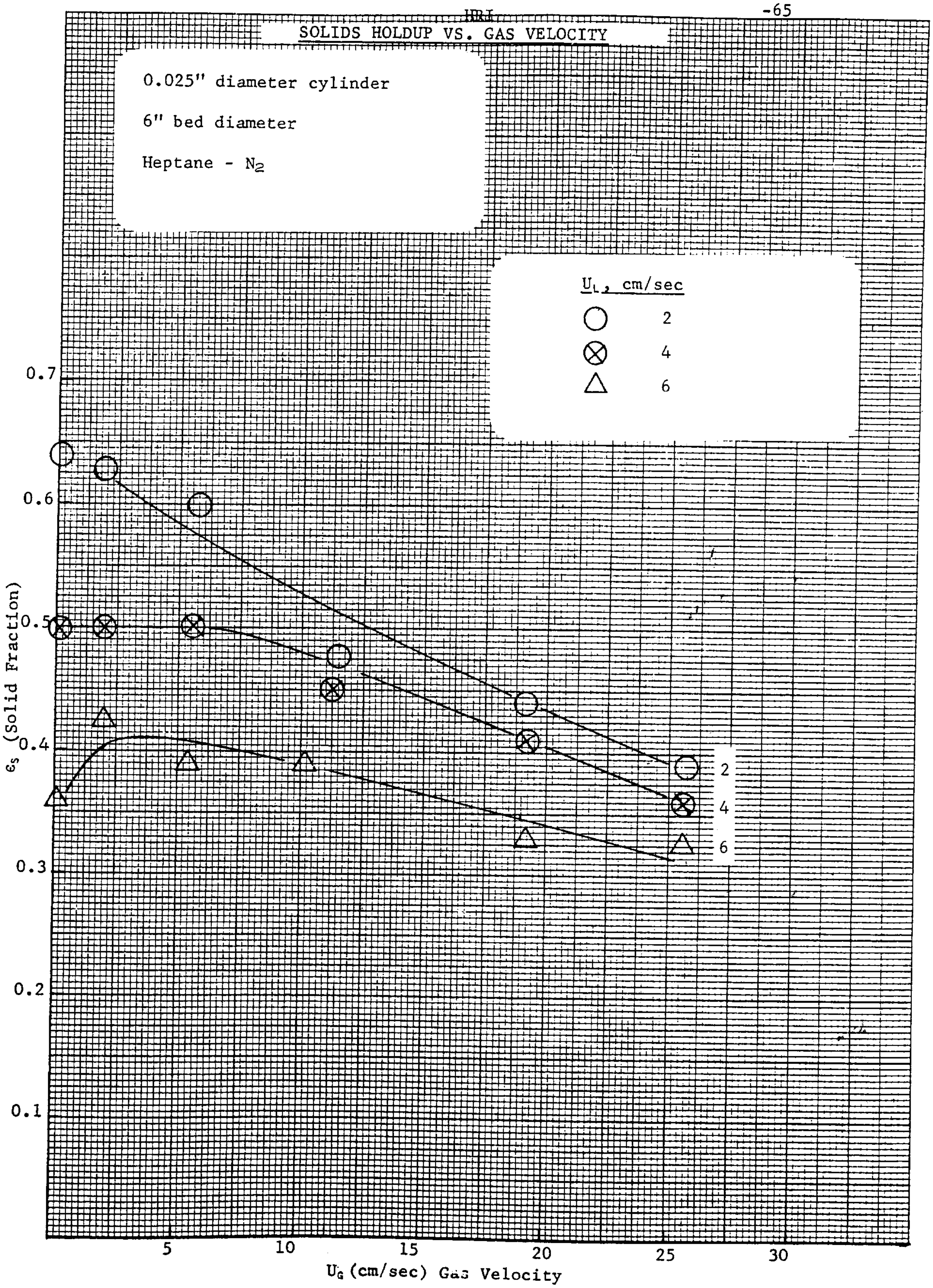
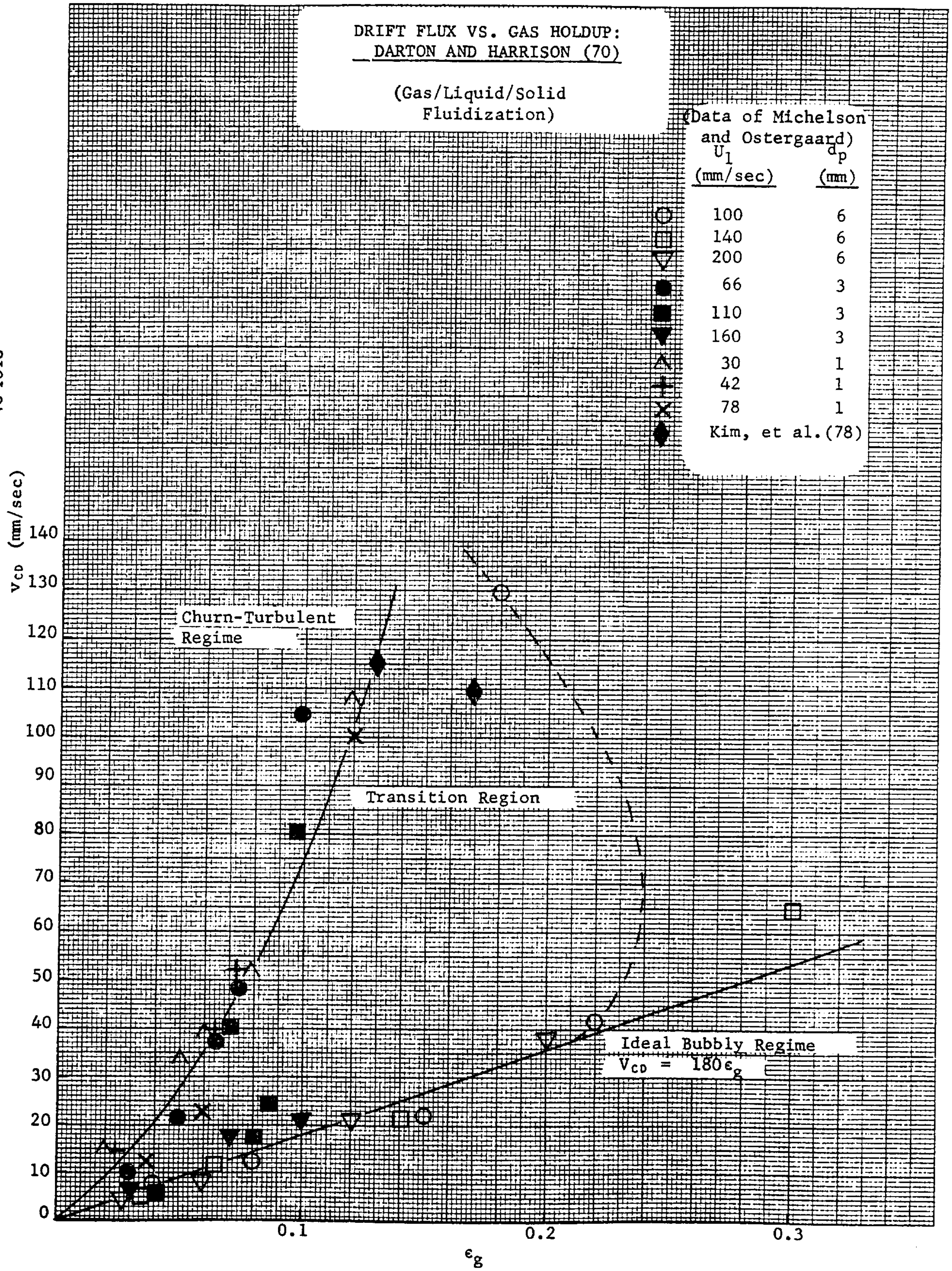

MODELS OF IDEAL BUBBLY FLOW
(Gas/Liquid Flow)
U∞ = 240 mm/sec
Nicklin Data (53)
46 1513
v_{CD} (mm/sec)
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
Churn Turbulent (61)
Davidson and Harrison (24)
Typical Transition (61)
Turner (60)
Marrucci (49)
Lockett & Kirkpatrick (48)
Richardson-Zaki n = 2.39
0.1
0.2
0.3
0.4
0.5
0.6
0.7
ε_g

Figure 10



46 1323

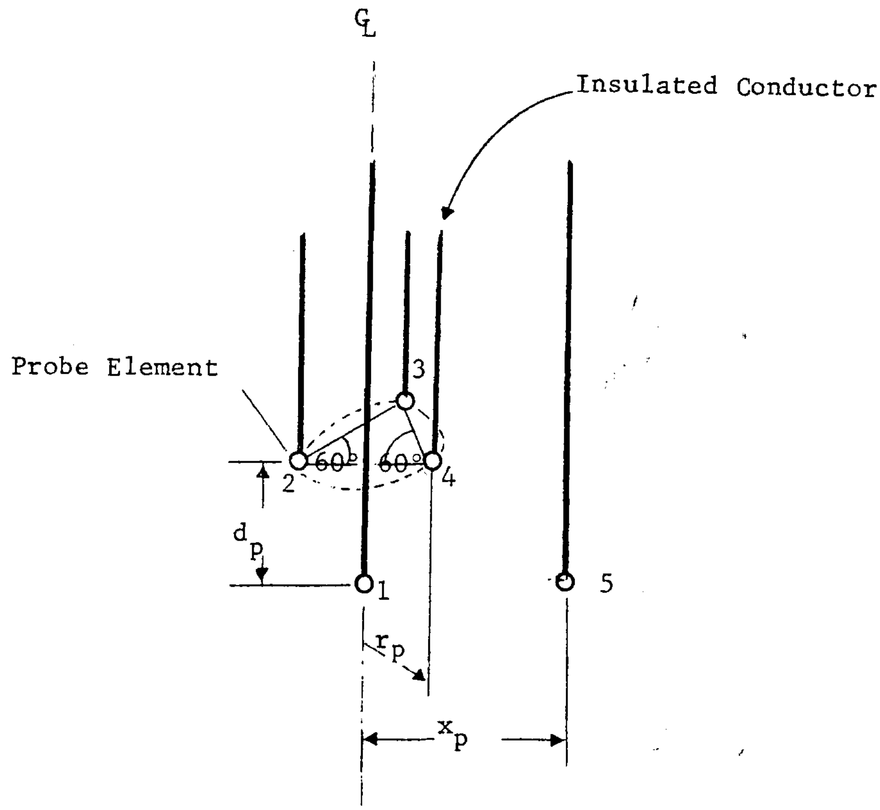
Figure 11



46 1513

Figure 12

FIVE-CONTACT CONDUCTIVITY PROBE



APPENDIX:

THE LITERATURE SEARCH--SCOPE AND METHODOLOGY

APPENDIX

THE LITERATURE SEARCH--SCOPE AND METHODOLOGY

The subject matter covered by this search was rather narrowly defined as "the fundamental hydrodynamics of fluidized-bed technology." Within this definition, two aspects of the subject were pursued: 1) Experimental data on 2 and 3-phase system behavior, and the theory and mathematical analysis of same; 2) The experimental and analytical techniques applicable to the study of such systems. The time period covered was 1950 to present.

A sequential plan was used in conducting the search. First, the presumed applicable literature files were searched, by interactive computer means where possible, and through manual indices for earlier years. The output from this, primarily abstracts, was then sifted and sorted to reduce it to the truly pertinent materials. Quantitatively, these two steps produced about 125 documents from a total of 454 citations. The reference lists from these documents were then utilized to "zero-in" on additional papers, of which another 87 were retrieved. The complete document output of the search was thus 212 items which was narrowed down to 200 in the final analysis. Seven additional references were supplied by H-Coal participants.

The indexed literature files searched were: Chemical Abstracts, American Petroleum Institute, Engineering Index, and the U. S. Energy R&D Administration's RECON file. Of the papers ending up in the final bibliography, the journal Chemical Engineering Science was the largest single contributor, with 36, while AIChE publications (papers, journals, and symposia) were second with 24. Foreign publications (non-Canadian) accounted for 53 of the utilized papers.

While the earliest literature reference to fluidization technology was that of Agricola in "De re Metallica" in 1556, and the first patent using it was issued in 1910 to Phillips and Bulteel, it started gaining widespread attention and basic scientific study in the early 1940's when it was applied to the catalytic cracking of vaporized petroleum fractions. The studies of the 40's and 50's provided a solid theoretical foundation for describing and analyzing fluidized systems, then the more sophisticated and system-specific work of the 60's and 70's has built from that. This literature review concentrates on the latter period but includes several basic works from the former. The 200 references included in this bibliography show the following time distribution:

		No. of Papers
pre-1960	-	15
1960-1970	-	89
1971-1977	-	96

The complete bibliography for this search is divided into 5 tables, according to subject matter, with Table I having 4 subdivisions. The organization is as follows:

Table A-I - Fundamental Hydrodynamics of Fluidization:

A. Liquid-Solid systems
B. Vertical Gas-Solid systems
C. Gas-Liquid-Solid systems
D. Gas-Solid systems

Table A-II - Experimental and Analytical Techniques and Equipment
Table A-III - Properties of Coal-Oil Mixtures
Table A-IV - General Literature Related to Fluidization
Table A-V - Literature Provided by H-Coal Participants

Each table gives a very brief indication of the systems or techniques covered and the significance of the paper relative to this study.

IAV:md
2/15/78

TABLE A-I

Literature on The Hydrodynamics of Fluidization

A. Liquid-Solid Fluidization:

Reference No.	Reference	Systems Covered	Significance to Project
1	Barnea, E. and Mizrahi, J. A Generalized Approach to the Fluid Dynamics of Particulate Systems Part 1 - General Correlation for Fluidization and Sedimentation in Solid Multiparticle Systems Chemical Engineering Journal, Vol. 5, pp. 171-189, 1973	No Experimental Work	Review Article, Model
2	Brea, F. M., Edwards, M. F., and Wilkerson, W. L. The Flow of Non-Newtonian Slurries Through Fixed and Fluidized Beds Chemical Engineering Science, Vol. 31, pp. 329-336, 1976	Water, Glycerol, Water-TiO_2 Slurries/Glass, Lead or Steel Spheres	**Fluidization with Slurries**
3	Finkestein, E., Letan, R., and Elgin, J. C. Mechanics of Vertical Moving Fluidized Systems with Mixed Particle Sizes A.I.Ch.E. Journal, Vol. 17, p. 867, 1971	Water - Glass Beads	**Particle Size Effects**
4	Fouda, A. E. and Capes, C. E. Hydrodynamic Particle Volume and Fluidized Bed Expansion Canadian Journal of Ch. Eng., Vol. 55, p. 386, 1977	Water - Glass Beads, Crushed Silica, Mica	**Model**
5	Garside, John and Al-Dibouni, M. R. Velocity - Voidage Relationships for Fluidization and Sedimentation in Solid-Liquid Systems Ind. Eng. Chem., Process Des. Dev., Vol. 16, No. 2, p. 206, 1977	No Experimental Work	**Review Article**
6	Richardson, J. F. and Zaki, W. N. Sedimentation and Fluidization: Part I Trans. Instn. Chem. Eng., Vol. 32, p. 35, 1954	Various Liquids and Solids	**Model**
7	Upson, P. C. and Pyle, D. L. The Behavior of Liquid Fluidized Beds Following Stepwise Changes in Flow Rate Chem. Eng. Science, Vol. 29, pp. 71-75, 1974	Water/Glass Ballotini	Fluidized Bed **Stability**
8	Volpicelli, G., Massimilla, L., and Zenz, F. A. Nonhomogeneities in Solid-Liquid Fluidization Chem. Eng. Progress Symposium Series, Vol. 62, No. 67, p. 42, 1966	Water and Glycerine/Steel Beads " " " /Aluminum Beads " " " /Plastic "	Background
9	Wallis, G. B. A Simple Correlation for Fluidization and Sedimentation Trans. Instn. Chem. Eng., Vol. 55, p. 74, 1977	No Experimental Work	Correlation
10	Wen, C. Y. and Yu, Y. H. The Mechanics of Fluidization Chem. Eng. Prog. Symp. Series, Vol. 62, No. 62, 1966		Correlation
11	Yu, Y. H., Wen, C. Y. and Bailie, R. C. Power-Law Fluids Flow Through Multiparticle System Canadian Journal of Chem. Eng., Vol. 46, p. 149, 1968	Water-Polyox 205/Glass Balls-Cubes " " 301/ " " "	Fluidization with Non-Newtonian Fluid

TABLE A-I

Literature on The Hydrodynamics of Fluidization
-2-

B. Vertical Gas-Liquid Systems

Reference No.	Reference	Systems Covered	Significance to Project
12	Anderson, J. L. and Quinn, J. A. Bubble Columns: Flow Transitions in the Presence of Trace Contaminants Chem. Eng. Science, Vol. 25, pp. 373-380, 1970	Air/Water and Impurities	Bubble Coalescence
13	Astarita, G. and Apuzzo, G. Motion of Gas Bubbles in Non-Newtonian Liquids A.I.Ch.E. Journal, Vol. 11, No. 5, p. 815, 1965	Gases/Non-Newtonian Liquids	Bubble Behavior in Non-Newtonian Fluids
14	Baker, J.L.L. and Chao, B. T. An Experimental Investigation of Air Bubble Motion in a Turbulent Water Stream A.I.Ch.E. Journal, Vol. 11, No. 2, p. 268, 1965	Air/Water	Bubble Behavior in Turbulent Flow
15	Bellman, R. and Pennington, R. H. Effects of Surface Tension and Viscosity on Taylor Instability Quart. Appl. Math., Vol. 12, p. 151, 1954	Theoretical Study	Bubble Break-up
16	Bridge, A. G., Lapidus, L., and Elgin, J. C. The Mechanics of Vertical Gas-Liquid Fluidized System I: Countercurrent Flow A.I.Ch.E. Journal, Vol. 10, No. 6, p. 819, 1964	Air/Water-Glycerine Solutions	Bubble Swarm Behavior
17	Calderbank, P. H., Moo-Young, M. B., and Bibby, R. Coalescence in Bubble Reactors and Absorbers 3rd Euro. Symp. on CH. React. Eng., No. 43, p. 91, 1964	Air/Water CO_2/Water Air, CO_2/Aqueous Glycerol	Bubble Coalescence
18	Chandrasekhar, S. The Character of the Equilibrium of an Incompressible Heavy Viscous Fluid of Variable Density Proc. Cambridge Philological Society, p. 162, 1955	Theoretical Study	Bubble Break-up
19	Clift, R. and Grace, J. R. The Mechanism of Bubble Break-up in Fluidized Beds Chem. Eng. Science, Vol. 27, pp. 2309-10, 1972	Air/Aqueous Sugar Solution Water/Lead Shot	Bubble Break-up
20	Collins, R. The Effect of a Containing Cylindrical Boundary on the Velocity of a Large Gas Bubble in a Liquid Journal, Fluid Mech., Vol. 28, pp. 97-112, 1967	Air/Water	Rise Velocity of Large Bubbles
21	Collins, R. Structure and Behavior of Wakes Behind Two-Dimensional Air Bubbles in Water Chem. Eng. Science, Vol. 20, pp. 851-853, 1965	Air/Water	Bubble-Wake Behavior
22	Crabtree, J. R. and Bridgwater, J. Bubble Coalescence in Viscous Liquids Chem. Eng. Science, Vol. 26, pp. 839-851, 1971	Air/Water-Sucrose	Bubble Coalescence

TABLE A-I

Literature on The Hydrodynamics of Fluidization

-3-

B. Vertical Gas-Liquid Systems

Reference No.	Reference	Systems Covered	Significance to Project
23	Crabtree, J. R. and Bridgwater, J. The Wakes Behind Two-Dimensional Air Bubbles Chem. Eng. Science, Vol. 22, pp. 1517-1518, 1967	Air/Water-Glycerol Solution	Bubble Wakes
24	Davidson, J. F. and Harrison, D. The Behavior of a Continuously Bubbling Fluidized Bed Chem. Eng. Science, Vol. 21, pp. 731-738, 1966	Theoretical Study	Gas-Liquid Model
25	Davidson, J. F. and Harrison, D. Fluidized Particles Cambridge U. Press, 1963		Bubble Formation
26	Davidson, J. F. and Schuler, B. O. G. Bubble Formation at an Orifice in a Viscous Liquid Trans. Instn. Ch. Eng., Vol. 38, pp. 144-154, 1960	Air/High Viscosity Liquids	Bubble Formation
27	Davies, R. M. and Taylor, G. I. The Mechanics of Large Bubbles Rising Through Extended Liquids and Through Liquids in Tubes Proc. Roy. Soc., Vol. A200, p. 375, 1950	Air/Nitrobenzene Air/Water	Single Bubble and Slug Behavior
28	Davenport, W. G., Richardson, F. D., Bradshaw, A. V. Spherical Cap Bubbles in Low Density Liquids Chem. Eng. Sci., Vol. 22, pp. 1221-1235, 1967	Air, Nitrogen, CO_2/Water, Aqueous Polyvinyl Alcohol, Ethyl Alcohol	Rise Velocity of Single Bubbles
29	Grace, J. R., Wairegi, T., and Nguyen, T. H. Shapes and Velocities of Single Drops and Bubbles Moving Freely Through Immiscible Liquids Trans. Instn. Eng., Vol. 54, p. 167, 1976	Air/Ethylene Glycol Air/Paraffin Oil	Behavior of Single Bubbles
30	Grace, J. R. Shapes and Velocities of Bubbles Rising in Infinite Liquids Trans. Instn. Ch. Eng., Vol. 51, p. 116, 1973	Various Gases/21 Liquids	Behavior of Single Bubbles
31	Grace, J. R. and Harrison, D. The Influence of Bubble Shape on the Rising Velocities of Large Bubbles Chem. Eng. Science, Vol. 22, pp. 1337-1347, 1967	Air/Water	Bubble-Slug Shape
32	Grace, J. R., Krochmalnek, I. S., Clift, R., and Farkas, E. G. Expansion of Liquids and Fluidized Beds in Slug Flow Chem. Eng. Science, Vol. 26, pp. 617-628, 1971	Air/Water Air/Aqueous Sugar Solution	Slug Behavior
33	Guthrie, R. I. L. and Bradshaw, A. V. Spherical Capped Gas Bubbles Rising in Aqueous Media Chem. Eng. Science, Vol. 28, pp. 191-203, 1973	CO_2/Water CO_2/PVA Solutions	Behavior of Single Bubbles
34	Hide, R. The Character of the Equilibrium of an Incompressible Heavy Viscous Fluid of Variable Density: An Approximate Theory Proc. Cambridge Phil. Society, p. 179, 1955	Theoretical Study	Bubble Break-up

TABLE A-I

Literature on The Hydrodynamics of Fluidization

-4-

B. Vertical Gas-Liquid Systems

Reference No.	Reference	Systems Covered	Significance to Project
35	Hills, J. H. The Rise of a Large Bubble Through a Swarm of Smaller Ones Trans. Instn. Ch. Eng., Vol. 53, p. 224, 1975	Air/Water	Behavior of Bubble Swarms
36	Hills, J. H. Radial Non-Uniformity of Velocity and Voidage in a Bubble Column Trans. Instn. Ch. Eng., Vol. 52, p. 1, 1974	Air/Water	Behavior of Bubble Swarms
37	Hinze, J. O. Fundamentals of the Hydrodynamic Mechanism of Splitting in Dispersion Processes A.I.Ch.E. Journal, Vol. 1, No. 3, p. 289, 1955	Theoretical Study	Bubble Break-up
38	Hughmark, G. A. Holdup in Vertical Upward Slug Flow A.I.Ch.E. Journal, Vol. 12, No. 5, p. 1023, 1966	Steam/Water Air/Water - Salt. Sol.	Slug Behavior
39	Jameson, G. J. and Kupferberg, A. Pressure Behind a Bubble Accelerating from Rest: Simple Theory and Applications Chem. Eng. Science, Vol. 22, pp. 1053-1055, 1967	Theoretical Study	Bubble Formation
40	Kirkpatrick, R. D. and Lockett, M. J. The Influence of Approach Velocity on Bubble Coalescence Chem. Eng. Science, Vol. 29, pp. 2363-2373, 1974	Air/Water	Bubble Coalescence
41	Kojima, E., Akehata, T., and Shirai, T. Rising Velocity and Shape of Single Air Bubbles in Highly Viscous Liquids	Air/Glycerine, Castor Oil, Corn Syrup	Single Bubble Behavior
42	Koide, K., Kato, S., Tanaka, Y., and Kubota, H. Bubbles Generated from Porous Plate Journal Ch. Eng. of Japan, Vol. 1, No. 1, p. 51, 1968	Air/Water, Hydrocarbons, Aqueous Solutions	Coalescence Bubble Formation
43	Koide, K., Hirahara, T., and Kubota, H. Average Bubble Diameter, Slip Velocity and Gas Hold-up of Bubble Swarms Kagaku Kogaku, Vol. 5, No. 1, p. 38, 1967	Air/Water Air/Aqueous Glycerine	Bubble Formation
44	Krishnamurthi, S., Kumar, R., and Kuloor, N. R. Bubble Formation in Viscous Liquids Under Constant Flow Conditions Ind. and Eng. Chem., Vol. 7, No. 4, p. 549, 1968	Air/Glycerol	Bubble Formation
45	Krishnamurthi, S., Kumar, R., and Kuloor, N. R. Formation of Bubbles Chem. and Process Eng., p. 91, Jan. 1968		Bubble Formation
46	Kutateledze, S. S. and Styrikovich, M. A. Hydraulics of Gas-Liquid Systems Moscow, Wright Field Trans., F-TS -9814/V, 1958		Bubble Formation

TABLE A-I

Literature on The Hydrodynamics of Fluidization

-5-

B. Vertical Gas-Liquid Systems

Reference No.	Reference	Systems Covered	Significance to Project
47	Lindt, J. T. Note on the Wake Behind a Two-Dimensional Bubble Chem. Eng. Science, Vol. 26, pp. 1776-1777, 1971	Air/Water	Wake Behavior
48	Lockett, M. J. and Kirkpatrick, R. D. Ideal Bubbly Flow and Actual Flow in Bubble Columns Trans. Instn. Chem. Eng. Vol. 53, p. 267, 1975	Air/Water	Coalescence Mechanisms Review of Gas-Liquid Bubble Models
49	Marrucci, G. Rising Velocity of a Swarm of Spherical Bubbles Ind. and Eng. Chem., Vol. 4, p. 224, May 1965	Theoretical Study	Behavior of Bubble Swarms
50	Mendelson, H. D. The Prediction of Bubble Terminal Velocities from Wave Theory A.I.Ch.E. Journal, Vol. 13, p. 250, 3/1967	Non-Soluble Gas/Low Viscosity Liquids	Single Bubble Rise Velocity
51	Narayanan, S., Goossens, L. H. J., and Kossen, N. W. F. Coalescence of Two Bubbles Rising in Line at Low Reynolds Numbers Chem. Eng. Science, Vol. 29, pp. 2071-2082, 1974	Air/Glycerine	Bubble Wakes Bubble Coalescence
52	Nicklin, D. J., Wilkes, J. O., and Davidson, J. F. Two-Phase Flow in Vertical Tubes Trans. Instn. Ch. Eng., Vol. 40, p. 61, 1962	Air/Water	Slug Behavior
53	Nicklin, D. J. Two-Phase Bubble Flow Chem. Eng. Science, Vol. 17, pp. 693-702, 1962	Air/Water	Behavior of Swarms
54	Nicolitsas, A. J. and Murgatroyd, W. Precise Measurements of Slug Speeds in Air-Water Flows Chem. Eng. Science, Vol. 23, pp. 934-936, 1968	Air/Water	Slug Behavior
55	Peebles, F. N. and Garber, H. J. Studies on the Motion of Gas Bubbles in Liquids Chem. Eng. Progress, Vol. 49, p. 88, 1953	Air/22 Liquids	Single Bubble Behavior
56	Rippin, D. W. T. and Davidson, J. F. Free Streamline Theory for a Large Gas Bubble in a Liquid Chem. Eng. Science, Vol. 22, pp. 217-228, 1967	Theoretical Study	Background
57	Schwerdtfeger, K. Velocity of Rise of Argon Bubbles in Mercury Chem. Eng. Science, Vol. 23, pp. 937-938, 1968	Argon/Mercury	Single Bubble Behavior
58	Slaughter, I. and Wraith, A. E. The Wake of a Large Gas Bubble Chem. Eng. Science, Vol. 23, p. 932, 1968	Gas/Water-Glycerol	Wake Behavior
59	Taylor, G. I. The Instability of Liquid Surfaces When Accelerated in a Direction Perpendicular to Their Planes Proc. Royal Society, Vol. 201, Series A, p. 192, 1950	Theoretical Study	Bubble Break-up