AN ABSTRACT OF THE THESIS OF

DWIGHT NORRIS LOCKWOOD for the degree of Master of Science in Mechanical Engineering presented on APR 15, 1976

Title: AN INVESTIGATION OF THE EFFECTS OF IMMERSED HEAT EXCHANGER TUBE SPACING AND ARRANGEMENT ON THE QUALITY OF FLUIDIZATION IN A COLD PHASE TWO-DIMENSIONAL FLUIDIZED BED

Abstract approved: Redacted for Privacy

(David C. Junge)

The feasibility of fluidized bed combustion of coal for commercial and industrial steam power generation has been established and reported in the literature. Satisfactory removal of sulfur oxides from the combustion product gases has also been reported.

In this experiment various heat exchanger tube patterns, of commercial size tubes, were examined in a two-dimensional, cold phase fluidized bed of limestone and dolomite. Several variables such as tube pitch (triangular and rectangular), tube spacing (horizontal and vertical), array location with respect to the distributor plate, and superficial gas velocity were considered and their effect on the quality of fluidization reported. Dolomite with a mean surface/volume size of 569 microns (28 Tyler mesh) and

limestone with a mean surface/volume size of 1379 microns (12 Tyler mesh) were used as bed material.

The results indicate that the horizontal as well as vertical spacing of tubes has a significant effect upon the start up phase of fluidization and bed stability. Also, horizontal spacing which is too close inhibits solids circulation. Triangular pitch arrangements yielded good solids circulation and did not experience gas by-passing to the extent seen with rectangular arrangements. Overall bed stability was improved with the tube arrays closer to the distributor plate. Rapid bubble growth and associated instabilities were observed when a relatively thick layer of solids were above the tube arrays, indicating that the expanded bed surface should probably not extend above the tubes. Further research in the area of fluidized bed quality is recommended.

An Investigation of the Effects of Immersed Heat Exchanger Tube Spacing and Arrangement on the Quality of Fluidization in a Cold Phase Two-Dimensional Fluidized Bed

by

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I. INTRODUCTION

Background

Optimum use of the energy available in coal is a major concern in the world and in this country in particular. Several avenues of achieving this goal are presently being pursued. Included in the list are gasification, liquification, pyrolysis as well as advances in direct combustion. All of these processes are being shown to be potential alternatives when considering the extent of this country's energy resources. The relevant question, though, is when will they become viable? For the newer processes, most notably gasification and liquifaction, time and money will probably be required, in large amounts, before the technology will be advanced enough to make them commercially viable. The author feels that the greatest potential, for rapid, significant improvements, lies in the area of direct combustion of coal. Much is already known about this process and it has probably been developed about as far as possible using present technology. What is needed is a major breakthrough in the state of the art, a new technology.

Fluidized bed combustion of coal can, in a relatively short time, be a commercially viable process. The important words here are "relatively short". Westinghouse Research Laboratories (10), has designed a small commercial scale, pressurized, fluidized bed boiler demonstration plant and estimated construction could be completed in about five years. Follow-on plants could come almost immediately. By contrast, for the newer processes, such as liquifaction, 5 to 10 years may be needed to achieve a demonstration plant and several more for a commercial one. Thus, for the near future at least, direct combustion of coal appears to be the process most amenable to significant improvements in terms of power generation efficiency, economics of construction and operation and, in the author's view, with the least research and development required. Another advantage, and an important environmental one, is the ability of the limestone bed material, in fluidized beds, to absorb sulfur dioxide from the combustion gases. Rice and Coates (5) reported 90% sulfur removal from several grades of coal with various sulfur contents, in a fluidized bed combustor.

The Problem

The technological breakthrough suggested above is actually a complex one. While much is known about fluidization, a process which is in fact used in industry today, relatively little has been published specifically dealing with the problems related to steam power generation using coal in a fluidized bed. Apparently, little fundamental work has been done to design fluidized bed combustors independent of conventional combustion technology and practice. Published works, to date, can generally be catagorized as feasibility studies, used to see if fluid bed combustion of coal should even be considered. Some of the questions dealt with include 1) will a fluid bed combustor even work, 2) whether or not SO_2 and NO_x emissions can be reduced further than by conventional methods and 3) to determine if pumping costs will be tolerable, to suggest a few. Now that these questions have been answered affirmatively researchers must take the next step and attack the fundamental design problems, but with an eye on the practical utility of the results. Some of the questions to be answered include:

1. What is the optimum distributor plate design with respect, primarily, to pressure drop across it.
2. What is the optimum heat exchanger tubing size, arrangement, orientation, and location within the bed.
3. What superficial velocity will provide the required excess combustion air.
4. What size bed material should be used to minimize entrainment as well as fluidize properly.

5. What fluidization phenomena (such as bubbling and slugging) are acceptable and to what extent.

Questions such as these should be answered relative to optimizing the quality of fluidization to achieve maximum heat transfer, and energy conservation at minimum cost. They should be answered on a scale large enough to be representative of commercial applications.

The purpose of this work was to provide preliminary answers to some of the questions, posed above, related to the quality of fluidization; answers which can be used to predict or anticipate behavior to be be experienced in a large fluidized bed being built at Oregon State University as part of a 39 month research project which began on January 1, 1975. Funds for the project are provided by Electric Power Research Institute under Contract No. RP315-1. Parameters to be studied in the main project include: gas and solids flow and mixing, heat transfer, elutriation, tube erosion, and tube stress.

Specifically, the problem of this work is stated as follows: investigate the effect of arrangement and spacing of heat exchanger tubing and the tube array location, on the quality of fluidization in a two-dimensional fluidized bed at various superficial velocities. Qualitative judgements were based on visual observation of the fluidized bed in operation. Quantitative data were also taken, primarily in the form of differential pressure measurements and fluctuations in the system. Comparisons between the various fluidization conditions were made based on desired fluidization qualities, which will be discussed later.

II. REVIEW OF THE LITERATURE

Fluidized Beds

History

A good historical summary of fluidization is provided in Kunii and Levenspiel's Fluidization Engineering (4) and is summarized here. Commercial gasification of powdered coal using, by todays standards, a relatively inefficient fluidized bed was patented by Fritz Winkler in 1922. Increased availability of petroleum and excessive use of oxygen caused the process to fall into disuse. World War II created a demand in this country for large quantities of high octane aviation fuel. The Thermofor Catalytic Cracking (TCC) process using a fluid bed reactor and regenerator as well as inter-vessel gas transfer was developed in 1940 to help fill this need. In a parallel effort the then Standard Oil Development Company developed the Fluid Catalytic Cracking (FCC) process, which was based on pioneering work by Lewis and Gilliland of Massachusetts Institute of Technology. In the late 1940's the use of fluidization went outside the petroleum industry. Independently Dorr-Oliver in the United States, Badische Anilin Und Soda-Fabrik (BASF) in Germany and a Japanese chemical company developed fluidized bed roasters. Dorr-Oliver also pioneered fluid bed driers and calciners.

The Phenomena

Fluidization is a unit operation where particulate solids are put into a fluid like state through contacting with a gas or liquid.

It is appropriate, at this point, to provide definitions of the various states of fluidization. The following list and the accompanying Figure 1 are suggested by Kunii and Levenspiel (4).

Fixed Bed: When a fluid passes up through a bed of particles at a low flow rate, it percolates through the void spaces between stationary particles.

Incipiently Fluidized Bed, Minimum Fluidization: As the flow rate is increased it reaches a point where the inertial and frictional forces on the particles are just overcome. At this flow rate the pressure drop across any portion of the bed is simply the weight of the fluid and particles in that portion, analogous to the hydrostatic head.

Particulately or Liquid or Smoothly Fluidized Bed: This occurs at a fluid flow rate above minimum fluidization. The bed undergoes a smooth, progressive expansion with increased flow rate and is most commonly seen with liquid-solid systems.

Aggregative, Bubbling or Gas Fluidized Bed: Gas-solid systems demonstrate instabilities with bubbling and channeling for gas flow rates above minimum fluidization. Solids movement is

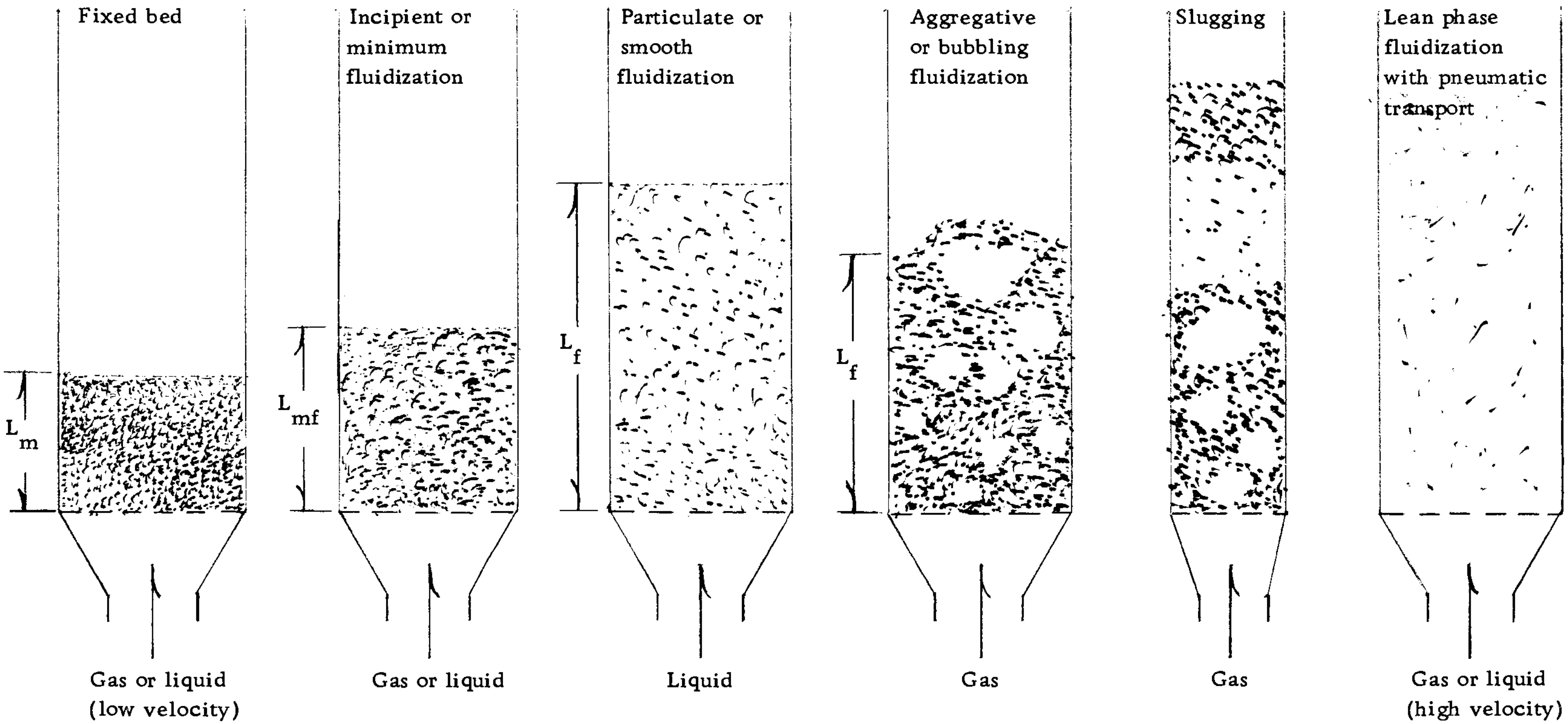


Figure 1. Various types of fluidization of solids by a fluid (4).

quite vigorous and bed expansion above that of minimum fluidization is minimal.

Dense-Phase Fluidized Bed: This term describes both gas-solid and liquid-solid systems when there is a fairly well defined upper limit or surface of the bed.

Disperse or Lean-Phase Fluidized Bed: As the fluid flow rate is increased further the terminal velocity of the solids is exceeded, the upper surface of the bed disappears, entrainment becomes appreciable and solids are carried from the bed. This type of fluidization is used for pneumatic transport of solids.

Slugging Fluidized Bed: This can be considered an aggrevated bubbling fluidized bed and it is strongly affected by vessel geometry. Gas bubbles coalesce and grow as they rise. When a bubble becomes large relative to the cross-section of the bed it pushes the portion of the bed above it up ahead of it like a piston. Particles fall down past the bubble until it disintegrates. Bubble disintegration often leads to particle entrainment and nonuniformity and instability in the bed. Slugging is usually undesirable and can lead to structural damage to bed internals such as heat exchangers.

Advantages

Some of the advantages of fluidized beds are listed below as summarized from Kunii and Levenspiel (4).

1. Smooth, liquid like particle flow allows continuous, controlled operations.
2. Isothermal conditions in the bed due to rapid mixing.
3. Circulation of solids between two fluidized beds allows for the transport of large quantities of energy produced or needed in large reactors.
4. Heat and mass transfer rates between gas and solids are high.
5. High heat transfer coefficients between the fluidized bed and immersed internals are experienced.
6. Low pressure drops are generally experienced across the fluidized bed, minimizing the energy required for pumping and therefore the cost.

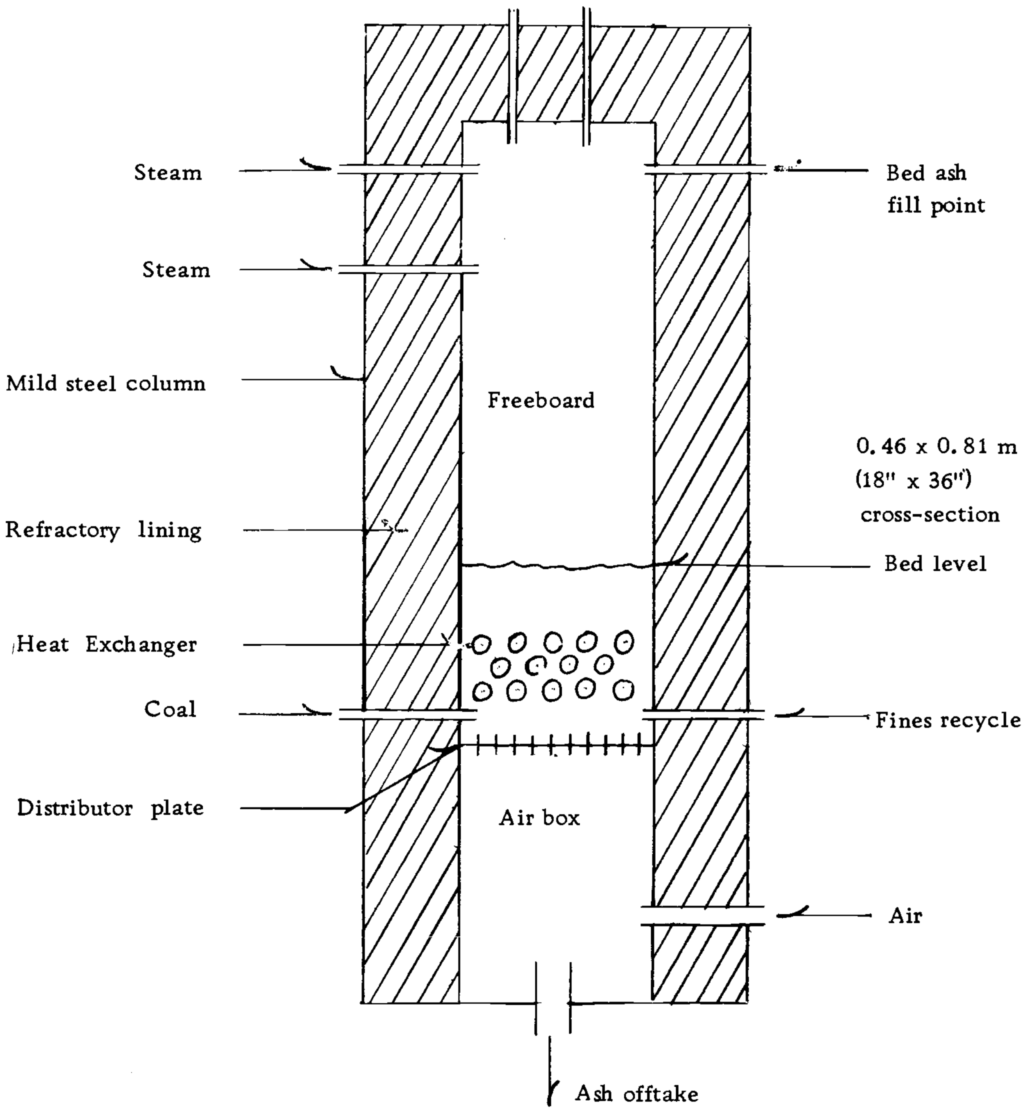
These are some of the more noteworthy characteristics of fluidized beds which lend them to diverse commercial applications.

Fluidized Bed Combustors

Considerable experimental work has been done, in the past several years, in an effort to demonstrate the feasibility of fluidized bed combustors. The experiments were aimed at: (1) showing that the process was workable; (2) developing an understanding of their operating conditions; (3) and identifying some of the advantages such as the reduction of oxides of sulfur and nitrogen as air pollutants, to name a few. The programs generally consisted of constructing a fluidized bed which was large enough for the desired purpose, and instrumenting and operating it.

In September, 1971, the U.S. Environmental Protection Agency (8) published a report, "Reduction of Atmospheric Pollution", of work they sponsored, conducted by the National Coal Board, London, England. The main thrust of the research was aimed at the reduction of sulfur oxides, and nitrogen oxides, and particulate matter. Several separate studies were made and are summarized below.

First, a combustor of 0.42 m^2 (4.5 ft^2) cross-sectional area was used to study and quantify the products of combustion, of various United States and United Kingdom coals, under various fluidizing conditions. A sketch of the unit is shown in Figure 2. The combustor consisted of a steel column about 4.57 m (15 ft) high which was refractory lined to give inner column cross-sectional dimensions of 0.91 by 0.46 meters (36 by 18 inches). The heat exchanger consisted of 14 - 51 mm (2 in.) O.D., horizontal tubes arranged on a 0.11 m (4.5 in.) triangular pitch. The distributor plate was a flat plate with 12.7 mm (0.5 inch) diameter standpipes, with four horizontal holes drilled in each one, threaded into holes in the plate. This work operated with bed depth to diameter, L/D, ratios ranging from 0.84 to 2.9 and fluidizing velocities from 0.61



Column depth	4.6 m (15.0 ft) above distributor
Bed depth	0.61 to 2 m (2 to 7 ft); 40 = 0.8 to 3.0
Pressure	101.28 kPa (1 atm)
Superficial velocity	0.61 to 2.44 m/s (2 to 8 ft/sec)
Distributor	1.3 cm (0.5 in) stand pipes on 7.6 cm (3 in) square pitch
Heat exchanger	14 tube, 5.1 cm (2 in.) O.D., 11.4 cm (4.5 in.) triangular pitch
Elutriation	up to 80%

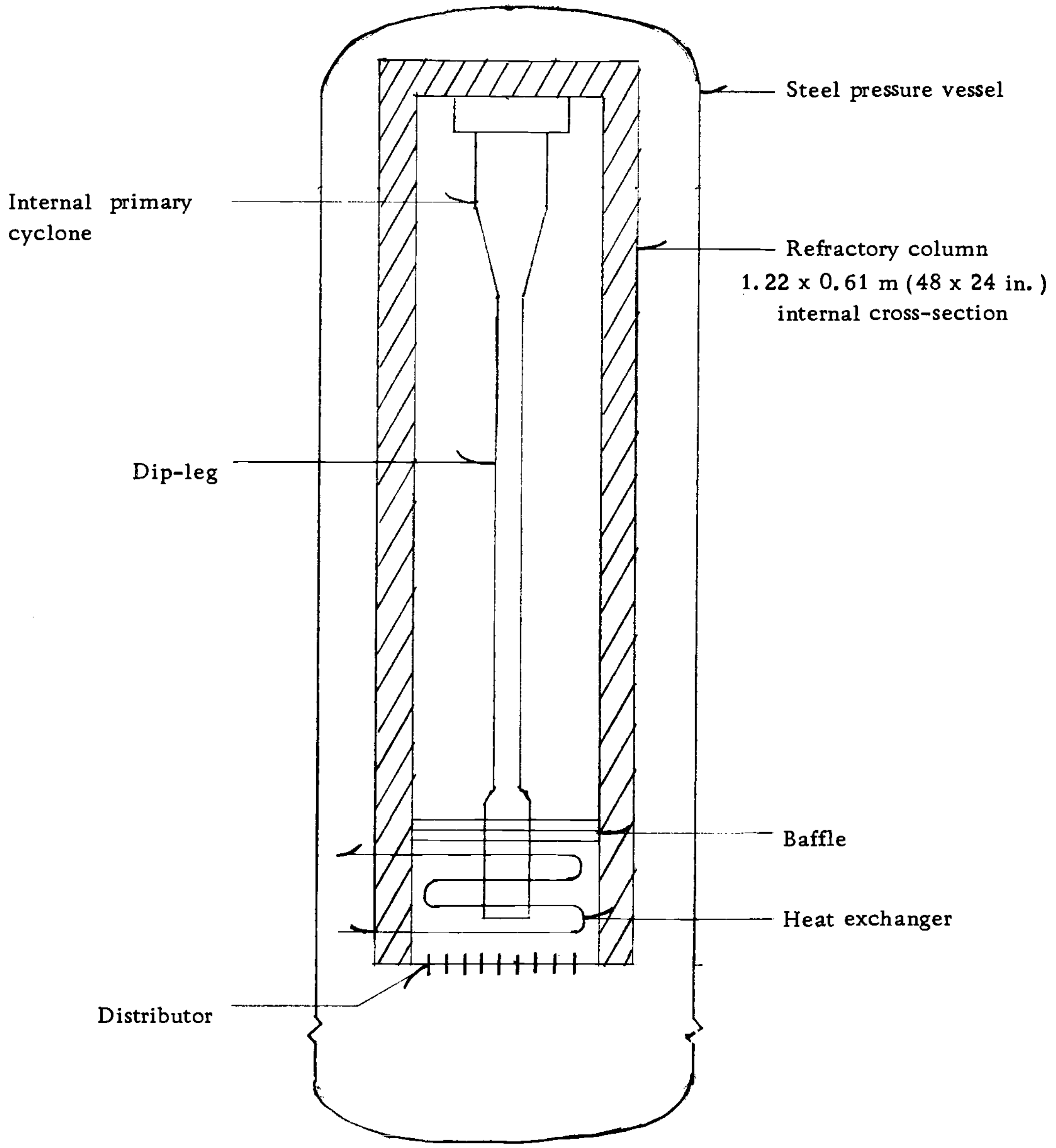
Use: Measurement of products of combustion

Figure 2. Cut away schematic of 0.91 m (36 in.) atmospheric fluidized bed combustor built by the National Coal Board of London, England.

to 2.44 m/s (2 to 8 fps). The investigators found that SO_2 reduction is less affected by operating temperature than by fluidizing velocity. Lower temperatures will tend to reduce SO_2 reduction. Higher velocities substantially reduce SO_2 reduction. Higher limestone to sulfur ratios by weight will increase sulfur recovery.

Another study, aimed at reduction of the products of combustion, used a 1.22 by 0.61 m (48 by 24 in.) combustor contained in a pressure vessel. The operating conditions, which were held essentially constant, were 0.61 m/s (2 fps), 1.14 m (3.75 ft.) bed depth, 799° C (1470° F) bed temperature and 354.6 to 506.6 kPa (3.5 to 5 atm) absolute pressure. The distributor plate consisted of 465 bubble caps on a 40 mm (1.5 in.) square pitch. The heat exchanger consisted of approximately 128 tubes on 0.15 m (6 in.) horizontal by 40 mm (1.5 in.) vertical pitch. The tubes were used for water cooling, air cooling, corrosion studies, preheating and some were simply used as dummies. Figure 3 shows the apparatus. The results indicated that SO_2 reduction was not affected by pressure in the 354.6 to 506.6 kPa (3.5 to 5 atm) range.

Corrosion studies were conducted in a 0.686 m (27 in.) diameter combustor. This combustor was not refractory lined, rather it had a water-cooled jacket. Heat exchangers were used at the top of the vessel to cool the hot gases. Figure 4 is a simplified drawing of the combustor. Four 51 mm (2 in.) diameter tubes,

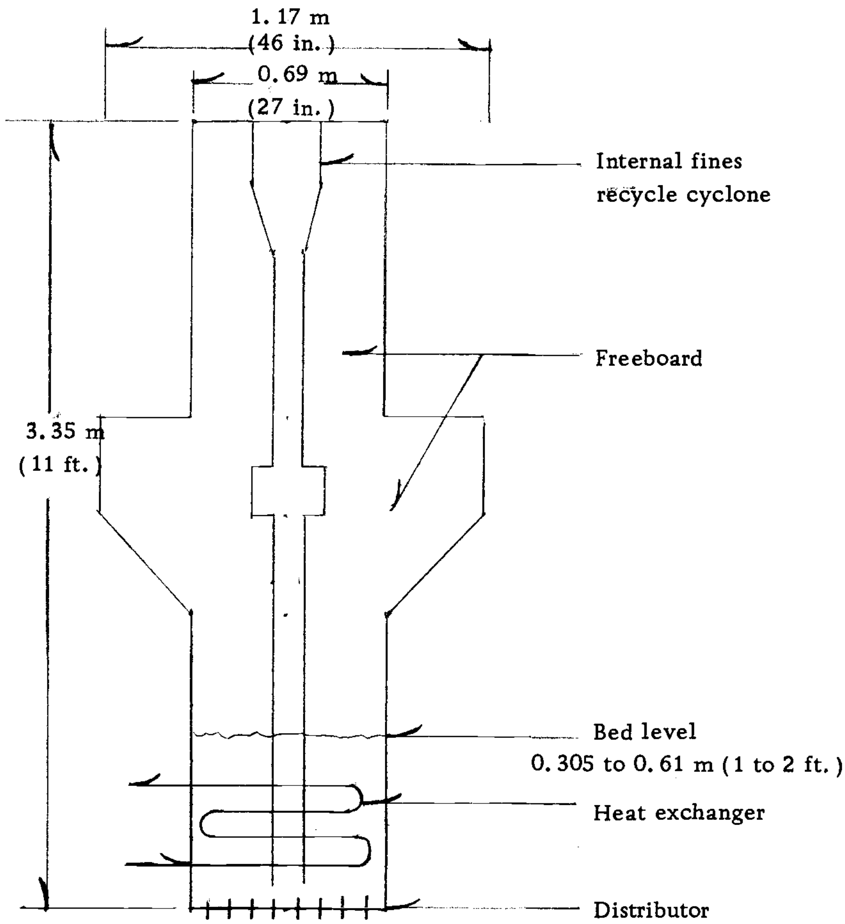


Column height	3.05 m (10 ft.) above distributor
Bed depth	1.07 to 1.2 m (3.5 to 4.0 ft.); L/D = 1.1 to 1.25
Pressure (total)	354.7 to 506.7 kPa (3.5 to 5.0 atm) abs.
Pressure vessel	Contains column, secondary cyclones and all associated hardware
Distributor	465 bubble caps, 3.8 cm (1.5 in.) square pitch
Heat exchanger	18 rows, 2.5 cm (1.0 in.) O.D. staggered pitch
Horizontal baffle	4 rows tubing, 3" triangular pitch

Recirculation believed to be essentially zero.

Use: Measurement of products of combustion

Figure 3. Cut away schematic of 1.22 m (48 in.) pressurized fluidized bed combustor build by the National Coal Board of London, England.



Pressure	Atmospheric
Bed depth	0. 305 to 0. 61 m (1 to 2 ft); L/D = 0. 44 to 0. 89
Minimum fluidizing velocity	1. 22 m/s (4. 0 ft/sec)
Fluidizing velocity	1. 98 to 3. 35 m/s (6. 5 to 11. 0 ft/sec)
Distributor	bubble cap
Heat exchanger	5. 1 cm (2. 0 in.) O. D. tubes, staggered pitch

Internal cyclone and dip-leg for fines recycle

Use: Corrosion testing

Figure 4. Cut away schematic of 0. 69 m (27 in.) atmospheric fluidized bed combustor built by the National Coal Board, London, England and used for corrosion testing.

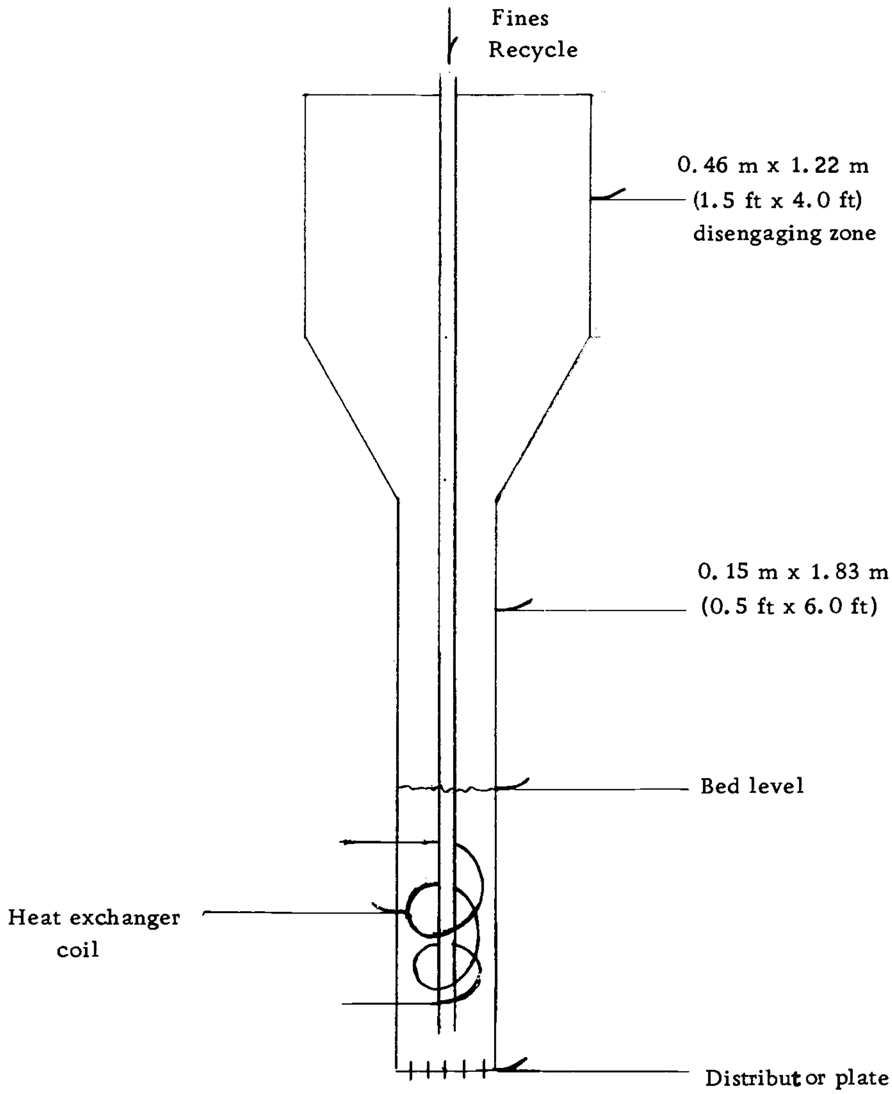
arranged on 0.13 m (5 in.) centers horizontally and 0.162 m (6 3/8 in.) centers vertically, were inserted into the 0.61 m (2 ft) bed for corrosion, errosion and deposition studies. An internal, low efficiency cyclone exhausted collected solids via a dip leg directly into the bed. A bubble cap distributor plate, similar to the previous study was used to support the bed. Results obtained in this study indicate coarser bed material yields higher SO_2 reduction from combustion gases. Direct metallic errosion by ash particles did not occur. This was predictable since the fluidizing velocities were low [0.61 - 2.44 m/s (2-8 fps)]. Scouring of the tubes by ash was not sufficient to remove the oxide layer. Deposition on tubes in the bed consisted of a thin (< 0.1 mm), even hard and adherent deposit. Thicker and looser deposits were found on tubes which were close to the coal feed nozzle.

A 0.31 m (12 in.) diameter combustor was also used to study corrosion. It was constructed of refractory lined steel with an internal cross-section of 0.008 m^2 (12 in^2). The air distributor consisted of 9 short vertical tubes, with horizontal holes drilled in them, arranged on a 0.11 m (4.5 in.) square pitch. Four rows of 25.4 mm (1 in.) diameter air-cooled tubes were immersed in the bed on a 0.15 m (6 in.) triangular pitch. The primary observation from this test was deposition of fine ash on the underside and coarse ash on the top side of tubes placed in the freeboard above the bed.

Other results were similar to those found in the 0.69 m (27 in.) combustor previously mentioned.

The final combustor used in this series by the National Coal Board of England was a 0.15 m (6 in.) diameter, stainless steel vessel. Its purpose was to study SO_2 reduction from various coals with calcium based additives. Comparisons were made with the results of a similar size combustor operated by Argonne National Laboratories in the United States; whose research will be discussed in subsequent paragraphs. This combustor was heated by electrical-wall heaters. The distributor plate was made from a drilled flat plate covered with three layers of 9.5 mm (3/8 in.) alumina balls. Excess heat was removed from the bed by means of a water-cooled metal coil immersed in the bed. Figure 5 shows a schematic of this system.

In 1973 Vogel, G. J. et al., of Argonne National Laboratories (9), reported on bench scale combustion and additive regeneration studies they had conducted. Their combustor was constructed from 0.15 m (6 in.) schedule 40 pipe about 3.35 m (11 ft.) in length. This was then encased in a 0.31 m (12 in.) schedule 10 pipe to permit operating pressures up to 1013 kPa (10 atm.). A bubble-cap-type distributor was attached to the inner combustor vessel. Electrical resistance heaters provided necessary vessel heating and cooling coils around the vessel provided some of the cooling. Additional



Stainless steel column	
Bed height	0.61 to 0.91 m (2 to 3 ft); L/D = 4 to 6
Pressure	Atmospheric
Fluidizing velocity	0.61 to 0.91 m/s (2 to 3 ft/sec)
Distributor	Drilled flat plate covered with three (3) layers 0.95 cm (0.375 in.) diameter alumina balls
Heat exchanger	Six (6) coils, 1.27 cm (0.5 in.) O.D. tubing.

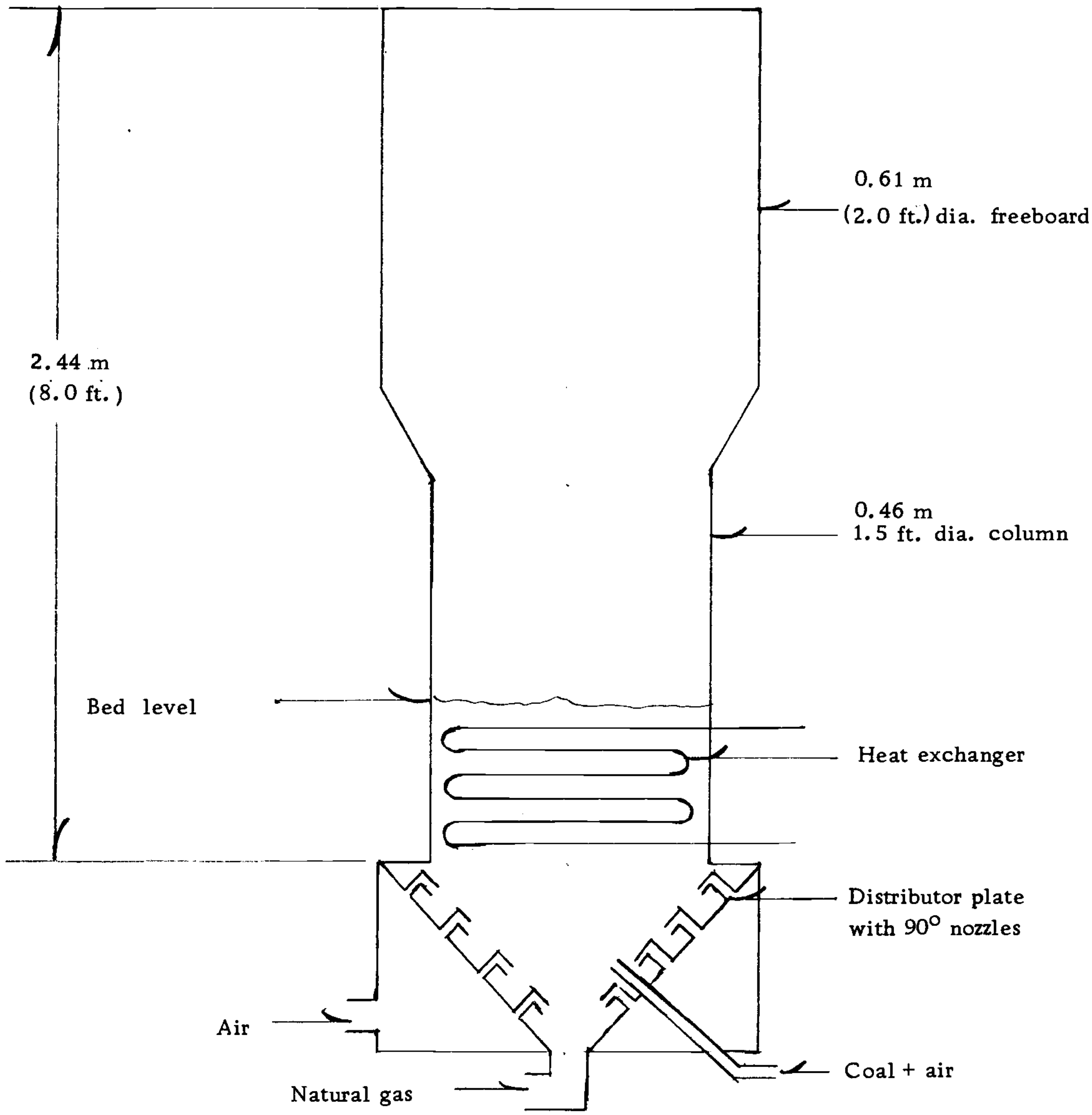
Figure 5. Schematic diagram of the six inch pilot size fluidized bed combustor built by the National Coal Board, London, England.

cooling coils were suspended into the bed for further cooling capacity.

Argonne's experiments were conducted in both excess air and air deficient modes. In the excess air mode the calcium to sulfur, Ca/S, ratio directly effected sulfur retention. Experimental evidence indicated that there is an optimum bed temperature, at which sulfur retention is maximized. This optimum varies with the type of coal used and Ca/S ratio but is generally near 816° C (1500° F.). Sulfur retention was found to increase with decreased superficial or fluidizing gas velocity [in the range of 1.07 to 2.26 m/s (3.5 to 7.4 ft/sec)]. Higher velocities will require coarser calcium additive to ensure its retention in the fluidized bed. Oxygen deficient experiments used a two-stage combustion concept, substoichiometric combustion of coal with additional air injected into the particle disengaging section to burn the gaseous hydrocarbons, H_2 and CO from the first stage. Preliminary results for the two-stage combustion process indicate the following advantages over the one-stage process: (1) lower NO emissions; (2) sulfur retention in the form of calcium sulfide (rather than sulfate), allowing for potentially easier additive regeneration; and (3) production of a combustible gas that could be used in a gas turbine system.

Rice and Coates, of Morgantown Energy Research Center, conducted research in 1973 (5) to compare sulfur retention using various coals in fluidized beds of limestone. Heat transfer coefficients were also determined for tubes immersed in the bed, shown in Figure 6. An 2.44 m (8 ft) high combustor with a 1.5 ft diameter combustion zone and a 0.61 m (2.0 ft) diameter, disengaging section was built of refractory lined carbon steel. The distributor plate was conical with stainless steel elbows welded over 3.18 mm (1/8 in.) drilled holes. This allowed injection of fluidizing air axially and parallel to the cone surface. Water-cooled 19.1 mm (3/4 in.) pipe served as a heat exchanger. Fluidizing velocities of 3 and 6 ft/sec were used. Results of this work indicated that sulfur retention by a limestone bed decreases with increased fluidizing velocity and the Ca/S ratio must be increased to compensate. Carbon burn-up was found to be too low, for commercial purposes, without recycling of fines. Heat transfer coefficients were found to vary, from about 181 to 370 W/m^2K (32 to 65 Btu/hr ft^2 ^oF), for water-cooled tubes, depending upon limestone size distribution.

Ehrlich (1) of Pope, Evans, and Robins Corporation and Bryers of Foster Wheeler Corporation reported, in June 1975, on experimental studies using an 0.743 m^2 (8 ft^2) combustor and 3.34 m^2 (36 ft^2) cold model fluidized beds. Both beds used horizontal, 51 mm (2 inch) O.D. heat exchanger tubes on a triangular pitch. A shallow [0.61 m (2 ft) static depth] bed was used and found satisfactory for combustion of coarsely crushed coal, 6.35 mm (1/4 in). Bed temperature control required about 2 m^2 of tube



Pressure	101.3 kPa (1 atm) abs.
Bed height	0.61 m (2.0 ft)
Fluidizing velocity	0.91 to 1.83 m/s (3 to 6 ft/sec)
Heat exchanger	1.6 cm (0.625 in.) O.D. tubing on 3.2 cm (1.25 in.) triangular pitch
Distributor	Steel cone, 0.125 in. drilled holes fitted with 90 degree elbows welded in place to give air flows both axial and parallel to cone.

Figure 6. Schematic diagram of fluidized bed combustor built by Morgantown Energy Research Center.

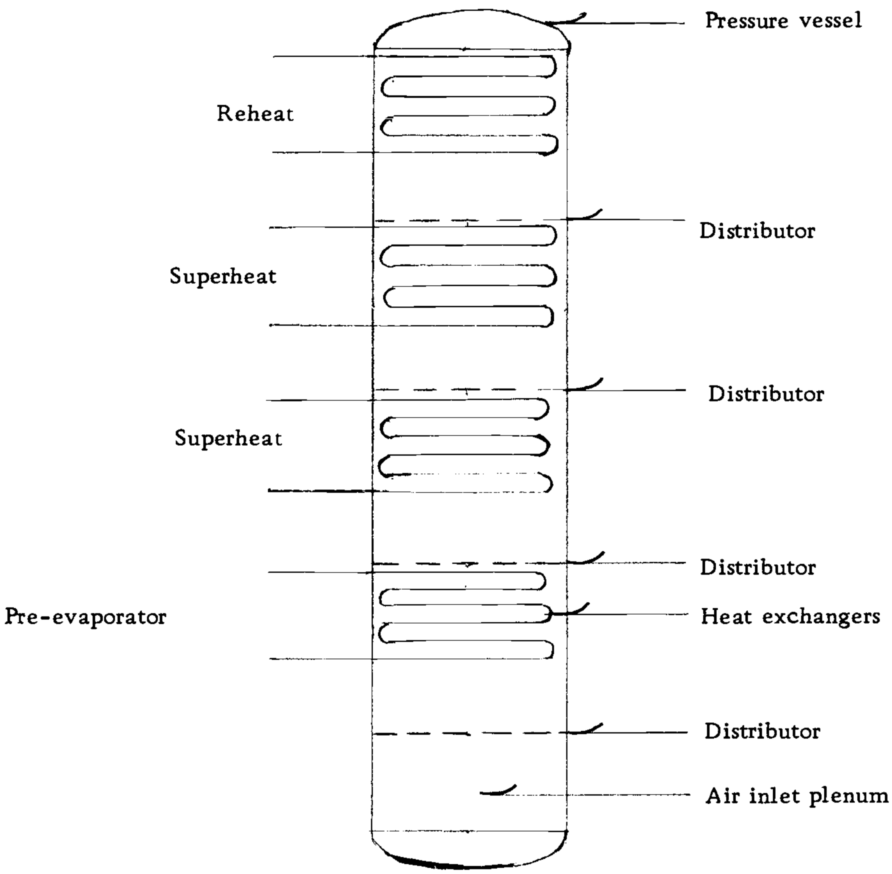
surface per square meter of bed cross-section. Most of the heat exchanger tubing was above the slumped bed level. The objectives were to determine if the heat exchanger could adequately control bed temperatures, and, for the cold model, to see if the bed would expand to fill the heat exchanger and to see if bubbling would be moderated by the presence of the tubing. Results indicate that beds will expand to fill a heat exchanger and heat transfer to pressurized water yielded a heat transfer coefficient of 227 W/m^2K (40 Btu/hr, ft, ^{2o} F). Total heat flux was found to be proportional to fluidizing velocity and to bed mass. Also noted was that internals in the splash zone (near the upper surface of the bed) will significantly reduce pressure fluctuations due to bubbling.

Ruth (6), of Exxon Research and Engineering Company, reported, in June 1975, his work in a 11.4 cm. (4.5 in.) I. D. refractory lined steel pipe combustor. Operating conditions were 1033-1253^{o}K (1400-1800^{o}F), 510-910 kPa (74-132 PSI), 0.91-1.8 m/sec (3-6 ft/sec), and 0.3-1.5 m (1-5 m) expanded bed height. A high L/D ratio and closely spaced heat exchanger tubing was found to cause severe hot spots and poor temperature distribution in the bed. Vertical coils were found to substantially eliminate this problem. Desulfurization of combustion gases was consistantly achieved in the 85-95 percent range, meeting Environmental Protection Agency (EPA) standards for new coal fired plants. Emissions on NO_x increased with increased excess air and were higher with horizontal tubes than with vertical ones. A potential advantage, of fluidized bed systems over conventional combustors, was found in the retention of hazardous trace elements, released during combustion, in the solid constituent. Combustion of the coal was on the order of 93-98 percent complete, increasing with percent excess air. Finally, Ruth measured heat transfer coefficients, for vertical coils, of 400-450 $W/m^2 \cdot {}^oC$ (70-80 $Btu/hr \cdot ft^2 \cdot {}^oF$).

Westinghouse Research Laboratories (10), reported on a design project completed in 1971. The project was to evaluate the "effectiveness and economics of fluidized bed combustion boilers in pollution abatement and steam/power generation." The report compared designs of 300 and 600 megawatt pressurized plants. Based on data available at the time of the report, capital cost of a once-through limestone system may be reduced by 20 percent and the effective increase in fuel costs for pollution control may be reduced 30 to 50 percent, below wet scrubbing systems. A 10 to 30 MW development plant was recommended as the next size for commercial fluidized bed combustion development.

Boiler design specifications, for a pressurized utility steam/power generation plant, call for maximum shop fabrication of four fluidized bed modules for the overall combustor. Each module serves a separate purpose; one for evaporation, two for superheat and one for reheat. The modules, shown schematically in Figure 7

STEAM GENERATION MODULE



Module size	HT=33.5 m (110 ft); DIA=3.66 m (12 ft) for 320 MW, 5.18 (17 ft) for 620 MW
Construction	Four primary fluidized beds stacked on top of one another
Bed	Area=1.52 x 2.13 m (5 x 7 ft); Depth=3.35 to 4.27 m (11 to 14 ft)(expanded)
Fluidizing velocity	1.83 to 3.66 m/s (6 to 12 fps); L/D = 1.7 to 2.1
Pressure	1013.37 kPa (10 atm) abs.
Heat Exchangers	2.54 or 5.1 cm (1.0 or 2.0 in.) O.D. tubing

ΔP_d = 2.69 kPa (10.8 in. H_2O), ΔP_b = 6.85 kPa (27.5 in. H_2O), ΔP_t = 11.79 kPa (47.33 in. H_2O)

d = distributor, b = bed, t = total

Modules required	4 for 265-620 MW
	3 for 165-465 MW
	2 for 90-320 MW
	1 for 30-145 MW

Figure 7. Schematic diagram of one module of a pressurized, fluidized bed, commercial power plant designed by Westinghouse Research.

are assembled on location. Primary combustor dimensions are about 1.5 by 2.1 m (5 ft x 7 ft) with a bed depth of 3.7 m (12 ft). Heat transfer surface is provided by 3.8 to 5 cm (1-1/2 to 2 in) diameter horizontal, water-cooled tubes. The system is designed to operate with both steam and gas turbine power generators. Four complete modules, as shown in Figure 7, would comprise the boilers of either a 320 or 635 MW plant (depending upon module size).

More recent research, completed in September of 1973, was a study sponsored by the U.S. Department of Interior (7) and performed by the British Coal Utilization Research Association Ltd (BCURA). This effort involved the modification of BCURA's existing pressurized combustor to enable operation at higher temperatures. Figure 3 shows the combustor which was basically refitted with better refractory and heat exchangers. Operating conditions included a pressure of about 483 kPa (70 psig), fluidizing velocity of 0.76 m/s (2.5 fps), 17 percent excess air, temperatures of 1172°K and 1228°K (1650°F and 1750°F), and calcium to sulfur, Ca/S ratio of about 2. Results obtained included combustion efficiencies in excess of 99 percent (without recirculation), sulfur emissions from coal of 3% sulfur content of 45.4 gm/1.1(10^6)J (0.1 lbm/10^6 Btu), signficant deposition of turbine blade specimens only at 950° K (1250° F), and minimal corrosion of heat exchanger tube specimens. Heat transfer coefficients in the 400 W/m^2K (70 Btu/ft^2, hr, ^oF) range were measured.

III. EXPERIMENTAL PROGRAM

Objectives

The objective of the experimental program was to qualitatively evaluate the effect of various immersed tube heat exchanger designs on the quality of fluidization in a two-dimensional fluidized bed. The study included evaluation of:

1. Triangular and rectangular pitched arrays of various spacings.
2. Varied distances between the distributor plate and the base of the tube arrays.
3. Tubes both totally immersed in the bed and extending into the freeboard.
4. The effect of fluidizing velocity on fluidization quality.

Description of Equipment

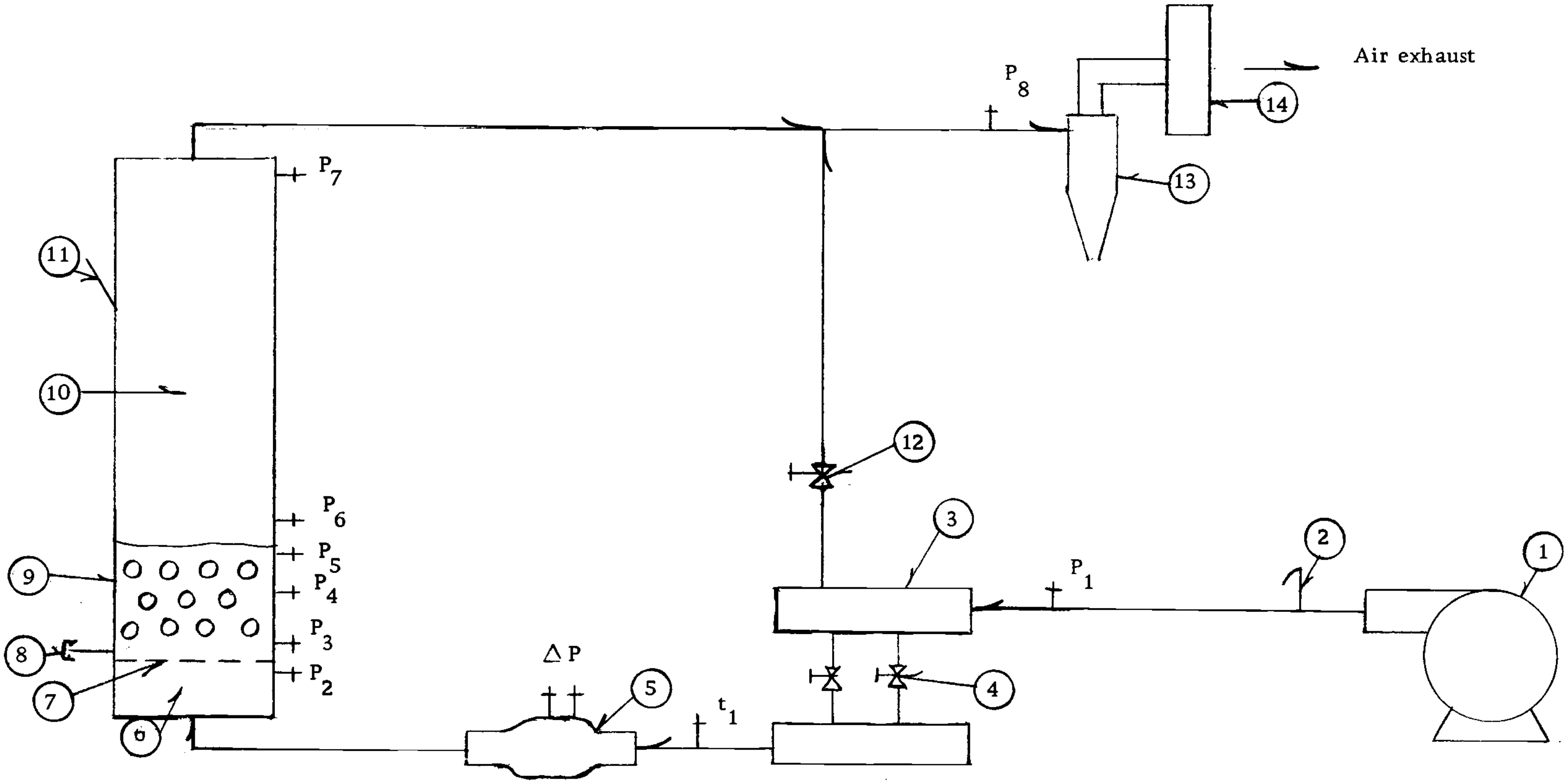
Design criteria for the two-dimensional fluidized bed experimental system were as follows:

1. A two-dimensional fluidized bed must be constructed to accommodate a sufficiently large number of commercial size tubing to give meaningful results.
2. Tube arrays must be easily interchangeable.

3. Distributor plates must be easily interchangeable.
4. Distributor plate upper surface should be visible.
5. Means of easily loading and unloading solids should be provided.
6. The fluidized bed column front should permit visual observation and photographic recording of the fluidization phenomena without abrasive degradation of the inner surface.
7. A means of continuously monitoring and varying the fluidizing velocity must be provided.
8. Entrained solids recovery should be provided.
9. System pressure and temperature measurements should be provided for.

A schematic diagram of the fluidized bed system used is shown in Figure 8. Discussion of individual components follows.

It should be noted that for the system component descriptions which follow, dimensions of materials used are in engineering units and pertinent fluidized bed dimensions and operating conditions are in SI units. For example, 1/2" plywood was used rather than 0.0127 m. Much of the data was taken in engineering units corresponding to the instrumentation used. Unit conversions were made to SI units for use in the calculations.



5. Laminar flow element
6. Air inlet plenum
7. Distributor plate
8. Solids unloading line with cap
9. Array test section

1. Gas compressor
2. Pressure relief valve
3. Air manifold
4. System air balancing valves

10. Freeboard
11. Solids loading port
12. By-pass valve
13. High efficiency cyclone
14. Cloth fiber filter

Figure 8. Schematic diagram of two-dimensional fluidized bed system. Descriptions of major components are on the following pages.

Fluidized Bed Column

The fluidized bed column consisted of several component parts integrated into a single unit, as shown in Figure 9. As shown in Figure 10, air enters the rear of the air plenum, via the laminar flow element and a 2" diameter fitting, below the distributor plate. Flowing up through the drilled distributor plate the air enters the tube array test section and limestone bed. Above the bed/array region, in Figure 9, is the solids disengaging zone, a region provided to permit the heavier solids to disengage from the rising gas stream and fall back to the bed surface. At the top of the column are air exhaust ports which lead to the inertial separator. Column dimensions, excluding the air plenum, are 0.51 m (1.67 ft) wide by 0.05 m (0.17 ft) deep by 2.1 m (6.9 ft) high. The bottom 0.76 m (2.5 ft) is the array test section. Column construction is of cut 2 x 4 sides and a 3/4" plywood back. The front is 1/2" acrylic held in place with clamps made of 1-1/2" x 1-1/2" x 1/4" steel angle. A 1/2" recess was provided for the array test panels to slide into via the base of the column. This ensured a constant cross-sectional area over the entire column height. Pressure taps and temperature measuring points were provided in the air plenum below the distributor plate and at several locations in the column itself. A 1" diameter plastic pipe was inserted into one side of the column

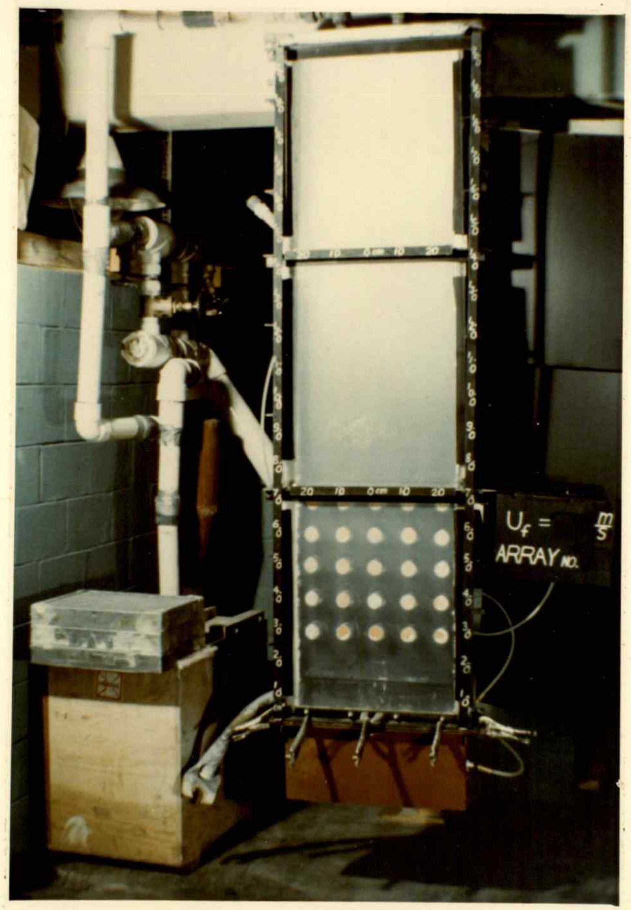


Figure 9. Photograph of the two dimensional fluidized bed system showing the column with an array in place, some of the associated piping and the box containing the exhaust filters.

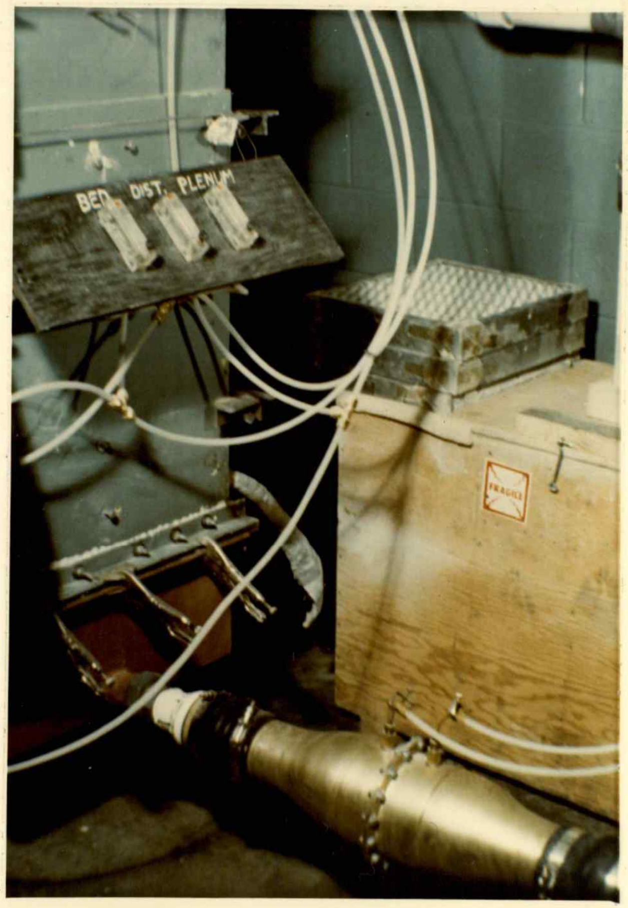


Figure 10. Photograph showing the connection between the laminar flow element (flow measuring orifice) and the air inlet plenum.

through which bed material could be loaded. At the base of the column, just above the distributor plate, a flexible hose was installed to provide a means of unloading the bed material. By simply removing the cap, while the bed was being fluidized, the solid material would pour out. All interior surfaces of the column, except the acrylic front were painted flat black.

The air distributor plate was fabricated from two 1/8" mild steel plates, each drilled with the desired number of 3/16" diameter holes. These were welded together at the edges with copper screen of approximately 44 mesh sandwiched between. Percent open area, for the plate, was about four percent (4%). Rubber O-Ring material was attached to both sides of the distributor plate to seal against air leaks from either the column or the inlet plenum side of the plate. The distributor plate was designed to give optimum performance at superficial velocities from 1.83 to 2.44 m/s (6 to 8 ft/sec) as well as acceptable performance at lower and higher velocities, and is shown in Figures 11A and 11B.

Holding the distributor plate in place was the inlet air plenum, a 0.1 x 0.61 x 0.25 meter (4.0 x 24 x 10 inch) box, made of 3/16" steel, into which the air was piped. Air entered via a 2" opening located at the rear center of the plenum and spread out below the distributor plate. The percent open area in the distributor plate as well as the location of the air inlet to the plenum provided a

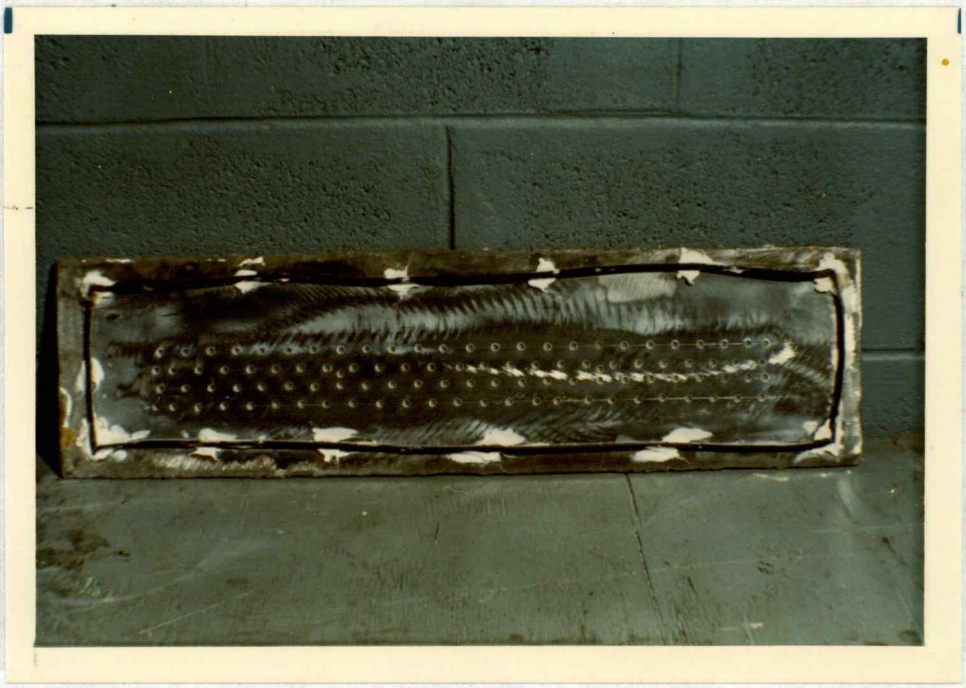


Figure 11A. Photograph of plan view of the distributor plate showing the hole pattern used. The screen is visible in the holes.

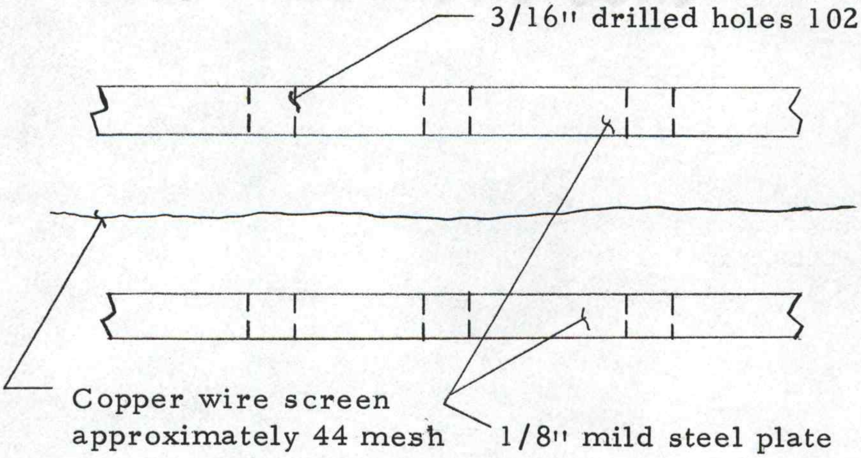


Figure 11B. Schematic drawing of distributor plate construction, with wire screen sandwiched between.

uniform distribution of air above the distributor.

Array Test Panels

Heat exchanger test panels were constructed of 1/2 x 20 x 24 inch plywood panels with short sections of 1-7/8 in. O.D. polyvinyl chloride (PVC) pipe glued into the plywood in the desired pattern, an example of which is seen in Figure 12. The completed test panels, when placed in the column test section, presented the observer with an end view of the horizontal tube array. A six-inch wide plywood spacer was used to vary the vertical location of the array within the 0.76 m (2.5 ft) high test section. The panels could be inverted to provide more flexibility in the positioning of the arrays.

Both triangular and rectangular pitched arrays were studied. Tube spacing was varied from 1/2 to 1 and to 1-1/2 tube diameters, both horizontally and vertically. Thus there were nine spacing combinations for each of the basic patterns, for a total of eighteen different test panels.

Entrained Solids Collection

Inertial separation of entrained solids from the fluidized bed column was achieved with a high efficiency cyclone, seen in Figure 13. A 2-1/2" pipe served to convey the gas-solid mixture to the cyclone. Bypass air also entered the cyclone. This served to

Figure 12. Photograph showing construction of the array test panels. Plastic pipe sections are glued into a sheet of 1/2 in. plywood in the desired pattern.

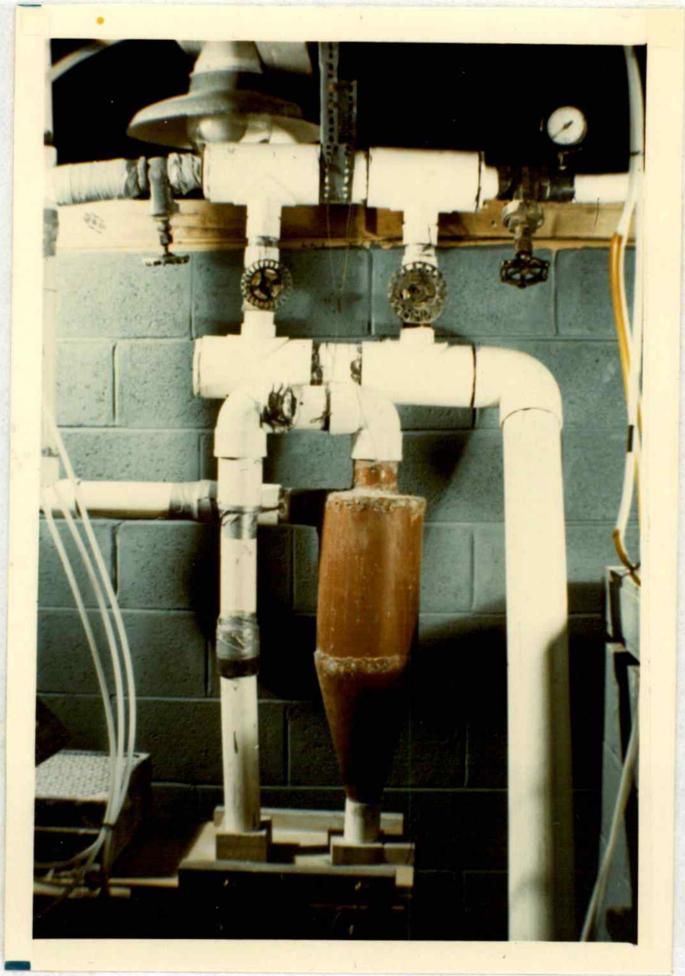


Figure 13. Photograph showing the high efficiency cyclone and its associated piping. The flow control manifold and valves are seen above the cyclone.

provide some noise attenuation for the by-pass air, rather than venting it directly to the atmosphere. Solids were collected at the outlet of the cyclone and the clean air exhausted via a cloth fiber bag filter to the atmosphere. The cyclone effectively collected solids larger than approximately 25 microns and the bag filter system collected particles larger than about 5 to 10 microns.

Air Compressor and Controls

Air was supplied from a positive displacement blower and its associated piping as shown in Figure 14. The blower had the following operating specifications:

1. 5 x 6 inch Roots-type lobes manufactured by Sutorbilt.
2. 1750 rpm.
3. Rated at 280 cfm at 3.5 psig with 7.0 psig design limit.

The blower was driven by a 15 hp., induction motor running at 3500 rpm. Vibrational isolation of the system was achieved by mounting the motor-blower unit on a six inch thick, steel reinforced concrete pad with one inch thick hard rubber pads between the unit and the concrete and between the concrete and the floor. Accoustical suppression of machinery noise was accomplished by constructing a sand-filled cinder-block wall around the unit and lining it with glass fiber insulation and "accoustical" tile, as seen in Figure 15. Plywood sheets on either side of 2 x 4 frames formed two lids which

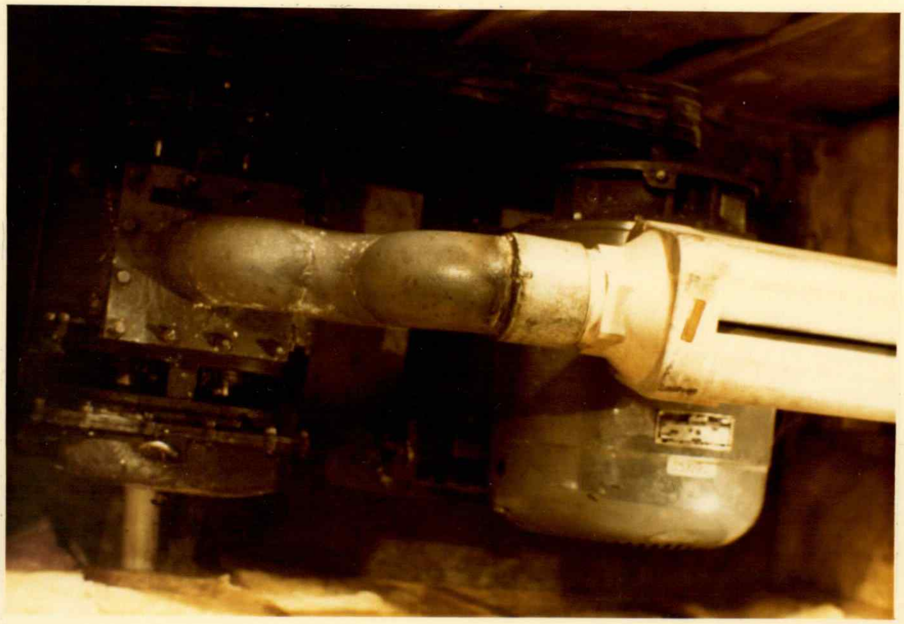


Figure 14. Photograph of the roots type positive displacement compressor, on the left, and its electric drive motor. The compressor exhaust line can be seen in the lower left of the picture.

Figure 15. Photograph showing the glass fiber insulation and "accoustical" tile used to supress the machinery noise of the compressor.

were filled with sand and placed on top of the walls. Four inch thick foam rubber gaskets sealed leaks between side walls and the lids. The inner side of the covers were lined with accoustical tile. Figure 16 shows the construction.

Figure 16. Photograph showing the cinder-block enclosure built around the compressor. Also shown are the plywood and 2 x 4 lids prior to being filled with sand.

Flow control was achieved with the use of a three-valve manifold. Two 2 inch valves connected the inlet and outlet halves of the manifold. The third 2 inch valve connected the inlet half to the by-pass line. A 6.5 psig pressure relief valve was installed ahead of the manifold to protect the system.

Air Flow Measurement

Volumetric air flow rate to the fluidized bed was measured with a Laminar Flow Element manufactured by Meriam, Model 50MC2-4F rated at 400 cubic feet per minute (cfm) at 8 in. H_2O and shown in Figure 17. The operating manual for the device included tables of correction factors for deviations from both standard temperature and local atmospheric pressure. Differential pressures across the laminar flow element are measured in inches of water. A chart is provided with volumetric flow rate in cubic feet per minute plotted against inches of water. The graph of these values is linear throughout the range of the device, and is reproduced in Appendix D.

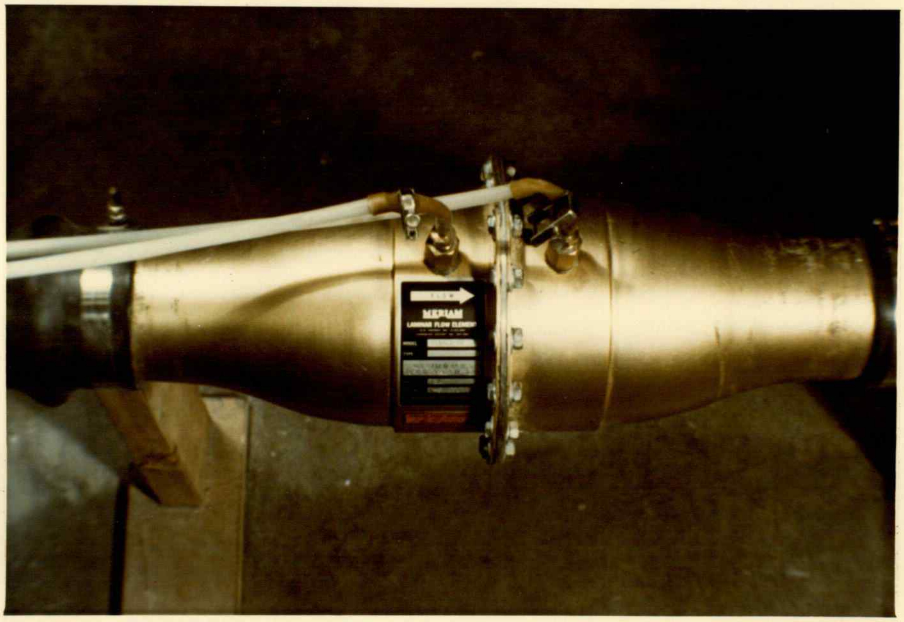


Figure 17. Photograph showing the Meriam Laminar Flow Element.

Pressure and Temperature Measurements

Several pressure and temperature measuring points were provided in the system as shown in Figure 8. A mercury manometer, with a scale graduated for equivalent inches of water, was used to measure differential pressure across both the distributor plate and the fluidized bed. A water manometer measured differential pressures across the laminar flow element. Temperature measurements were provided for with copper-constantan thermocouples installed in the system. Except for the air temperature at the laminar flow element, temperature measurements for this work were unnecessary and were provided for primarily for future work. A United Systems Corporation Thermocouple Thermometer, Model 590TF, type T, with digital display in degrees fahrenheit was used to provide the air temperature at the inlet to the laminar flow element (orifice).

Solids for Bed Material

Several samples of limestone and dolomite were obtained in various sizes from Kaiser Refractories and Pfizer Minerals, Pigments, and Metals Division. These were each sieved, using Tyler sieves shaken by hand, to determine their approximate size distribution and then fluidized without internals in the bed. Number twenty (20) dolomite, with a mean size of 569 μm (28 mesh), was selected, partially based upon compressor capacity considerations, for further use. Table 1 shows the six grades examined, along with their sieve sizes and weight fraction.

Comparison of these calcium samples with Geldart's (2) powder classification criteria places them in Group D, with the possible exception of the sample with the finest mean size. The primary characteristics of Group D solids are that they are large and dense, bubbles tend to rise very much slower than the intersticial fluidizing gas, and gas by-passing through the bubbles.

For the second portion of the experimental program, which involved changing the array location relative to the distributor plate as will be discussed below, number 9 mesh limestone with a mean particle size of 1379 μm (12 mesh) was also used to provide an indication of the effect of particle size on fluidization.

All solids were sieved periodically throughout the experiment to keep track of the extent of size degradation. Portions of the elutriated fines were remixed, as necessary, with the unentrained solids in an effort to maintain constant size distribution as close as realistically possible.

Table 1. Table showing the weight fraction of each particle size for each of the six samples studied.

Material Description		Particle Size Range										
	μm	+6730	-6730 +4760	-4760 +3360	-3360 +2380	-2380 +1680	-1680 +1410	-1410 +1190	-1190 +841	-841 +595	-595 +297	-297
	Tyler Screen	+3	-3 +4	-4 +6	-6 +8	-8 +10	-10 +12	-12 +14	-14 +20	-20 +28	-28 +48	-48
Roofing grade dolomite	Weight Fraction	0.073	0.408	0.315	0.157	0.026	0.021	----(3)	----	----	----	----
Crude dolomite #6 dolowhite(1)	Weight Fraction	----	----	0.007	0.636	0.312	0.019	0.019	0.007	----	----	----
#20 dolowhite	Weight Fraction	----	----	----	----	----	----	0.014	0.403	0.458	0.111	0.014
Calcium grit #1	Weight Fraction	----	0.176	0.703	0.110	0.011	----	----	----	----	----	----
Calcium grit #9	Weight Fraction	----	----	----	0.222	0.343	0.162	0.121	0.121	0.030	----	----
Marblewhite (2) -16+40	Weight Fraction	----	----	----	----	----	----	0.053	0.487	0.342	0.118	----

(1) Dolowhite is a Kaiser Refractories brand name

(2) Marblewhite is a Pfizer M, P & M Division brand name

(3) Blank spaces at fine end of each row include quantities too small to be significant.

Design Problems and Solutions

Several design problems were encountered during the course of this project which the author would like to pass on for the benefit of others.

Plate Glass versus Acrylic

Knowing that limestone/dolomite are abrasive and that a clear front of the column was desired for photographic purposes, plate glass was used for its abrasion resistant qualities. It was also felt that if properly restrained, the glass could withstand the pressure loads on it from the fluid bed. No technical assistance about the subject was available locally. The two problems were experienced. First, it was difficult to clamp the glass in place with sufficiently even pressure that it would not crack while being installed or while the bed was in operation. A sheet of half inch thick acrylic plastic was then placed outside the glass to support the glass uniformly as seen in Figure 18. However, it was apparent that the glass was entirely too fragile. Half inch acrylic was then installed by itself and has served well. The inner surface of the acrylic did not abrate to the point of having to be replaced, during a total estimated operating time of 15 hours. The primary concern was to be able to photograph through it.

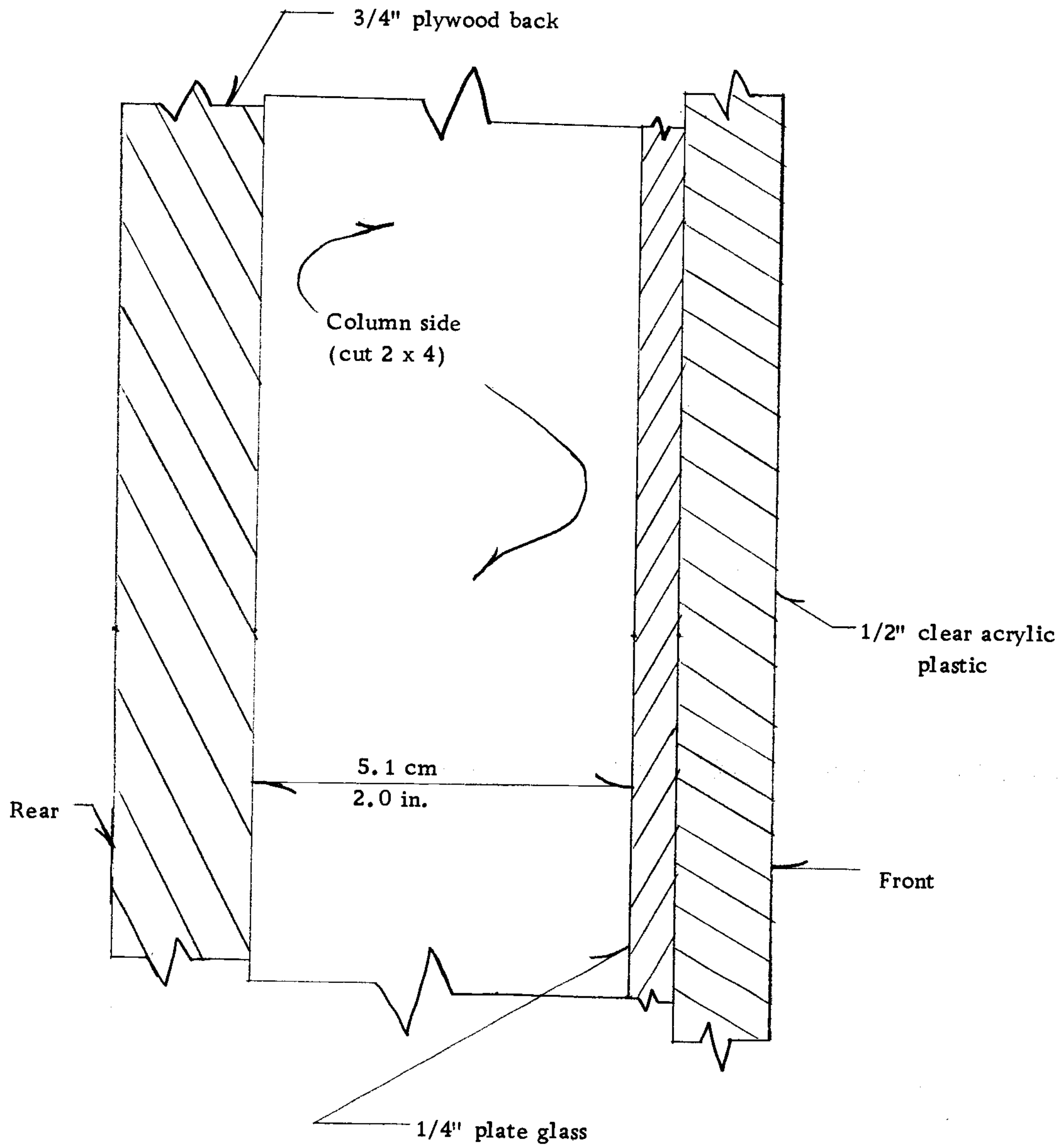


Figure 18. Schematic drawing showing the 1/4 in. plate glass being held in place and supported by 1/2 in. acrylic plastic. Clamps were placed along the edges of the column with a flat surface against the plastic and adjusting screws at the rear on the 3/4 in. plywood back. (Use of the plate glass was discontinued in favor of the acrylic plastic by itself.)

Distributor Plate Design

Originally, the distributor plate was to be sandwiched between the front and rear of the column and held in place by the air inlet plenum. This would permit the upper surface of the distributor plate to be visible and photographed. Difficulty was encountered in sealing the air inlet plenum, with this arrangement. Gas by-passing was discovered to have taken place at the front and rear edges of the original distributor plate. A major design change was then made. The final distributor plate was held in place by the air plenum but sealed at its upper and lower surface rather than around its edges, as with the first design. The upper surface of the distributor was no longer visible but the arrangement was much more workable.

Tube Array Panels

Since many different tube arrangements were planned for study, it was decided to make them all in advance and change them by sliding them in and out of the bottom of the column. To make each tube easily visible from the front of the column corks were used in the ends of the plastic pipe sections which formed the arrays. Springs (with a spring constant of 1 lb_f/in or 0.181 kg/cm) were used to hold the corks against the acrylic front; shown schematically in Figure 19. It was found that the springs were too weak and had to be stretched to increase the force on the corks. The bed material had a tendency to get behind the corks and bind them against the inner walls of the tubes rather than permitting them to "float" against the acrylic front. When this occurred bed material was then able to work its way between the corks and acrylic front, degrading somewhat the view of the fluidization.

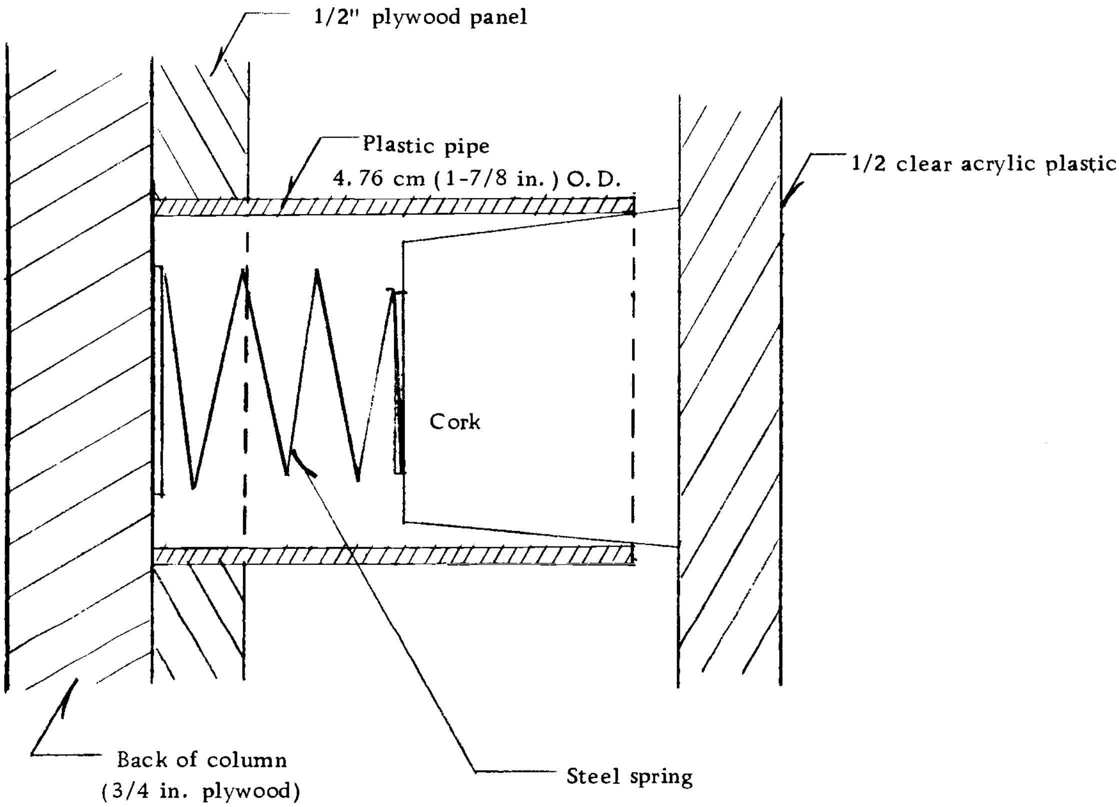


Figure 19. Schematic diagram showing the use of springs to hold the corks (used to make the ends of the tubes visible) up against the acrylic front.

Solids Hold Up Behind the Panels

Though the tube array panels were fastened to the back of the column, approximately two to three kilograms (2-3 kgm) or about one pound of bed material always became held up behind the panel at the beginning of each run. While this did not present a particular problem, it was necessary to readjust the bed height to the desired level.

Experimental Procedure

As mentioned in the section on bed materials, the first step for this investigation was to select one grade of limestone from the six samples available to be used for the balance of the study. This was accomplished by fluidizing each sieved sample using a 0.45 m (1.48 ft) "slumped depth" bed with no internals. The bed material which fluidized easiest, that is at the lowest superficial velocity, and which yielded the most stable fluidizing conditions over the widest range of velocities was chosen for further use.

The Program

In order to systematically evaluate each of the eighteen test panels, to assess their effect on the quality of fluidization, the following experimental program was followed:

1. To establish a basis for comparison, the bed was fluidized with no internals, at several velocities. Since gross slugging was the dominant mode of fluidization observed during trial runs, it was decided that fluidizing the bed with the tube arrays as close to the distributor plate as possible would most graphically demonstrate the effect of internals on the quality of fluidization. Thus the tube arrays were initially placed 2.5 cm (1.0 in) above the distributor plate.

2. Dolomite, with a mean size of 569 μm (28 mesh), was loaded into the column so that the free surface of the bed was 45 cm (17.7 in) above the distributor plate; which also placed it approximately even with the top row of the arrays.

3. The bed was fluidized, with each test array, from the maximum superficial velocity of either 3.05 m/s (10 ft/sec) or 2.75 m/s (9 ft/sec), depending on the local atmospheric pressure and compressor temperature, down to 0.61 m/s (2 ft/sec) or the minimum fluidization velocity which ever came first, in four increments. In any event, the minimum fluidization velocity was always identified at the end of each velocity series. Starting with the maximum velocity first minimized the rising temperature effect on the fluidizing air, due to compression, and more importantly due to the rising temperature of the compressor equipment itself.

4. At each velocity the following parameters were measured:

   a. Pressure drop across the distributor plate.

   b. Maximum pressure drop across the bed.

   c. Minimum pressure drop across the bed.

   d. Average pressure drop across the bed.

   e. The gage pressure at the compressor outlet.

   f. The change in slumped bed depth at the end of each velocity increment.

5. At each velocity, notes were made on the various qualities of fluidization observed. These notes were based upon criteria established ahead of time and which will be discussed later.

6. Bed depth was returned to the desired slumped level, after each velocity increment.

7. Several photographs as well as high speed (54 frames per sec) motion picture films were taken, at each velocity, for a permanent record as well as to permit critical evaluation of the fluidization phenomena observed.

8. In order to achieve the desired superficial velocity as quickly as possible, primarily due to the rapidly rising temperatures being experienced, a table was made in advance which automatically corrected the volumetric flow rate, based on the orifice pressure drop, for temperature and atmospheric pressure and converted it into velocity in meters per second. These tables were prepared for

a wide range of atmospheric pressures which could be expected. These calculations used the temperature and pressure correction factors provided in the operating manual for the Meriam Laminar Flow Element used. A copy of the calibration curve for this device is in Appendix D.

No attempt was made, during this phase of the experimental work, to make value judgments on each tube array tested. Rather, the effort was to identify the various qualities of fluidization which might be indicative of a particular tube arrangement; based upon operation in a two-dimensional fluidized bed.

However, as the second portion of the experimental program called for observing the fluidization process with the arrays placed further from the distributor plate and with two different bed depths, it was decided that, due to time constraints, two tube array patterns would be selected from the eighteen for this portion of the study. One each of the triangular and square pitch arrangements was chosen by a method to be described later.

The two-dimensional studies consisted of:

1. With the same bed depth of 45 cm the tube arrays were located in the column with the tubes 15 cm (6 in.) and 25 cm (10 in.) above the distributor plate. This permitted observations of the effect of having the tubes extend into the freeboard above the bed.

2. The bed depth was set at both 45 cm and 23 cm (17.7 in. and 9 in.) with the tubes in each of the two positions in the bed mentioned above. Thus further evaluation of the effect of tube location relative to bed depth was possible.

3. One coarser grade of limestone was also fluidized under the above bed and array conditions. The coarser grade, chosen primarily because of limited compressor capacity, was mesh number nine (9) and had a mean size, as stated earlier, of 1379 μm (12 mesh).

A total of thirty-six (36) runs were accomplished from eighteen (18) test panels, each at five superficial velocities.

Fluidization Quality Characteristics

There are several characteristic traits of fluidized beds which when considered together form an overall quality for the fluidization being considered. Some of these are percolating, bubbling, slugging, and channeling. It is easy to ask, for example, "How much slugging is taking place or how severe is it?". So, following that thinking, three levels or degrees were assigned, admittedly arbitrarily, to each of several quality traits. With these as a basis, value judgments were possible when considering the effect of each tube array on the quality of fluidization.

In general slugging is an undesirable trait and trial runs showed that it was possible to distinguish between levels of severity by observing frequency, size, and regularity. While it would be nice to have a uniformly fluidized bed or a homogeneous one, some bubbling is acceptable if not unavoidable. Size of bubbles on the average, growth rate, and frequency are definable qualities. On the basis of the above examples the following list of characteristics of interest was established to fascilitate the subjective evaluation of each of the heat exchanger tube arrangements tested:

Fixed Bed

F1 - Solids movement in over 75% of the bed.
F2 - Solids movement in over 50% of the bed.
F3 - More than 50% of the bed is unfluidized.

Bubbling

B1 - Small uniform bubbles, uniformly distributed in the bed with slow growth.
B2 - Medium sized bubbles experiencing moderate growth.
B3 - Large bubbles with rapid growth and more randomly located in the bed.

Slugging

S1 - Bubble growth causing intermittent slugging, with noticeable column movement. *

* The reader is reminded here that the column height was 200 cm (6.5 ft.) while the slumped bed depth was 45 cm (1.5 ft.). This provided a considerable disengaging zone.

S2 - Regular slugging with moderate solids carryover into the freeboard.

S3 - Severe slugging with large bubbles and extensive solids carryover into the freeboard.

Gas Channeling

CG1 - Gas establishes a path of least resistance up the column and maintains it for a definite period of time. Gas rises in the form of bubbles.

CG2 - Gas stream definitely established which bypass much of the heat exchanger bundle. Gas stream is fed intermittently by near by bubbles.

CG3 - High gas velocities in established channels causing extensive gas bypassing. Solids are thrown well up into the freeboard.

Elutriation and Entrainment

E1 - Few solids in the freeboard, most all of which fall back to the bed.

E2 - Moderate amounts of solids in the freeboard, up to 50% of the freeboard height.

E3 - Significant amounts of solids carried into the upper half of the freeboard, indicating significant loss of solids from the bed.

Data Collected

The raw data collected during the tests included the items shown in Figure 20 on pages 54 and 55.

Items numbered (1) through (26) in Figure 20 were transferred to data punch cards and input to a computer program for basic reduction. All of the raw data are included in Appendix A and tabulated with the array number as the primary variable. The

No.	Symbol	Description
1.	DATE	Date of the particular run; month day year.
2.	TUBE ARRAY(1)	Alpha numeric identifier indicating horizontal and vertical spacing and pitch arrangement.
3.	ARRAY LOC.	Distance of first row of tubes above distributor plate, cm & in.
4.	DPM	Mean partical size of solids, μm & in.
5.	UO	Gas superficial velocity, m/s & ft/sec.
6.	PATM	Atmospheric pressure during run, kPa & in Hg.
7.	PORF	Pressure drop across the orifice (laminar flow element), kPa & in H_2O.
8.	TORF	Temperature of air entering the orifice, K & F.
9.	DPD	Pressure drop across the distributor plate, kPa & in H_2O.
10.	DPBAV	Average pressure drop across the bed, kPa & in H_2O.
11.	DPBMX	Maximum pressure drop across the bed, kPa & in H_2O.

---

(1) Tube array identifiers are composed as follows:

A : 1-1/2 tube diameters horizontal spacing between tubes.
B : 1 tube diameter horizontal spacing between tubes.
C : 1/2 tube diameter horizontal spacing between tubes.

1 : 1-1/2 tube diameters vertical spacing between tubes.
2 : 1 tube diameter vertical spacing between tubes.
3 : 1/2 tube diameter vertical spacing between tubes.

S : Square pitch arrangement.
T : Triangular pitch arrangement.

Example: A2-S = 1-1/2 tube diameters horizontal spacing, 1 tube diameter vertical spacing, and square pitch.

C3-T = 1/2 tube diameter horizontal spacing, 1/2 tube diameter vertical spacing, and triangular pitch.

EMPT = No internals used at all.

No.	Symbol	Description
12.	DPBMN(2)	Minimum pressure drop across the bed, kPa & in H_2O.
13.	PS	Total system pressure at the outlet of the compressor, kPa & PSIG.
14.	LI	Slumped bed height (initial), cm & in.
15.	LF	Slumped bed height (final), cm & in.
16.	LE(3)	Expanded bed height, cm & in.
17.	H1	Location in the bed, above the distributor plate, cm & in.
18.	H2	Location in the bed, above the distributor plate, cm & in.
19.	H3	Location in the bed, above the distributor plate, cm & in.
20.	DB1	Bubble diameter at height H1, cm & in.
21.	DB2	Bubble diameter at height H2, cm & in.
22.	DB3	Bubble diameter at height H3, cm & in.
23.	DTIME	Duration of run at the particular conditions, sec & min.
24.	UMF	Minimum fluidizing velocity, m/s & ft/sec.
25.	QUAL(4)	Alpha numeric quality of fluidization identifiers within array.
26.	QUAL	Alpha numeric quality of fluidization identifiers above array.

(2) As the pressure drops across the bed were measured with an undamped manometer, it was possible at times to record negative pressures during extremely unstable operating conditions. These negative excursions are felt to be caused by a large mass of solids moving past the upper pressure tap with a large bubble or void below. This situation causes a lower pressure at the bottom of the column than at the top; with the reverse normally being the case.

(3) Values for the expanded bed height are best estimates of the average expanded bed height. If the operating conditions are such that there was no defineable bed height then a ND will be used to signify No data.

(4) These are code identifiers which correspond to the various qualities of fluidization observed and which are discussed in the text.

Figure 20. List of the values included in the raw data collected for each array and operating condition.

superficial velocity was varied incrementally for each array. The first two-thirds of the raw data section consists of the data for each of the initial nineteen tube arrays (including the blank one). The last third of the section involves just two different arrays but also two bed depths, two different solid sizes, and two different array locations above the distributor plate. Each portion of the raw data has two sections, the first in the International System of Units (SI) and the second in English Units. The raw data was manipulated by the computer to achieve necessary unit conversions and to achieve the desired output format. It should be reiterated here that, for convenience, the raw data was collected in both SI and English units as appropriate to the instrumentation used.

IV. RESULTS

The stated intent of this work was to qualitatively assess the fluidization characteristics of various heat exchanger tube arrangements and locations within the bed, with the underlying desire to aid the design engineer in making practical decisions relative to particular, specified operating conditions. Listed below are many of the parameters which may independently or collectively affect overall fluidization quality:

1. The presents or absence of objects immersed in the bed area.
2. Immersed heat exchanger tube arrangement (rectangular or triangular).
3. Immersed heat exchanger tube spacing (horizontal and vertical).
4. Immersed heat exchanger array location relative to the distributor plate.
5. Superficial Gas Velocity.
6. Mean size of the bed material.
7. Bubbling (though it is itself dependent on the other variables).
8. Quantity of bed material used.
9. Size of heat exchanger tubes.
10. Shape of heat exchanger tubes.

11. The presents or absence of finned surfaces on heat exchanger tubes.
12. Heat exchanger tube orientation (vertical or horizontal).
13. Baffles above the bed for supression of solids carryover.
14. Distributor plate design.

While each of these parameters may affect fluidization, in the interest of a specific, well defined research project, only the first eight were considered for this work. Each area is discussed in some detail as to its effect on the quality of fluidization. The discussion is primarily subjective in nature, based upon visual observations made during the experimental work. Additionally, tube errosion is discussed with respect to tube array location relative to the distributor plate.

The Presence of Internals

A fluidized bed with no internals is one which has no objects or structures rigidly attached to the interior of the reaction vessel, which are within or extend into the bed region (typically at the bottom of the vessel) while the bed is in its fluidized state. The bed region is that volume of the bed which contains the majority of the mass of bed material with fairly well defined upper surface. For the purposes of this discussion it is not intended to include that region immediately above the bed, in the freeboard, where baffles are typically located to minimize solids carryover. A fluidized bed with no internals may be subjected to considerable gross bubbling and/or slugging behavior. Whether a bed has a tendency to slug or not depends greatly upon the size of the bed, its aspect ratio and upon the density or specific gravity of the bed material used.

Two different sizes of limestone/dolomite were used for this study. With a specific gravity range of 2.5 to 2.9 the calcium groups are particularly susceptible to rapid, large bubble growth and slugging, such as is shown in Figures 21A and 21B. With both sizes, as the fluidizing velocity was increased, the bubbles became larger faster and bed instability (reflected in pressure drop fluctuations) more pronounced. The smaller the particle size the greater the tendency for large bubbles at lower velocities. For the smaller solids, bubbles were on the order of from 25-30% larger at lower velocities, to 25-50% larger at higher velocities, at the same level in the bed. Again, these were subjective judgments based upon visual observations, but do include the results of photographic examination.

Tube Arrangement

Tube arrangement variations for this study are either triangular or rectangular, and the discussion is aimed at relating

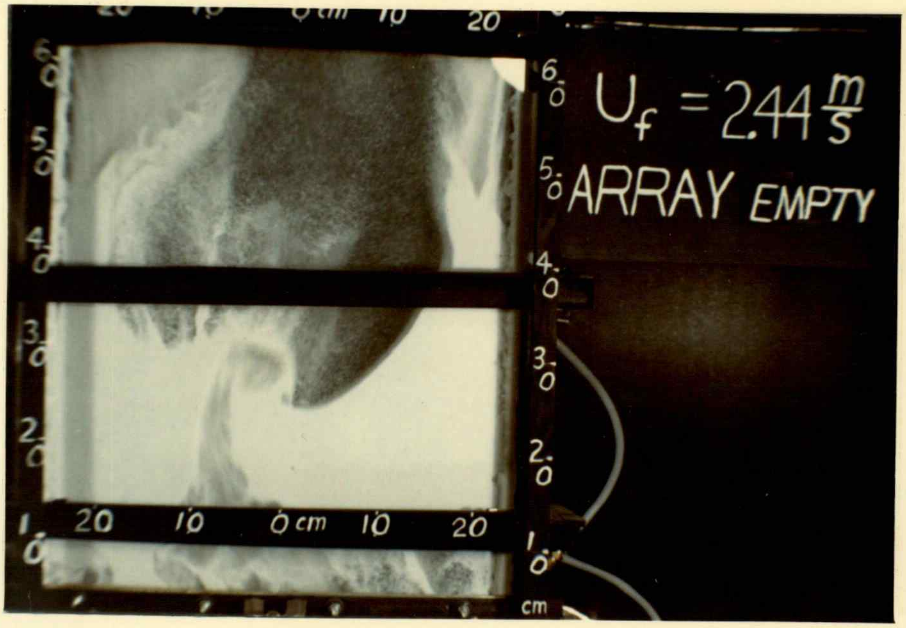


Figure 21A. Photograph showing rapid bubble growth with dolomite of mean size 569 μm (28 Tyler mesh) at 2.44 m/s (8 ft/sec) superficial velocity.

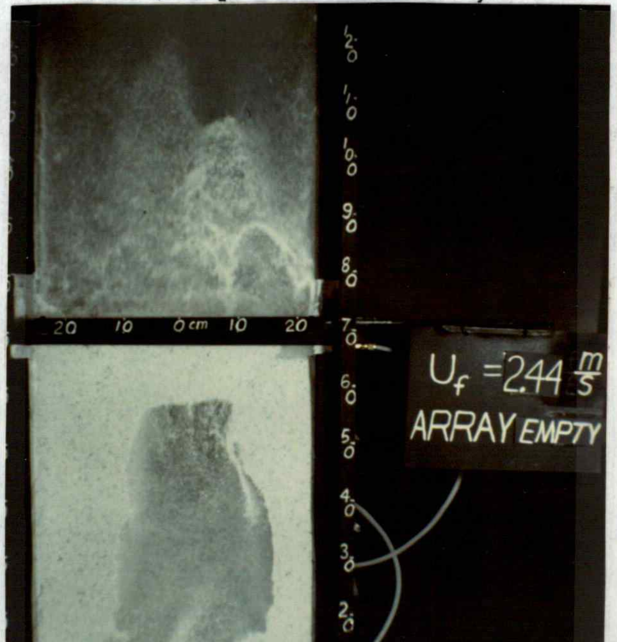


Figure 21B. Photograph showing a very large bubble starting very near the distributor plate. Limestone of mean size 1379 μm (12 Tyler mesh) is being fluidized at 2.44 m/s (8 ft/sec).

the effect of this simple variation to fluidization quality.

Channeling or gas by-passing through the array and bed material was predominant in rectangular arrangements. Good examples of channeling can be seen in Figures 22 and 23. Channeling may be experienced in triangular arrangements too, though to a lesser extent, as shown in Figure 24. In this case the gas by-passing was observed to be in a diagonal direction, rather than vertically. Visual observations suggested that rectangular arrangements permit the solids to have longer residence times on top of the tubes. While generally all tubes have a pile of solids on top of them, regardless of arrangement, this characteristic seems to be enhanced by the rectangular pattern. The quantity and duration of residence on the tubes appears to depend upon both fluidizing velocity and the height of the particular tube above the distributor plate. Solids collecting on top of the tubes, to the point of forming a discernable layer across a horizontal row of tubes is shown in Figure 25.

Gas-solids mixing appeared to be negatively affected by channeling in rectangular arrangements when compared to triangular ones. The degree and quality of mixing on a scale of poor to excellent, is admittedly subjective and difficult to keep in perspective. It was attempted to visually assess the mixing and make judgments concerning the extent to which solids moved about or circulated (how

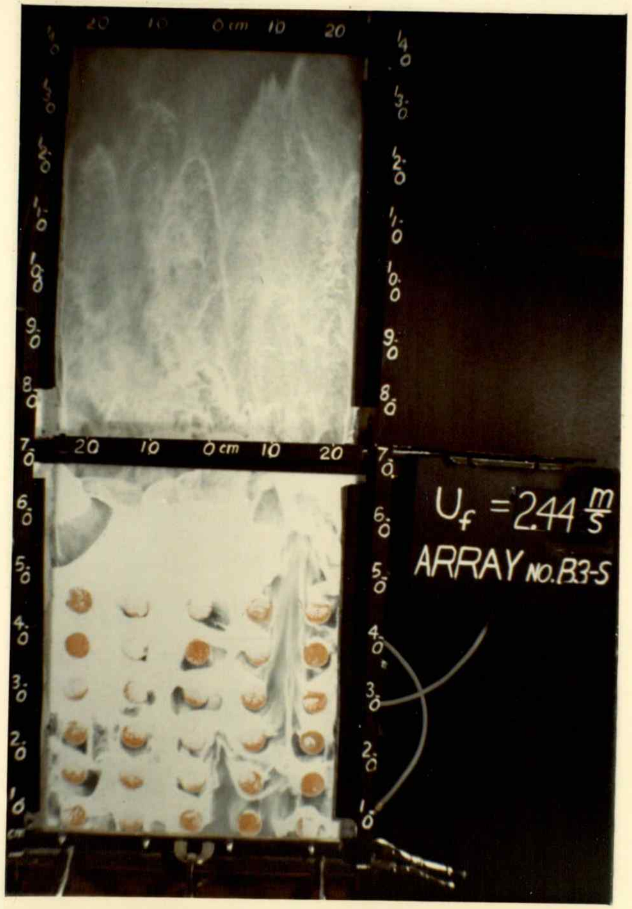


Figure 22. Photograph showing channeling or gas by-passing in a rectangular array. The 569 μm (28 Tyler mesh) solids are being fluidized at 2.44 m/s (8 ft/sec).

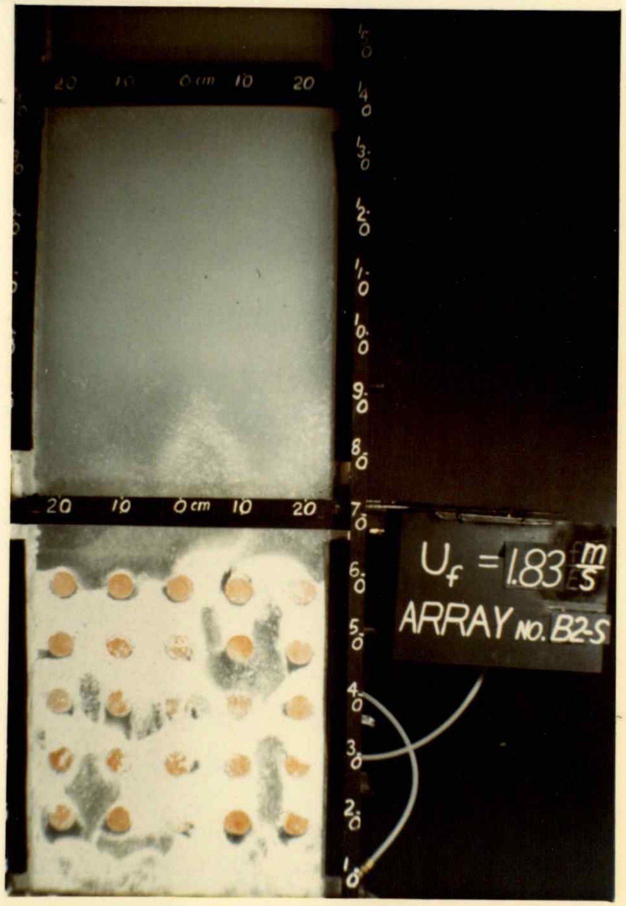


Figure 23. Photograph showing both vertical channeling and relatively large bubbles. The 1379 μm (12 Tyler mesh) solids are being fluidized at 1.83 m/s (6 ft/sec).

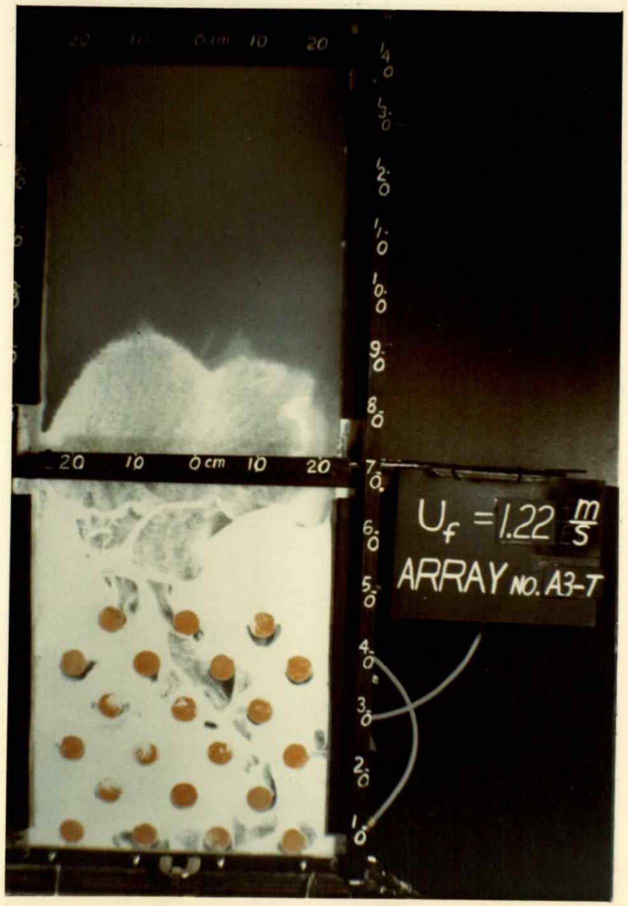


Figure 24. Photograph showing diagonal channeling or gas by-passing in a triangular array. The 569 μm (28 Tyler mesh) solids are being fluidized at 1.22 m/s (4 ft/sec).

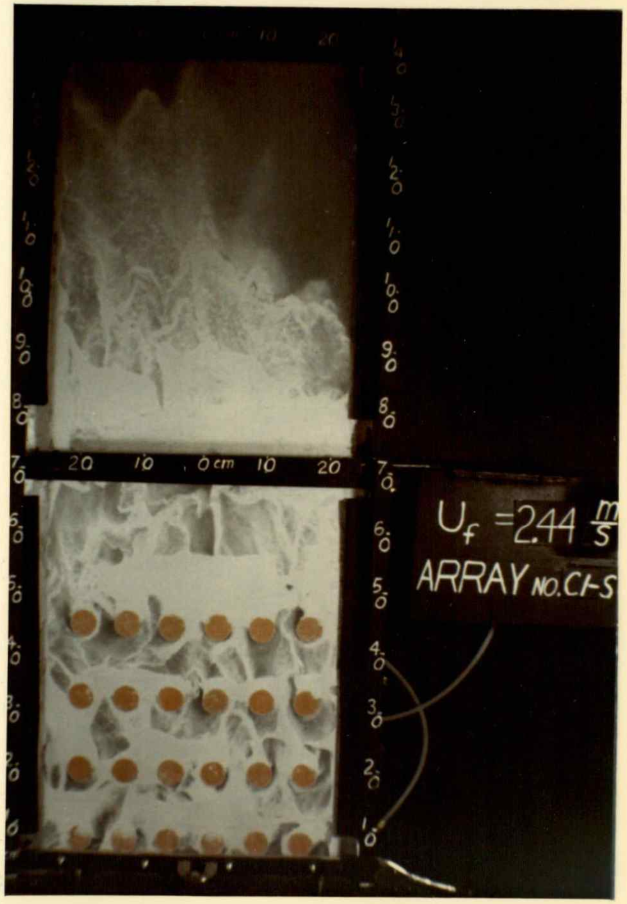


Figure 25. Photograph showing the solids forming layers above rows of tubes due to the combination of the tubes being too close together and the rising gas stream holding them up. The 569 μm (28 Tyler mesh) solids are being fluidized at 2.44 m/s (8 ft/sec).

far, how fast, and how randomly) and what the estimated average bed voidage was. Channeling or by-passing was considered to be an undesirable trait and was considered in the evaluation of mixing quality. Triangular arrangements force the gas to follow a more irregular path through the array, as shown in Figure 26. Because of this flow pattern, solids tend to have shorter residence times on top of the tubes, better gas-solids mixing, and solids circulation throughout the array is more uniform. A triangular arrangement also tends to limit bubble size to a greater extent than a rectangular array, due to the great probablity of the bubble encountering a tube and being influenced by it.

The average pressure drop across the bed tends to be about the same for both arrangements but the extremes of the fluctuations are greater with the triangular arrays, as can be seen by examination of the raw data in Appendix A.

Tube Spacing

Tube spacing refers to the horizontal and vertical separations between the tubes. As shown schematically in Figure 27, the spacing refers to the distance between parallel tangents of adjacent tubes. The spacings were varied, independently, in the horizontal

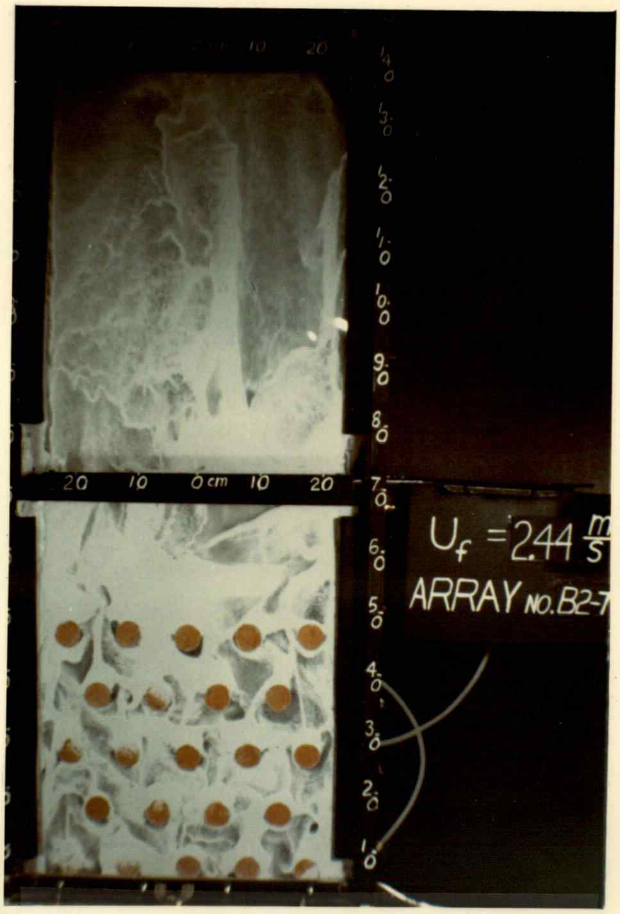


Figure 26. Photograph showing how a triangular tube arrangement forces the fluidizing gas to follow an irregular path through the bed, yielding a more uniform gas-solids mixture.

and vertical directions, from 1-1/2 to 1 to 1/2 tube diameters. Tube diameter, chosen to be representative of commercial size heat exchangers, was 4.76 cm (1.875 in.) O.D.

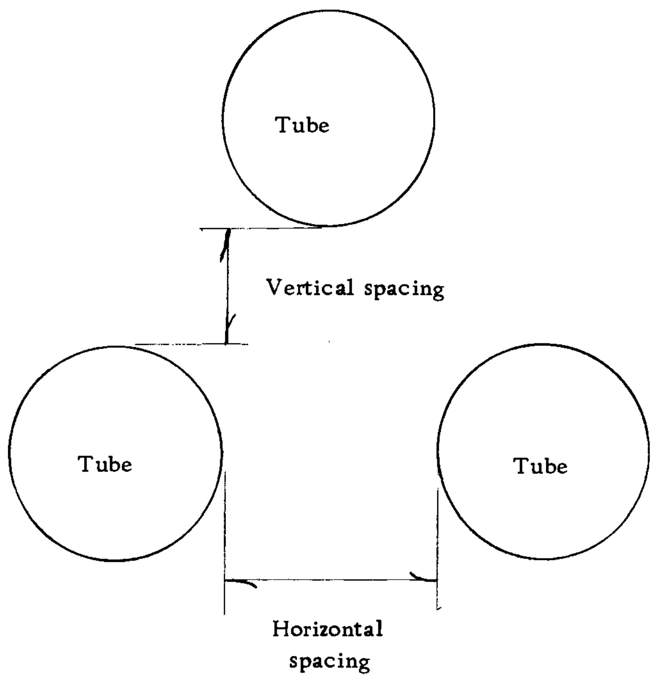


Figure 27. Schematic diagram depicting the meaning of the terms horizontal and vertical spacing as used in this work.

Horizontal spacing appears visually to have a greater affect on fluidization than vertical spacing. Observations indicate that the design of fluid bed heat exchangers should avoid close spacing. When too close together horizontally, the tubes form a barrier to vertical solids movement. Solids are naturally carried upward through the array. Figure 28 shows that if the tubes are too close

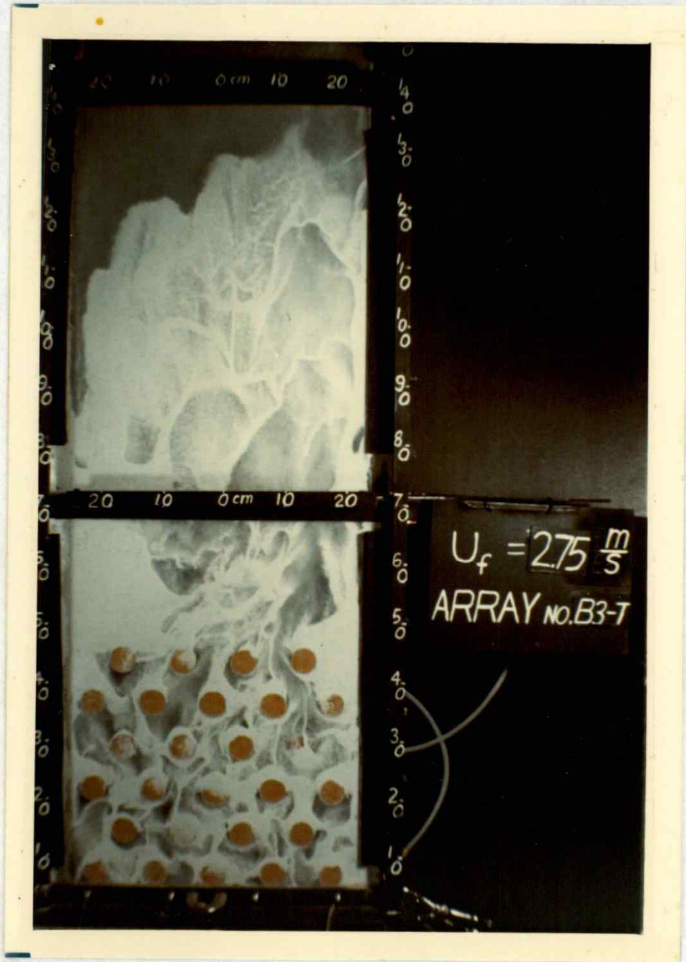


Figure 28. Photograph showing the effect that close tube spacing with a high gas velocity has on the bed material. The solids are carried up above the array and due to the tube spacing and rising gas velocity can not get back down into the array.

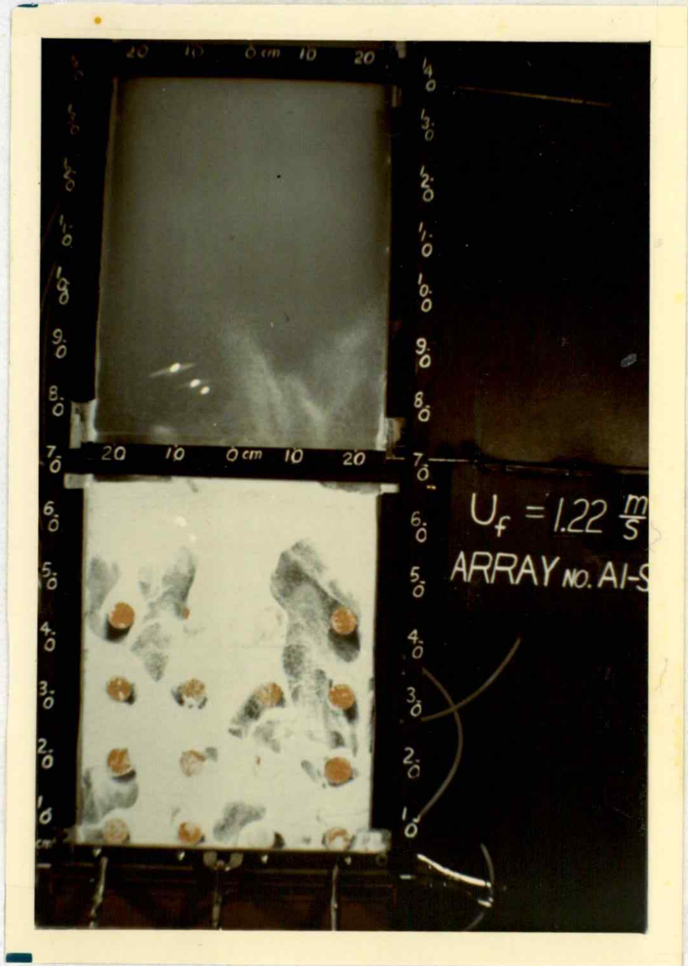


Figure 29. Photograph showing that too wide a spacing may permit gas bubbles to grow larger than desired.

together, the barrier they form coupled with the rising gas stream will cause the solids to be held up above the tubes. Too wide a spacing may tend to permit bubbles to grow more than might be desired, as seen in Figure 29.

Vertical spacing, when balanced with horizontal spacing, will promote good gas-solids mixing and solids circulation. The proper balance must be one which will achieve the desired goal for the reaction vessel, for given operating conditions which include superficial velocity and solids size. Wide vertical spacing increases the unencumbered path length of the rising gas, thereby reducing gas-solids mixing and solids circulation, particularly if the horizontal spacing is also wide. In rectangular arrays, if the vertical spacing is too close, there will be less tendency for the gas to move laterally between adjacent vertical tubes. This could result in a relatively static group of solids between vertical tubes. Observations indicate that, in general, wide horizontal spacing and narrow vertical spacing will probably yield the most overall stability in a fluidized bed of limestone. It is strongly suggested, however, that all parameters be considered in the design for the specific operating conditions.

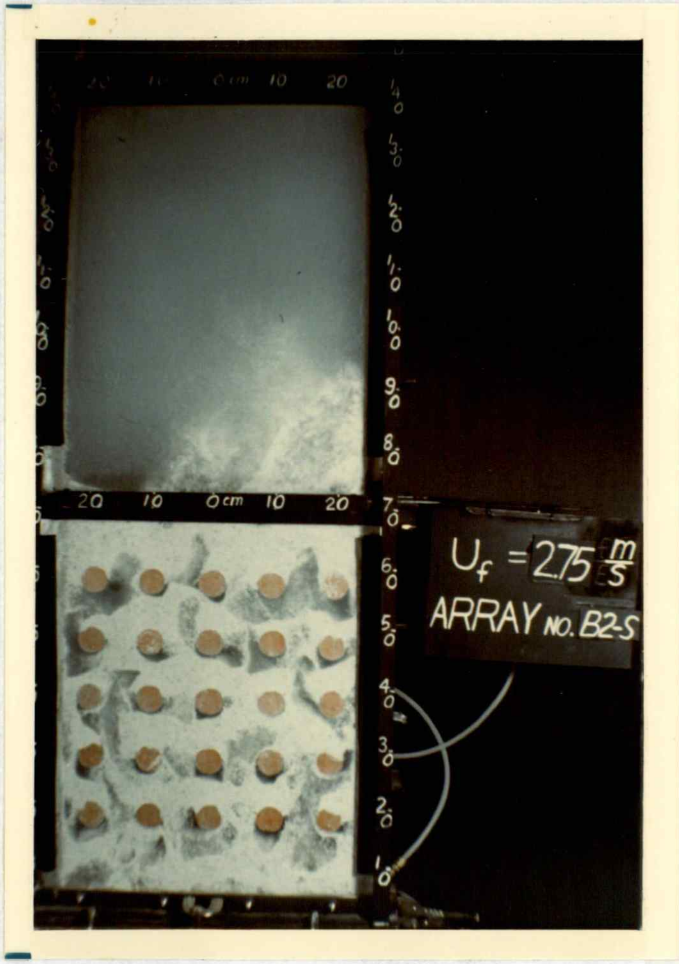
The ideas discussed above are particularly applicable to rectangular tube arrangements. In both rectangular and triangular tube arrangements, if the spacing, both horizontally and vertically, was either too wide or too narrow the observed fluidization qualities were generally less than desirable, vis-a-vis bed stability or the minimization of pressure fluctuations. At high fluidizing velocities wide spacing, in both directions, typically results in large bubbles and instabilities. Wide spacing at low velocities results in poor solids circulation, that is, the solids appear to stay in one general region in the bed, moving only short distances as rising bubbles or gas displace them.

Array Location

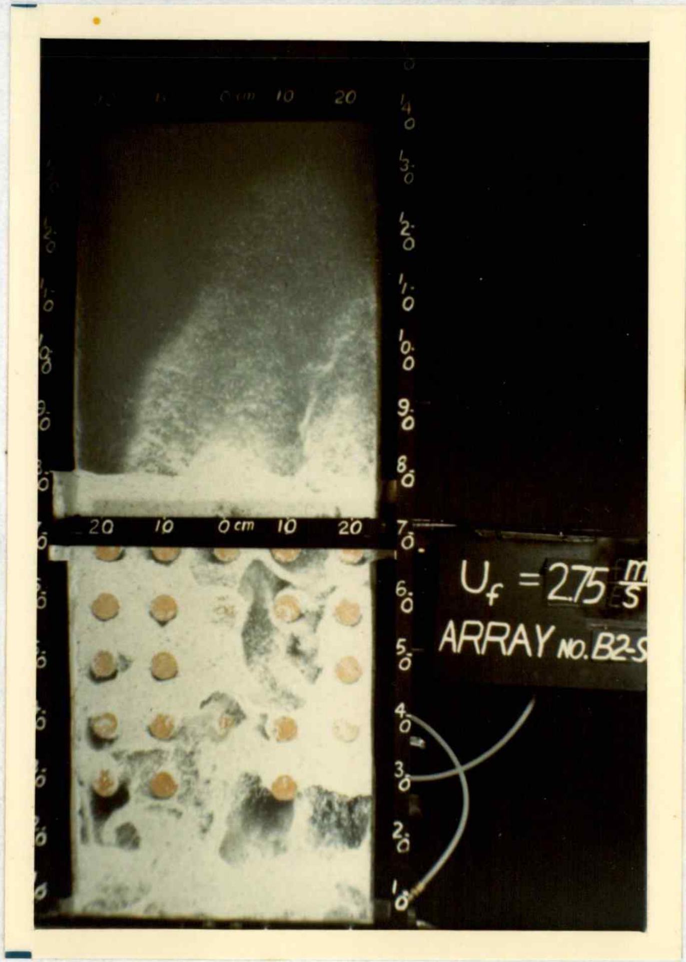
During the second portion of the experimental work the verticle distance between the tube arrays and the distributor plate was varied. Results were compared to those of the first portion of the work. The first portion was conducted with the array starting 2.5 cm (1.0 in.) above the distributor plate. For the second portion of the work the arrays were placed 15 and 25 cm (6 and 10 in.) above the distributor. The distances mentioned above were taken as the closest point between the bottom row of tubes and the distributor plate.

Bed stability was strongly influenced by array location relative to the distributor plate. Bed stability is manifested primarily in quantified pressure drop fluctuations and qualitatively in the degree of gross or irregular fluidization. If a stable, uniformly fluidized or uniformly bubbling bed is the desired mode of operation, then the array should be located as close to the distributor plate as possible. The different sizes of bubbles, with an array at different heights above the distributor plate, can be seen in Figures 30A and 30B.

Considerable difficulty was experienced in achieving fluidization of the larger solids with the arrays close to the distributor plate. With the triangular pitch array (identified by C2-T) located 15 cm (6 in.) above the distributor, the 1379 μm (12 mesh) mean size solids would not fluidize. This of course, reflects limits in the capacity of the compressor. Considerable difficulty was also experienced in fluidizing these same solids with the rectangular pitch array (B2-S) located 2.5 cm (1.0 in.) above the distributor. Thus, the tubes, when close to the distributor plate, appear to have a "binding" effect upon the solids; not allowing room for movement or expansion of the bulk of bed material. Some authors have indicated that a wide size distribution of solids is necessary in order that the small fractions will "lubricate" the larger ones and aid their movement. This writer feels that the "lubrication" of large solids by small ones should be somewhat discounted. The reasoning is that wide size distributions were used in this work and difficulty was still encountered in fluidizing in the presents of tightly packed tubes. The conclusion is that the tubes themselves must have



A. Array is 15 cm (6 in.) above the distributor plate.



B. Array is 25 cm (10 in.) above the distributor plate.

Figure 30. Photographs showing the effect of array location relative to the distributor plate on bubble size. Both photographs show 1379 μm (12 Tyler mesh) solids being fluidized in the same array at 2.75 m/s (9 ft/sec).

an effect on the movement of solids. The explanations of observed phenomena reported to date, seen by this writer, have virtually all been with respect to freely bubbling beds, and it is this author's opinion that those explanations are not necessarily applicable to fluid beds with immersed tubes.

Whenever there is a relatively thick layer of solids (on the order of several centimeters) where there are no tubes present there is a tendency for bubbles to grow large, and given enough room they will slug, as seen in Figure 31. When the tube array is far from the distributor plate rapid bubble growth takes place below the array. Gross bubbling below the array produces a more pronounced differential pressure fluctuation across the bed than when the array is close to the distributor. With the upper row of tubes in an array is close to the distributor plate there was a greater tendency for solids to be carried higher into the freeboard and become entrained, than with the upper row farther from the distributor. In other words the upper rows of tubes, if properly located relative to the slumped bed surface, may effectively act as baffles and suppress solids entrainment during fluidization.

Superficial Gas Velocity

Fluidizing velocity refers to the superficial velocity of the inlet air to the fluid bed column. Based on the volumetric flow rate

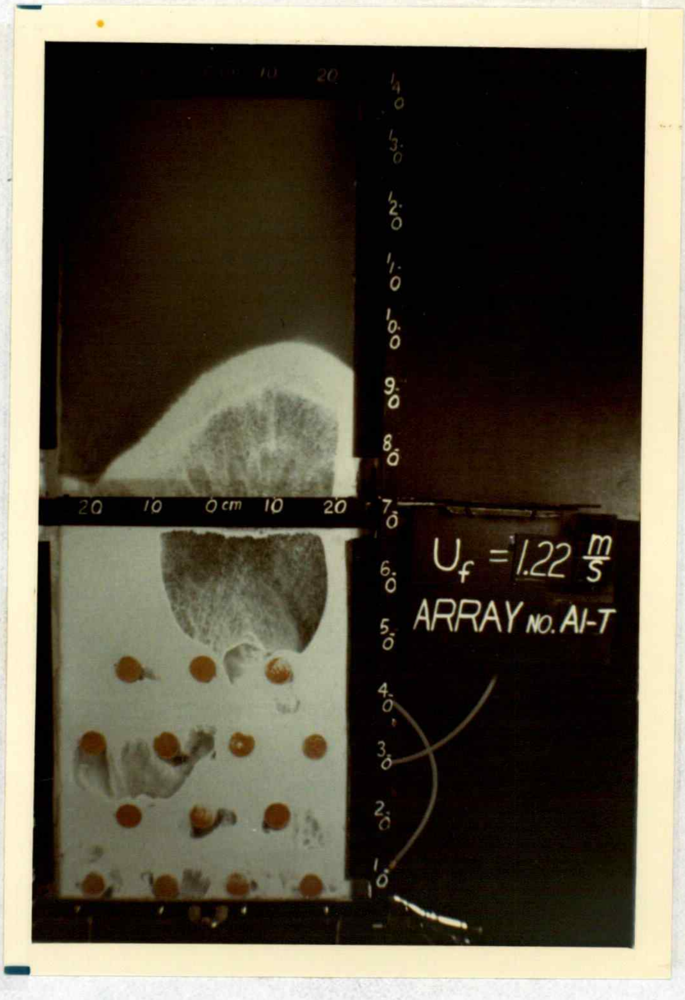


Figure 31. Photograph showing slugging above the array due to a thick layer of solids being above the tubes where the bubbles can not be broken up by the tubes.

into the column, it reflects the cross-sectional area of the bed region, corrected for the inlet air temperature and the atmospheric pressure during a particular run. There was no attempt, during this experimental work, to quantify or account for the higher than superficial gas velocities generated by the existence of heat exchanger tubes in the gas stream.

Gas by-passing is the main effect seen when high (in excess of 3 or 4 times U_{mf}) fluidizing velocities are used. Examination of a plot of pressure drop across the bed versus superficial gas velocity, Figure 32, shows a generally stable bed with relatively small pressure fluctuations. But, when a photograph of the bed at the same conditions, Figure 33, is examined one sees gas by-passing, generally not a desirable characteristic. Correspondingly, lower velocities (less than about 3 times U_{mf}) show characteristics which can be associated with rapid bubble growth and/or non-uniform bubbling, as seen in Figures 29 and 34. This results in large pressure drop fluctuations across the bed.

Bed expansion increases with superficial velocity, which, because of the reduced bulk density, promotes gas-solids mixing and solids circulation within the array. One must keep in mind that as the velocity approaches the solid's terminal velocity, the solids will have a tendency to enter the freeboard region above the array, leaving a leaner phase within the array, and possibly lower heat

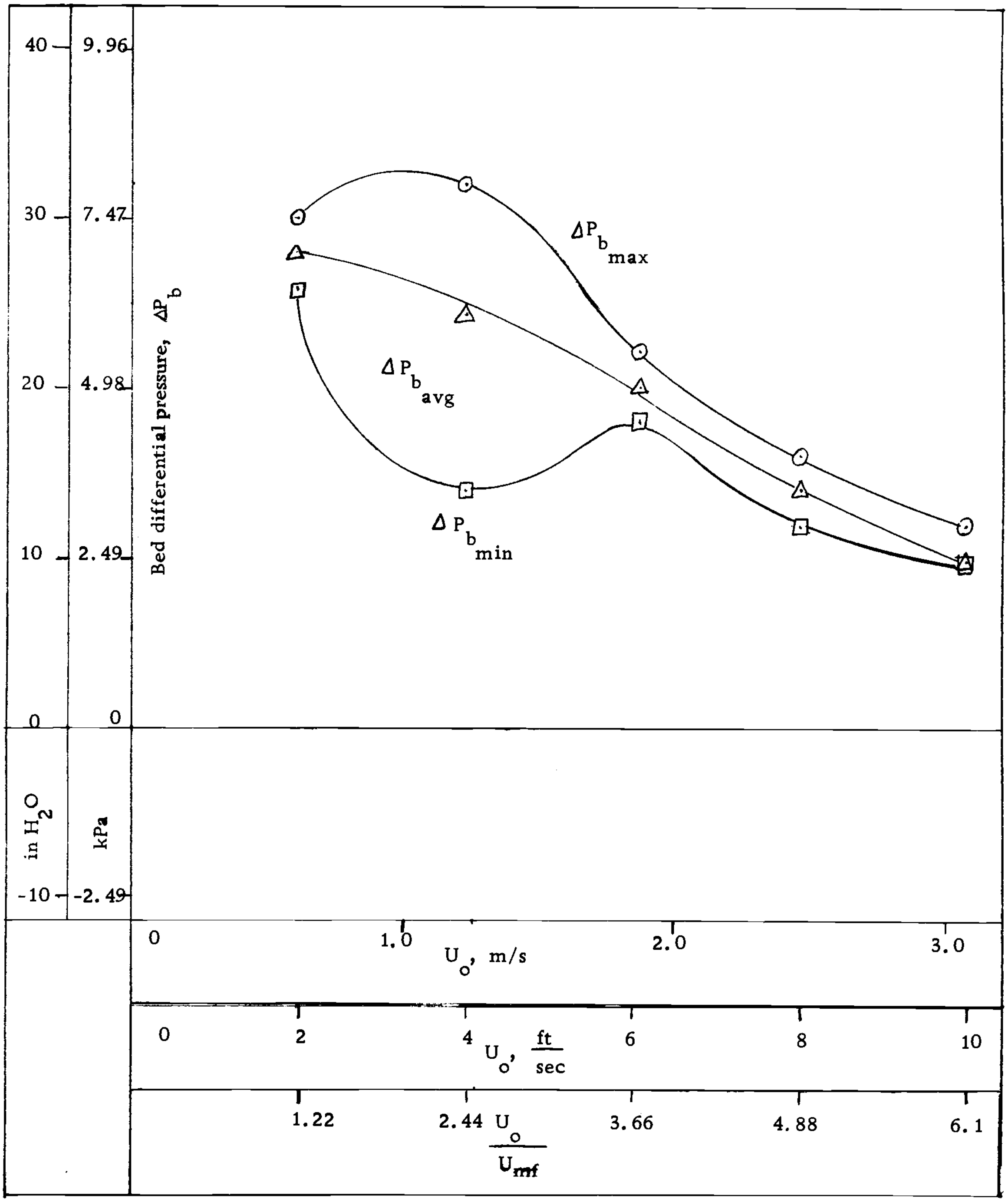


Figure 32. Graphic representation of bed differential pressure versus superficial velocity of 569 μm (28 Tyler mesh) solids in a 45 cm (17.7 in.) deep bed with array C2-T 15 cm (6 in.) above the distributor plate.

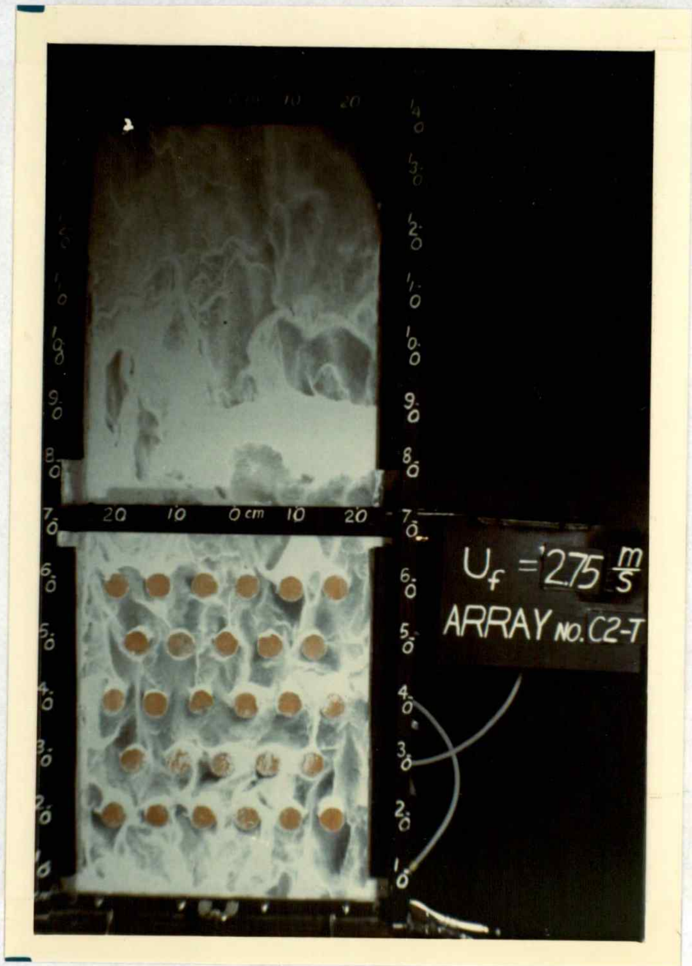


Figure 33. Photograph showing 569 μm (28 Tyler mesh) solids being fluidized, in array C2-T while it is 15 cm (6 in.) above the distributor plate, at 2.75 m/s (9 ft/sec). Note that considerable gas by-passing is taking place.

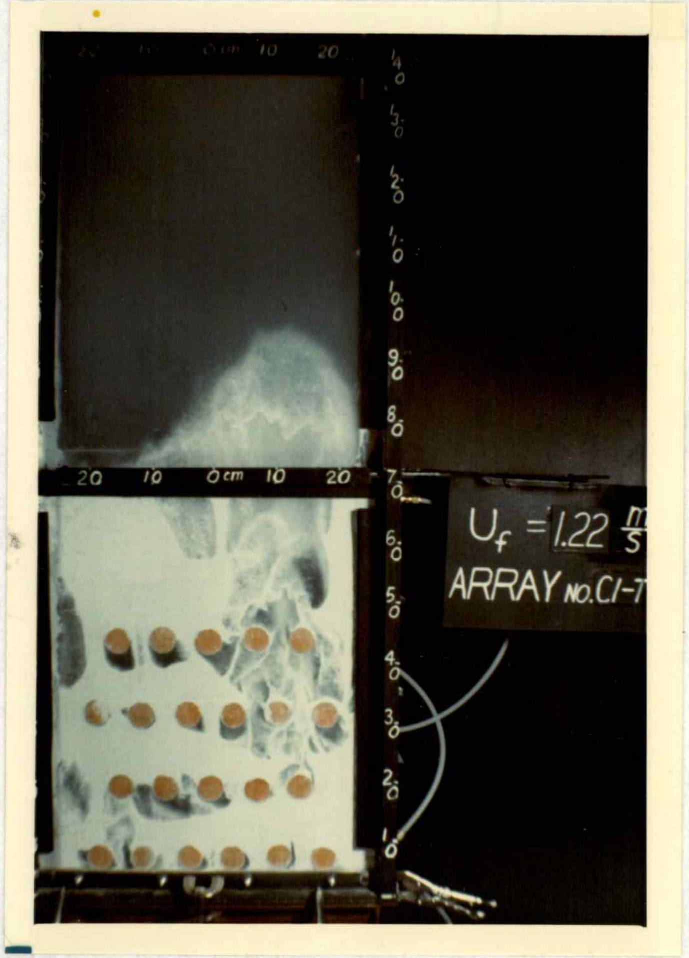


Figure 34. Photograph showing 569 μm (28 Tyler mesh) solids being fluidized at 1.22 m/s (2 ft/sec). Small bubbles and non-uniform bubbling were typical with low fluidizing velocities.

transfer and/or chemical reaction rates.

Size of Bed Material

The mean size of the bed material is obtained from the weight fractions of bed material sieved in each increment of the Tyler screens used. The equation used to obtain the mean size can be found in Appendix C and is taken from the work of Geldart (3).

Ease of fluidization and terminal velocity are two factors which must be taken into account when selecting the size of solids to be used. The density or specific gravity of the solids will effect both of these characteristics. The fluidizing velocity should be well below the terminal velocity of the solids, particularly if a wide size distribution is used. Size of solids must also be considered relative to the available compressor capacity. In general, small solids will fluidize easier than large solids. Further, as the mean size is decreased the minimum fluidizing velocity will typically decrease.

A bed of small particles will expand more than one of a larger particle size (on the order of 15% for 569 μm solids versus 10% for the 1379 μm solids at the minimum fluidizing velocity in a bed 45 cm deep with no internals). If the gas velocity is too high solids will have a tendency to climb up into or above the tube array, possibly leaving a lean or dispersed phase region below. This may inhibit the desired heat transfer or chemical reaction. There is also some tendency for solids to be held up in an array if they are too large for the tube spacing. Both of these phenomena are shown respectively in Figure 35.

Typically bed stability, as reflected by pressure drop fluctuations, is improved as solid mean size is increased. This effect is most prominant in triangular pitch array but is also characteristic of rectangular arrays. Larger sizes also improve fluidization quality, in that channeling is less likely to occur.

One important aspect of the size of bed material is attrition. With the abrasive action taking place in a fluidized bed, it is assumed that there will be a significant change in particle size with time. The 569 μm (28 mesh) mean size dolomite used for the main portion of this work, underwent an approximately twelve percent (12%) decrease in mean size in the course of five (5) hours of operation. The size analysis were only approximate since the solids were sieved by hand. The important point to be made is that one should expect solids attrition and loss of bed material from the reactor.

Bubbling

It is apparently desirable to minimize bubbling, as much as possible. A homogeneously (non-bubbling) or a uniformly bubbling fluidized bed will exhibit those desirable traits of a continuum,

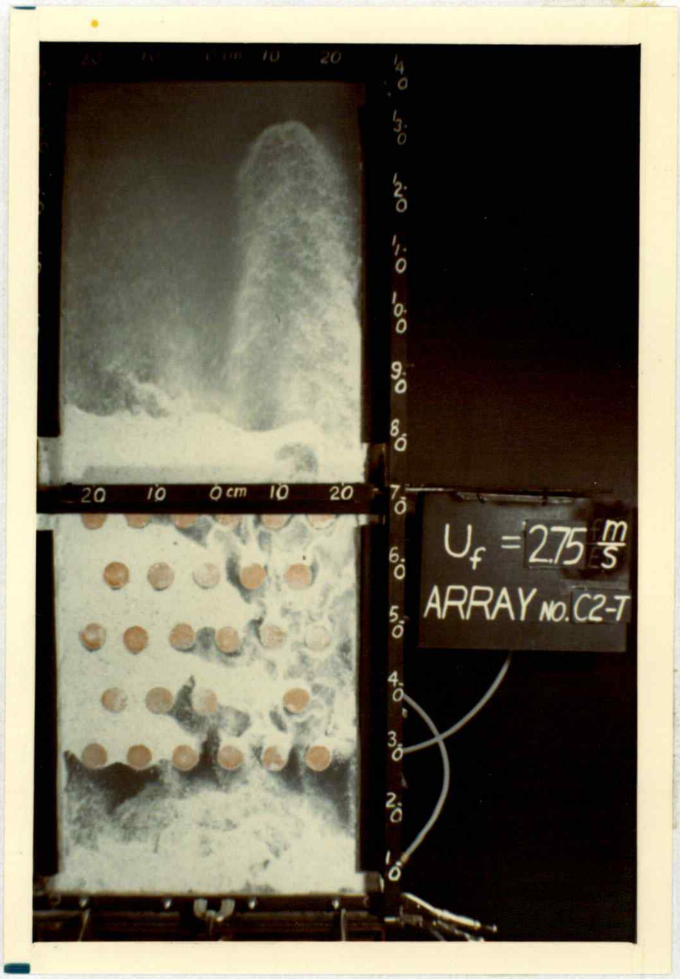


Figure 35. Photograph showing that too close of a horizontal tube spacing and too large of a solids size may cause the solids to become held up above the array. A dilute phase below the array and poor solids circulation will result.

(i.e., uniform gas-solids mixture and flat temperature profile) which promote complete combustion and/or chemical reactions. It therefore falls to the design engineer to achieve as much homogeniety in fluidization as is both economically and physically practical. To accomplish this, the designer should be aware of the character of the solids he intends to use.

The literature (3) and the experience of this writer indicate that large high density solids tend to bubble incipiently very near minimum fluidization. That is, the minimum bubbling velocity is virtually the same as the minimum fluidization velocity. Depending upon how one defines minimum fluidization with internals, minimum bubbling velocity may be reached first. For this work, the minimum fluidization velocity was determined by establishing a well fluidized state in the bed and then decreasing the gas flow rate until the pressure drop across the bed ceased to fluctuate. Qualitatively, at this point bubbles were relatively small throughout the bed. Portions of the bed may not have appeared to be fluidized, and there were virtually no gross displacements of solids in the bed. It was difficult to tell if bubbling was occurring or if the bed was fluidized since the 5 cm (2 in.) depth of the bed was sufficient to allow small bubbles or solids movement to be obscurred in its interior.

The arrays seemed to promote bubble formation as though the rising gases were drawn to the bottom of the tubes. Bubbles would form under one tube, split around the tube and disappear into the emulsion phase, only to reappear suddenly under the next tube up in the array. The primary exception to this is when channeling occurred. In that case the fast rising gas stream drew the bubbles from beneath the tubes and generally carried them to the top of the array, not allowing them to form distinguishable bubbles. As the characteristic shape of the bubbles was governed directly by their proximity to a tube. The most prominant appearance was that of a bubble wrapped around the bottom of a tube. Bubble diameter, for those adjacent to tubes, was recorded as the overall width of the bubble and included the spreading effect of the tube as seen in Figure 36. As stated earlier bubbles grew larger between tubes when the tube spacing was wide than when it was narrow. This resulted in greater pressure drop fluctuations across the bed. Visual observations and examination of the motion picture films suggested (though it was often difficult to tell without advancing the film frame by frame) that apparent bubble growth was predominantly by coalescence rather than by simple bubble expansion. Bubbles did exhibit growth by expansion but one might say that growth by coalescence was several times faster than by simple expansion. Many small (1 to 3 cm or 0.4 to 1.2 in.) bubbles were typically

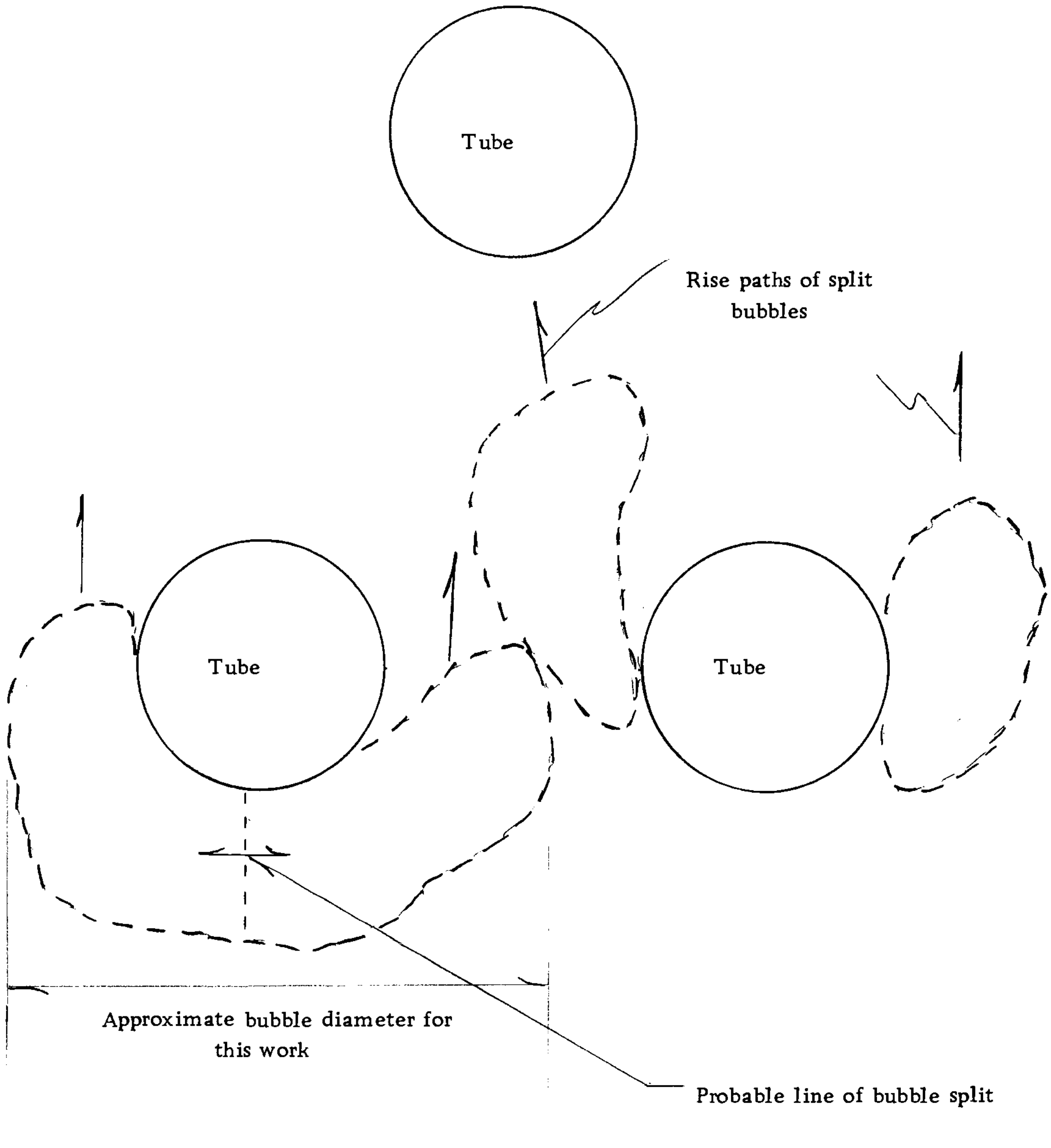


Figure 36. Schematic drawing showing the dimensions used in this work for bubble diameter. Also shown schematically is the typical bubble location and form relative to the tubes and the usual method of splitting.

generated at the distributor plate and within 5 to 10 cm or 2 to 4 in., up the column, there were only a few bubbles visible.

This subject of bubbling would not be complete without a discussion of the so called negative pressure gradient occasionally measured during the course of this work. Pressure gradients were recorded as negative values when the mercury manometer indicated that a higher pressure was occurring at the top of the bed than at the bottom. The mercury manometer, being an undamped device, was not especially sensitive. Consequently, during periods of gross instabilities in the bed, these indications of a negative gradient were not considered noteworthy. However, one must ask the question, "What is physically taking place in the bed when the negative pressure gradient is observed?". The inertia inherent in an undamped mercury manometer was considered first. For some of the smaller (-1 kPa or -4 in H_2O) readings inertia is indeed a valid explanation for the negative gradients observed. However, some of the readings were felt to be too large (-5 kPa or -20 in H_2O) to be explainable entirely by inertia. When slugging occurred, large masses of bed material were lifted up by large, rising bubbles and then abruptly dropped, as the pressure in the bubble overcame the forces of it. When, in the two-dimensional bed used in this work, the mass of solids was large enough it quickly closed off the path through which some of the air in the bubble had escaped, and settled as the same continuous solid mass it had been before it was lifted by the bubble, trapping some of the gas from the bubble below it. What remained was essentially a void below which there was another rising mass of solids. The gas in the void, it can easily be reasoned, experienced a sudden compression as the two masses of bed material, above and below the void, come together. Further, if that void happened to be adjacent to the upper pressure tap, when it was compressed, the pressure seen by that tap could easily have been greater than that seen by the lower pressure tap. Hence, an instantaneous negative pressure gradient was observed. Now, what are the implications of this, other than a very unstable bed? It seems logical that the existence of a negative pressure gradient would suggest that the solids in the emulsion phase are being forced or driven downward by this pressure, rather than simply settling as a bubble passes by. This would indicate a more rapid turnover rate of solids and a more rapid or complete gas-solids mixing than might otherwise be predicted.

Quantity of Bed Material

Two significant observations were made concerning bed depth. First, when the slumped bed depth is sufficient for solids to build up a significant layer (several centimeters) on top of the array, then rapid bubble growth and slugging could occur. When this happened the bed pressure fluctuations were greater and overall fluidization less uniform. Second, when the slumped bed depth was shallow, particularly for the smaller (569 μm or 28 Tyler mesh) solids, a lean or dilute phase type fluidization was observed at higher velocities.

Tube Errosion

Indications of potential problems of errosion of heat exchanger tubing were noted during the experimental work. Briefly stated, evidence of errosion was noted on the bottom of the tubes, particularly those closest to the distributor plate. Each tube array was painted flat black to contrast with the white limestone used in the study. Examination of each tube array, after its use, revealed that the paint was worn off the bottom of the tubes, (see Figures 37 and 38) and that the tube surfaces had been abrated. The amount of paint worn (the white areas in the photographs) from each tube might be taken as a relative indication of where tube errosion will be most prevelent in an array. This was particularly true for those tubes closest to the distributor plate, especially when the array was placed immediately above it. These observations are not intended to be conclusive. Rather they are made simply to make the reader aware that tube errosion is a valid consideration in the design of heat exchanger equipment for fluidized beds.

Figure 37. Photograph showing areas where black paint has been worn off of white tube material, suggesting areas where tube errosion might be of concern.

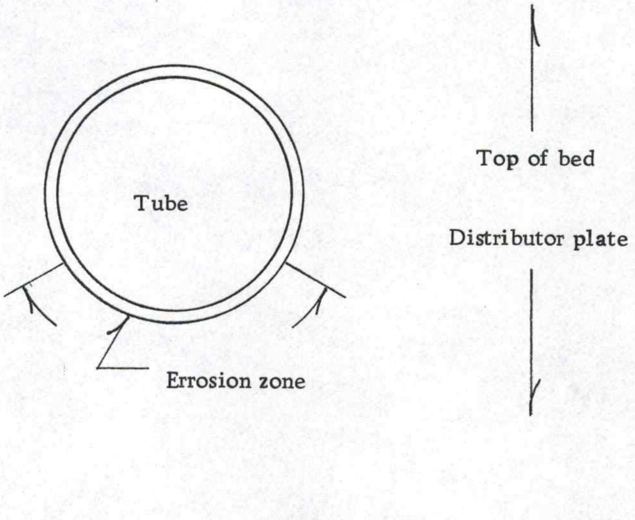


Figure 38. Schematic drawing showing the bottom portion of a tube which might be most susceptible to surface errosion.

V. CONCLUSIONS AND DISCUSSION OF ERRORS

Conclusions

Certain qualities of fluidization can be associated with different immersed heat exchanger tube arrangements. The following general conclusions may be drawn from qualitative evaluation of the data obtained during this work:

1. For rectangular pitch tube arrays, the channeling tendency, which increases with increased horizontal spacing and decreases with increased vertical spacing, results in:

   a. Greater gas by-passing.

   b. An apparently more stable fluidization.

   c. Less gas-solids mixing.

   d. Greater solids retention on top of the tubes.

   e. Less uniform solids circulation.

   Optimum superficial velocities appear to be in the range of 1.83 to 2.44 m/s (6 to 7 ft/sec) or 3 to 4 times U_{mf} for solids in the 569 μm (28 mesh) to 1379 μm (12 mesh) size range.

2. Triangular arrangements limit direction, unencumbered gas by-passing, but by-passing may occur in the form of either diagonal or pseudo-sinusoidal channeling up the array.

3. In both triangular and rectangular arrangements, too tight of a tube packing will result in the solids climbing up through the array, sitting on top, and leaving a virtual void within and/or below the array; the results of which are:

   a. Unstable fluidization, with large pressure drop fluctuations.

   b. Possibly, increased loss of solids from the reactor.

   c. Poor heat transfer or chemical reaction conditions.

4. The size of the solids used as bed material will also affect fluidization quality, as follows:

   a. Larger solids are more stable, with smaller differential pressure fluctuations.

   b. Larger solids require a larger compressor capacity to fluidize them.

   c. Wider horizontal spacing may be necessary for larger solids than for smaller ones. This, as discussed earlier, is so that the tubes do not act as a barrier to vertical solids movement, either up or down.

   d. Larger solids will not become entrained as readily as smaller ones and so will stay within the array/bed region longer and with greater bulk density. This promotes gas-solids mixing and solids circulation.

5. High fluidizing velocities are associated with gas by-passing, solids elutriation or entrainment and deceptively stable fluidization. Low velocities, on the other hand, are associated with irregular bubbling, unstable fluidization, and possibly poor solids circulation. Again, superficial velocities of approximately 1.83 to 2.44 m/s (6 to 8 ft/sec) or 3 to 4 times U_{mf}, appeared to be the range which optimized all of the desirable traits, for the sizes of solids studied (569 μm and 1379 μm or 28 and 12 mesh).
6. The quantity of bed material used should be limited, so that while the bed is fluidized, there are no solids above the heat exchanger array. The lack of tubes in a solids mass above the array permits rapid bubble growth and associated instabilities to occur. Also, solids above the array are not available for direct heat transfer with the tubes.
7. The location of a tube array, relative to the distributor plate, had a noticeable effect upon bed stability. Greater bed stability or smaller fluctuations in the differential pressure across the bed is experienced when the array is closer to the distributor plate. Rapid bubble growth and irregular fluidization were consistently noted below the arrays which were farther from the distributor. While

these large, non-uniform bubbles were generally effectively broken up and the instabilities apparently (by visual observation) damped out once they entered an array, the overall or net effect was that the fluidization was less uniform or stable than with the array close to the distributor.

Discussion of Errors

Several sources of error, which affected the sensitivity of both the quantitative as well as qualitative data collected, are identifiable; and are discussed below:

1. During normal operation of the bed the temperature of the fluidizing air was continually rising. Because of this there was only a relatively short time available during which maximum superficial velocities could be maintained. This necessitated working rapidly to establish a desired air flow rate and make pressure drop readings. The velocities were established quickly by measuring the differential pressure in a water manometer to within only about 0.32 cm (1/8 in.). Then the differential pressures across the bed were measured using an undamped mercury manometer with each graduation equivalent to 2.54 cm (1.0 in.) of water. Air temperature was monitored during the

pressure readings to ensure that the velocity was close to the desired value. It is felt that the fluidizing velocities, during these readings, were within about 5-10% of the desired value.

2. The photographic record and the subjective, qualitative observations were made after the bed had been fluidized for two to three minutes and it is estimated that the fluidizing velocities may only have been within about 10-20% of the desired value, at the higher velocities, and about 5-10% at the lower velocities. Qualitatively, these differences had little apparent effect on the visual appearance of the fluidized bed.

The time related variations of temperature and velocity of the fluidizing gas are suggested schematically in Figure 39.

This work and the data collected were intended for use in the preliminary design of a fluidized bed. While an effort was made to be as precise and careful as possible, the results are intended to be qualitative rather than definitive.

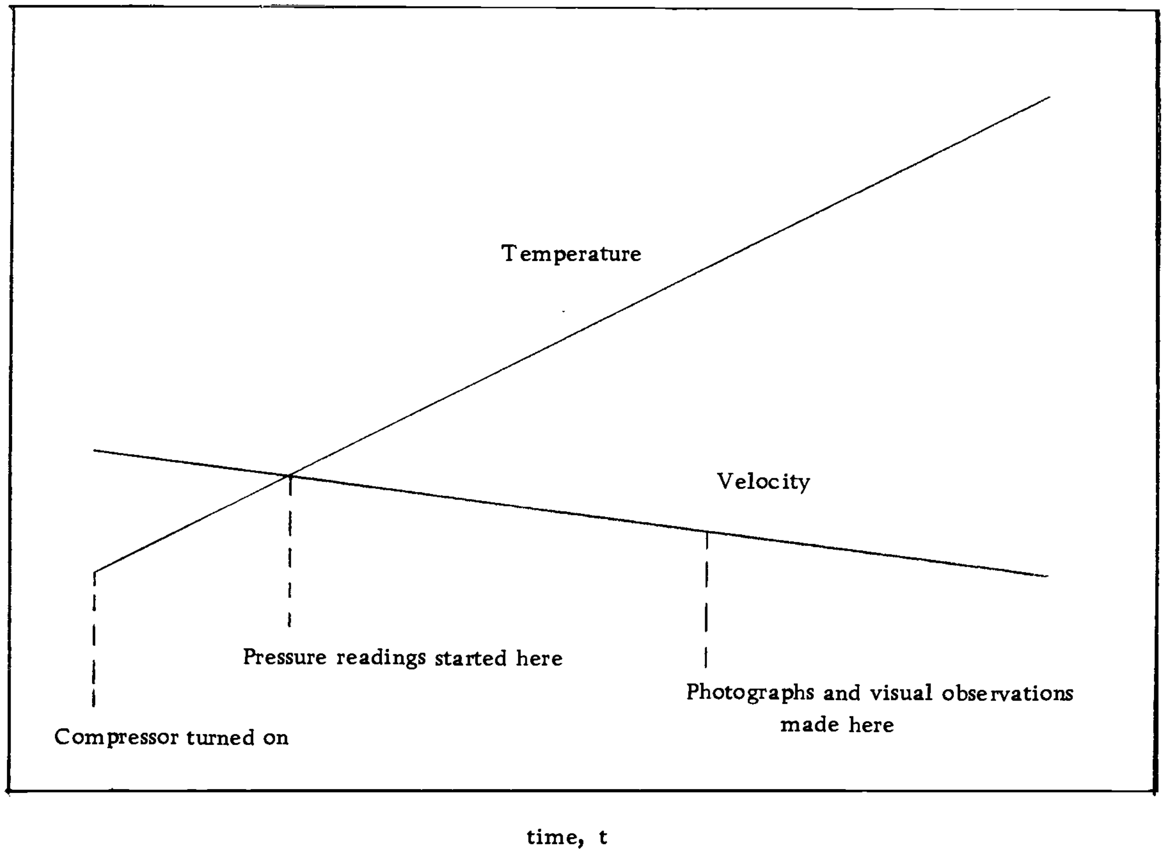


Figure 39. Graph depicting the time variations in fluidizing air temperature and superficial velocity which were experienced during each run.

VI. SUMMARY AND RECOMMENDATIONS

Summary of Work in a Two-Dimensional, Cold Phase Fluidized Bed

Several studies have been reported in the literature which demonstrate the feasibility of operating fluidized bed combustors with immersed heat exchangers for commercial steam power generation from the direct combustion of coal. But, little can be found, in the literature to date, which suggests that specific criteria have been or can be established for the design of immersed heat exchangers in fluidized beds.

Experimental equipment was designed and constructed to evaluate some of the parameters which should be considered in the design of internals for fluid beds. Tube arrangement (triangular or rectangular), tube spacing, (horizontally and vertically), tube array location within the fluid bed region relative to the distributor plate; and mean size of the bed material used were considerd as to their effect on the quality of fluidization. Gas velocities were varied typically from U_{mf} to 4 U_{mf}.

The conclusions reached show the importance of tube spacing on the movement of solids. They also show that tube arrangement effects gas by-passing and solids circulation. Superficial gas velocity and quantity of solids influence bed stability and fluidization quality.

Recommendations

As a result of the need for more, specific design knowledge concerning fluidized bed coal combustors, it is recommended that this research work be continued in the following specific areas:

1. Expand the scope of this work to three-dimensional fluidized bed units.
2. Investigate the effect of larger solids on the design decisions of internals. If the excess air requirements of fluidized bed combustion plants results in fluidizing velocities in excess of about 2.44 m/s (8 ft/sec), then larger solids than those studied here will probably be necessary in order that they do not become entrained and lost from the bed at intolerable rates. For those large solids, in the range of 6 mm (0.25 in.), this writer has seen no research published dealing specifically with the optimization of tube arrangement, spacing, and array location.
3. Investigate the possibility of a negative pressure gradient in an unstable or non-uniformly fluidized bed, and its effect on the direction and relative magnitude of intersticial

gas flow. This will improve the knowledge and understanding of gas-solids mixing and expected chemical reaction rates.

4. Investigate the qualities of fluidization in narrower increments of superficial velocity than those used in this work to increase the body of knowledge of bubble behavior, including coalescence in the vicinity of tubes.

5. Investigate those interesting regimes or modes of fluidization identified in this work, such as in (3) and (4) above, in a more severely two-dimentional fluid bed than the one used in this work. The suggestion is for a bed width to depth ratio of at least 20:1 or possibly 30:1, rather than the 10:1 from this work; and to retain the tube size, which is representative of commercial boilers. While this will severely increase the "wall effect" on the quality of fluidization, it will also permit the study of distinct, individual bubbles as they rise above the distributor plate and interact with the tubes.

6. Given the assumption that a fluidized bed should experience good gas-solids mixing, good solids circulation, minimum tube errosion, and easy start-up and if one were to use solids of the same size range and density as those in this

work then the following operating conditions are recommended:

a. Moderate tube spacing both horizontally and vertically.

   1. Horizontal spacing should be wide rather than narrow (1-1/2 vice 1/2 tube diameters).

   2. Vertical spacing should be close rather than wide (1/2 to 1 vice 1-1/2 tube diameters).

b. Triangular pitch arrangements are recommended over rectangular ones to promote solids circulation and minimize gas by-passing.

c. Greater overall bed stability and fluidizing quality can be expected with the tube array close to the distributor plate (2.5 cm or 1.0 in. vice 25 cm or 10 in.).

d. A superficial gas velocity in the range of 1.83 to 2.44 m/s (6 to 8 ft/sec) can be expected to optimize overall fluidization quality, particularly with respect to irregular bubbling instabilities and gas by-passing.

It must be pointed out here that this research was conducted in a cold two-dimensional bed. The influence of "wall effects" from the two-dimensional model were not specifically studied. Also, if a bed is to be operated in a hot mode then the gas temperature and density effects must be considered as they will affect fluidization more significantly than in this work.

7. Finally, this writer is aware that pilot or demonstration scale fluid bed combustors have been operated with the tube array some distance (on the order of 0.7 m or 2 ft.) above the distributor plate. This has apparently been done to provide a convenient location for coal injection nozzles (i.e., below the tube array). Based upon the data collected and observations made during this work, this writer feels that the effects of array location on bed stability and overall fluidization quality ought to be included in the design decisions.

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APPENDICES

APPENDIX A

Raw Data

Listed below are the units with each line in the Raw Data listings which follow. The units presented are first for the International System of Units (SI) followed by the conventional English or Engineering Units. An explanation of the symbol meanings is found in Figure 20 on pages 54 and 55.

Symbol	SI	ENGLISH
Date	--	--
Tube Array	--	--
Array Loc.	--	--
DPM	microns (μm)	inches (in.)
UO	m/s	ft/sec
P(ATM)	kilo-Pascals (kPa)	in Hg
P(ORF)	kPa	in H_2O
T(ORF)	^oK	^oF
DPO	kPa	in H_2O
DPB(AV)	kPa	in H_2O
DPB(MX)	kPa	in H_2O
DPB(MN)	kPa	in H_2O
PS	kPa	PSIG
LI	cm	in

Symbol	SI	ENGLISH
LF	cm	in
LE	cm	in
H1	cm	in
H2	cm	in
H3	cm	in
DBH1	cm	in
DBH2	cm	in
DBH3	cm	in
DTIME	seconds	minutes
UMF	m/s	ft/sec
QUAL	--	--
QUAL	--	--

NA=NOT APPLICABLE ND=NO DATA

	S. I. UNITS						*	ENGLISH UNITS					
DATE	1 26 76	2 15 76	1 24 76	1 24 76	1 24 76	1 24 76	*	1 26 76	2 15 76	1 24 76	1 24 76	1 24 76	1 24 76
TUBE ARRAY	EMPT	EMPT	EMPT	EMPT	EMPT	EMPT	*	EMPT	EMPT	EMPT	EMPT	EMPT	EMPT
ARRAY LOC	NA	NA	NA	NA	NA	NA	*	NA	NA	NA	NA	NA	NA
DPM	569.00	569.00	569.00	569.00	569.00	569.00	*	.022	.022	.022	.022	.022	.022
UO	3.05	2.75	2.44	1.83	1.22	.61	*	10.01	9.02	8.01	6.00	4.00	2.00
P(ATM)	101.96	100.75	101.96	101.96	101.96	101.96	*	30.11	29.75	30.11	30.11	30.11	30.11
P(ORF)	.80	.78	.68	.56	.35	.19	*	3.20	3.13	2.75	2.25	1.40	.75
T(ORF)	305.37	324.82	319.26	319.26	316.48	316.48	*	90.00	125.00	115.00	115.00	110.00	110.00
DPD	9.96	12.95	5.98	4.48	2.49	1.00	*	40.00	52.00	24.00	18.00	10.00	4.00
DPB(AV)	2.49	9.96	6.97	6.97	5.98	5.48	*	10.00	40.00	28.00	28.00	24.00	22.00
DPV(MX)	12.45	14.94	14.94	16.93	10.71	6.97	*	50.00	60.00	60.00	68.00	43.00	28.00
DPB(MN)	-2.49	5.48	9.96	-1.49	1.00	4.98	*	-10.00	22.00	40.00	-6.00	4.00	20.00
PS	38.61	38.61	37.23	31.03	26.20	23.44	*	5.60	5.60	5.40	4.50	3.80	3.40
LI	37.00	45.00	47.00	45.00	43.00	42.00	*	14.57	17.72	18.50	17.72	16.93	16.54
LF	35.00	43.00	45.00	43.00	42.00	42.00	*	13.78	16.93	17.72	16.93	16.54	16.54
LE	70.00	54.00	63.00	62.00	60.00	53.00	*	27.56	21.26	24.80	24.41	23.62	20.87
H1	20.00	20.00	30.00	40.00	40.00	30.00	*	7.87	7.87	11.81	15.75	15.75	11.81
H2	ND	ND	ND	ND	ND	50.	*	ND	ND	ND	ND	ND	19.6
H3	ND	ND	ND	ND	ND	ND	*	ND	ND	ND	ND	ND	ND
DBH1	28.00	25.00	25.00	25.00	25.00	7.00	*	11.02	9.84	9.84	9.84	9.84	2.76
DBH2	ND	ND	ND	ND	ND	20.	*	ND	ND	ND	ND	ND	7.8
DBH3	ND	ND	ND	ND	ND	ND	*	ND	ND	ND	ND	ND	ND
DTIME	600.00	180.00	300.00	300.00	240.00	360.00	*	10.00	3.00	5.00	5.00	4.00	6.00
UMF	.50	.50	.50	.50	.50	.50	*	1.64	1.64	1.64	1.64	1.64	1.64
QUAL	S3 E3	S3 E2	S3 E2	S2 E2	S1 S2	B3 S1	*	S3 E3	S3 E2	S3 E2	S2 E2	S1 S2	B3 S1
QUAL					E1		*					E1	

	S. I. UNITS					*	ENGLISH UNITS				
DATE	2 03 76	2 03 76	2 03 76	2 03 76	2 03 76	*	2 03 76	2 03 76	2 03 76	2 03 76	2 03 76
TUBE ARRAY	A1-S	A1-S	A1-S	A1-S	A1-S	*	A1-S	A1-S	A1-S	A1-S	A1-S
ARRAY LOC	2.5	2.5	2.5	2.5	2.5	*	.98	.98	.98	.98	.98
DPM	569.00	569.00	569.00	569.00	569.00	*	.022	.022	.022	.022	.022
UO	3.05	2.44	1.83	1.22	.61	*	10.01	8.01	6.00	4.00	2.00
P(ATM)	100.51	100.51	100.51	100.51	100.51	*	29.68	29.68	29.68	29.68	29.68
P(OPE)	.81	.68	.56	.35	.17	*	3.25	2.75	2.25	1.40	.70
T(OPE)	308.15	314.26	313.15	316.48	319.26	*	95.00	106.00	104.00	110.00	115.00
DPD	11.95	6.48	3.98	1.49	.50	*	48.00	26.00	16.00	6.00	2.00
DPB(AV)	2.99	3.98	4.48	5.48	5.98	*	12.00	16.00	18.00	22.00	24.00
DPV(MX)	4.98	5.98	6.48	9.96	6.48	*	20.00	24.00	26.00	40.00	26.00
DPB(MN)	2.49	1.99	2.99	3.49	4.98	*	10.00	8.00	12.00	14.00	20.00
PS	35.16	28.27	24.82	21.37	20.68	*	5.10	4.10	3.60	3.10	3.00
LI	45.00	4.50	45.00	45.00	45.00	*	17.72	1.77	17.72	17.72	17.72
LF	35.00	41.00	42.00	45.00	45.00	*	13.78	16.14	16.54	17.72	17.72
LF	ND	ND	70.	67.	50.	*	ND	ND	27.55	26.37	19.68
H1	10.	10.	30.	10.	10.	*	3.93	3.93	11.81	3.93	3.93
H2	25.	25.	25.	25.	25.	*	9.84	9.84	9.84	9.64	9.84
H3	50.	50.	50.	50.	50.	*	19.68	19.68	19.68	19.68	19.68
DPH1	ND	ND	10.	5.	3.	*	ND	ND	3.93	1.96	1.18
DPH2	ND	ND	ND	10.	8.	*	ND	ND	ND	3.93	3.15
DPH3	ND	ND	ND	20.	12.	*	ND	ND	ND	7.87	4.72
DTIME	300.00	300.00	360.00	480.00	660.00	*	5.00	5.00	6.00	8.00	11.00
UMF	.44	.44	.44	.44	.44	*	1.44	1.44	1.44	1.44	1.44
QUAL	B3 CG3	B2 CG2	B2CG2S1	B2 S1	B2-B1	*	B3 CG3	B2 CG2	B2CG2S1	B2 S1	B2-B1
QUAL	E3	CG2 E2	CG1	NA	NA	*	E3	CG2 E2	CG1	NA	NA

S. I. UNITS

ENGLISH UNITS

	S. I. UNITS						ENGLISH UNITS				
DATE	2 03 76	2 03 76	2 03 76	2 03 76	2 03 76	*	2 03 76	2 03 76	2 03 76	2 03 76	2 03 75
TUBE ARRAY	A2-S	A2-S	A2-S	A2-S	A2-S	*	A2-S	A2-S	A2-S	A2-S	A2-S
ARRAY LOC	2.5	2.5	2.5	2.5	2.5	*	.98	.98	.98	.98	.98
DPM	569.00	569.00	569.00	569.00	569.00	*	.022	.022	.022	.022	.022
UO	3.05	2.44	1.83	1.22	.61	*	10.01	8.01	6.00	4.00	2.00
P(ATM)	100.51	100.51	100.51	100.51	100.51	*	29.68	29.68	29.68	29.68	29.68
P(ORF)	.85	.75	.60	.37	.22	*	3.40	3.00	2.40	1.50	.88
T(ORF)	315.93	322.04	330.37	330.37	330.37	*	109.00	120.00	135.00	135.00	135.00
DPD	14.94	9.96	5.98	1.99	9.96	*	60.00	40.00	24.00	8.00	40.00
DPB(AV)	3.98	4.48	4.48	4.98	4.99	*	16.00	18.00	18.00	20.00	20.00
DPV(MX)	5.98	7.97	5.98	7.47	6.97	*	24.00	32.00	24.00	30.00	28.00
DPB(MN)	2.49	2.49	3.49	2.49	3.98	*	10.00	10.00	14.00	10.00	16.00
PS	38.61	35.85	31.03	26.20	23.44	*	5.50	5.20	4.50	3.80	3.40
LT	45.00	45.00	40.00	38.00	38.00	*	17.72	17.72	15.75	14.96	14.96
LF	36.00	40.00	38.00	38.00	38.00	*	14.17	15.75	14.96	14.96	14.96
LE	ND	75.	70.	55.	50.	*	ND	29.52	27.55	21.65	19.68
H1	10.	10.	5.	5.	5.	*	3.93	3.93	1.96	1.96	1.96
H2	25.	25.	25.	25.	25.	*	9.84	9.84	9.84	9.84	9.84
H3	50.	50.	50.	50.	50.	*	19.68	19.68	19.68	19.68	19.68
DBH1	ND	ND	5.	3.	3.	*	ND	ND	1.96	1.18	1.18
DBH2	ND	ND	10.	8.	5.	*	ND	ND	3.93	3.15	1.95
DBH3	ND	ND	12.	12.	10.	*	ND	ND	4.72	4.72	3.93
DTIME	420.00	360.00	240.00	300.00	360.00	*	7.00	6.00	4.00	5.00	6.00
UMF	.45	.45	.45	.45	.45	*	1.48	1.48	1.48	1.48	1.48
QUAL	B3 CG2	B3 CG1	B2 CG1	B2 CG1	B2-1 S1	*	B3 CG2	B3 CG1	B2 CG1	B2 CG1	B2-1 S1
QUAL	CG2	CG1	CG1 S1	NA	NA	*	CG2	CG1	CG1 S1	NA	NA

	S. I. UNITS					*	ENGLISH UNITS				
DATE	2 03 76	2 03 76	2 03 76	2 03 76	2 03 76	*	2 03 76	2 03 76	2 03 76	2 03 76	2 03 76
TUBE ARRAY	A3-S	A3-S	A3-S	A3-S	A3-S	*	A3-S	A3-S	A3-S	A3-S	A3-S
ARRAY LOC	2.5	2.5	2.5	2.5	2.5	*	.98	.98	.98	.98	.98
DPM	569.00	569.00	569.00	569.00	569.00	*	.022	.022	.022	.022	.022
UO	3.05	2.44	1.83	1.22	.61	*	10.01	8.01	6.00	4.00	2.00
P(ATM)	100.64	100.64	100.64	100.64	100.64	*	29.72	29.72	29.72	29.72	29.72
P(ORF)	.85	.68	.53	.35	.20	*	3.40	2.75	2.13	1.40	.80
T(ORF)	313.71	316.48	324.82	326.48	327.04	*	105.00	110.00	125.00	128.00	129.00
DPD	10.96	5.98	2.99	1.25	1.00	*	44.00	24.00	12.00	5.00	4.00
DPB(AV)	3.98	4.98	4.98	5.48	5.98	*	16.00	20.00	20.00	22.00	24.00
DPV(MX)	5.98	9.96	7.97	7.97	7.47	*	24.00	40.00	32.00	32.00	30.00
DPB(MN)	2.49	-1.00	2.49	2.99	4.48	*	10.00	-4.00	10.00	12.00	18.00
PS	35.85	35.16	24.13	21.37	20.68	*	5.20	5.10	3.50	3.10	3.00
LI	45.00	45.00	41.00	41.00	41.00	*	17.72	17.72	16.14	16.14	16.14
LF	35.00	41.00	41.00	41.00	41.00	*	13.78	16.14	16.14	16.14	16.14
LE	50.	70.	60.	53.	50.	*	19.68	27.55	23.62	20.86	19.68
H1	10.	5.	5.	5.	5.	*	3.93	1.96	1.96	1.96	1.96
H2	25.	25.	25.	25.	25.	*	9.84	9.84	9.84	9.84	9.84
H3	50.	50.	50.	50.	50.	*	19.68	19.68	19.68	19.68	19.68
DBH1	ND	3.	3.	3.	3.	*	ND	1.18	1.18	1.18	1.18
DBH2	ND	8.	8.	7.	10.	*	ND	3.15	3.15	2.75	3.93
DBH3	ND	25.	10.	10.	15.	*	ND	9.84	3.93	3.93	5.90
DTIME	180.00	360.00	360.00	480.00	420.00	*	3.00	6.00	6.00	8.00	7.00
UMF	.50	.50	.50	.50	.50	*	1.64	1.64	1.64	1.64	1.64
QUAL	B2 CG3	B3 CG2	B2 CG1	B2-1 CG1	B2-1 CG1	*	B2 CG3	B3 CG2	B2 CG1	B2-1 CG1	B2-1 CG1
QUAL	CG2	CG2 S1	S1 -S2		S1	*	CG2	CG2 S1	S1 -S2		S1

	S. I. UNITS						ENGLISH UNITS				
DATE	2 06 76	2 06 76	2 06 76	2 06 76	2 06 76	*	2 06 76	2 06 76	2 06 76	2 06 76	2 06 76
TUBE ARRAY	B1-S	B1-S	B1-S	B1-S	B1-S	*	B1-S	B1-S	B1-S	B1-S	B1-S
ARRAY LOC	2.5	2.5	2.5	2.5	2.5	*	.98	.98	.98	.98	.98
DPM	569.00	569.00	569.00	569.00	569.00	*	.022	.022	.022	.022	.022
UO	3.05	2.44	1.83	1.22	.91	*	10.01	8.01	6.00	4.00	2.99
P(ATM)	101.66	101.66	101.66	101.66	101.66	*	30.02	30.02	30.02	30.02	30.02
P(ORF)	.85	.72	.50	.35	.28	*	3.40	2.88	2.00	1.40	1.13
T(ORF)	314.26	322.04	305.37	327.59	330.37	*	106.00	120.00	90.00	130.00	135.00
DPD	15.94	11.46	5.98	2.49	1.99	*	64.00	46.00	24.00	10.00	8.00
DPB(AV)	19.43	18.93	4.98	5.48	5.48	*	78.00	76.00	20.00	22.00	22.00
DPV(MX)	20.92	20.92	6.97	6.48	6.48	*	84.00	84.00	28.00	26.00	26.00
DPB(MN)	18.93	17.93	2.49	3.49	4.48	*	76.00	72.00	10.00	14.00	18.00
PS	41.37	34.47	27.58	24.13	23.44	*	6.00	5.00	4.00	3.50	3.40
LI	42.00	44.00	43.00	43.00	43.00	*	16.54	17.32	16.93	16.93	16.93
LF	36.00	43.00	43.00	43.00	43.00	*	14.17	16.93	16.93	16.93	16.93
LE	57.	70.	65.	53.	50.	*	22.44	27.55	25.59	20.86	19.68
H1	5.	5.	5.	5.	5.	*	1.96	1.96	1.96	1.96	1.96
H2	25.	25.	25.	25.	25.	*	9.84	9.84	9.84	9.84	9.84
H3	50.	50.	50.	50.	50.	*	19.68	19.68	19.68	19.68	19.68
DBH1	ND	ND	3.	5.	3.	*	ND	ND	1.18	1.96	1.18
DBH2	ND	ND	8.	8.	8.	*	ND	ND	3.15	3.15	3.15
DBH3	ND	ND	20.	10.	10.	*	ND	ND	7.87	3.93	3.93
DTIME	360.00	420.00	420.00	480.00	360.00	*	6.00	7.00	7.00	8.00	6.00
UMF	.90	.90	.90	.90	.90	*	2.95	2.95	2.95	2.95	2.95
QUAL	B3 CG3	B3 CG3	B2 CG1	B2	B1-B2	*	B3 CG3	B3 CG3	B2 CG1	B2	B1-B2
QUAL	CG3	CG3 S2	B3 S2	B2 S1	NA	*	CG3	CG3 S2	B3 S2	B2 S1	NA

	S. I. UNITS						ENGLISH UNITS				
DATE	2 07 76	2 07 76	2 07 76	2 07 76	2 07 76	*	2 07 76	2 07 76	2 07 76	2 07 76	2 07 76
TUBE ARRAY	B2-S	B2-S	B2-S	B2-S	B2-S	*	B2-S	B2-S	B2-S	B2-S	B2-S
ARRAY LOC	2.5	2.5	2.5	2.5	2.5	*	.98	.98	.98	.98	.98
DPM	569.00	569.00	569.00	569.00	569.00	*	.022	.022	.022	.022	.022
UO	3.05	2.44	1.83	1.22	.81	*	10.01	8.01	6.00	4.00	2.66
P(ATM)	101.39	101.39	101.39	101.39	101.39	*	29.94	29.94	29.94	29.94	29.94
P(ORF)	.81	.72	.53	.37	.25	*	3.25	2.88	2.13	1.50	1.00
T(ORF)	308.15	330.37	333.15	333.15	330.37	*	95.00	135.00	140.00	140.00	135.00
DPD	17.93	11.95	6.97	3.49	1.49	*	72.00	48.00	28.00	14.00	6.00
DPB(AV)	3.98	4.98	5.48	5.48	5.48	*	16.00	20.00	22.00	22.00	22.00
DPV(MX)	5.98	6.97	6.97	6.97	6.97	*	24.00	28.00	28.00	28.00	28.00
DPB(MN)	2.49	2.99	3.49	3.98	3.98	*	10.00	12.00	14.00	16.00	16.00
PS	33.10	29.65	26.20	23.44	22.06	*	4.80	4.30	3.80	3.40	3.20
LI	45.00	45.00	43.00	43.00	43.00	*	17.72	17.72	16.93	16.93	16.93
LF	39.00	43.00	43.00	43.00	43.00	*	15.35	16.93	16.93	16.93	16.93
LE	65.	70.	65.	56.	50.	*	25.59	27.55	25.59	22.04	19.68
H1	5.	5.	5.	5.	5.	*	1.96	1.96	1.96	1.96	1.96
H2	25.	25.	25.	25.	25.	*	9.84	9.84	9.84	9.84	9.84
H3	50.	50.	50.	50.	50.	*	19.68	19.68	19.68	19.68	19.68
DBH1	ND	5.	4.	2.	2.	*	ND	1.96	1.57	.78	.78
DBH2	ND	10.	8.	5.	4.	*	ND	3.93	3.15	1.96	1.57
DBH3	ND	15.	10.	10.	5.	*	ND	5.90	3.93	3.93	1.96
DTIME	540.00	360.00	480.00	480.00	660.00	*	9.00	6.00	8.00	8.00	11.00
UMF	.81	.81	.81	.81	.81	*	2.66	2.66	2.66	2.66	2.66
QUAL	B3 CG3	B2 CG2	B2 CG1	B2 CG1	B2-B3	*	B3 CG3	B2 CG2	B2 CG1	B2 CG1	B2-B3
QUAL	CG3	B3 CG3	B2-B3	NA	NA	*	CG3	B3 CG3	B2-B3	NA	NA

	S. I. UNITS						ENGLISH UNITS				
DATE	2 07 76	2 07 76	2 07 76	2 07 76	2 07 76	*	2 07 76	2 07 76	2 07 76	2 07 76	2 07 76
TUBE ARRAY	B3-S	B3-S	B3-S	B3-S	B3-S	*	B3-S	B3-S	B3-S	B3-S	B3-S
ARRAY LOC	2.5	2.5	2.5	2.5	2.5	*	.98	.98	.98	.98	.98
DPM	569.00	569.00	569.00	569.00	569.00	*	.022	.022	.022	.022	.022
UO	3.05	2.44	1.83	1.22	.81	*	10.01	8.01	6.00	4.00	2.66
P(ATM)	101.39	101.39	101.39	101.39	101.39	*	29.94	29.94	29.94	29.94	29.94
P(ORF)	.90	.78	.53	.37	.22	*	3.20	3.13	2.13	1.50	.90
T(ORF)	316.48	334.26	325.37	334.26	333.71	*	110.00	142.00	126.00	142.00	141.00
DPD	20.92	16.93	6.48	3.98	1.49	*	84.00	68.00	26.00	16.00	6.00
DPB(AV)	3.98	3.98	4.98	4.98	4.98	*	16.00	16.00	20.00	20.00	20.00
DPV(MX)	5.98	7.47	7.47	6.48	6.48	*	24.00	30.00	30.00	26.00	26.00
DPB(MN)	1.49	.50	2.49	3.98	2.99	*	6.00	2.00	10.00	16.00	12.00
PS	35.16	33.10	28.96	23.44	21.37	*	5.10	4.80	4.20	3.40	3.10
LI	45.00	43.00	45.00	40.00	40.00	*	17.72	16.93	17.72	15.75	15.75
LF	40.00	40.00	43.00	40.00	40.00	*	15.75	15.75	16.93	15.75	15.75
LE	55.	65.	57.	55.	50.	*	21.65	25.59	22.44	21.65	19.68
H1	5.	5.	5.	5.	5.	*	1.96	1.96	1.96	1.96	1.96
H2	25.	25.	25.	25.	25.	*	9.84	9.84	9.84	9.84	9.84
H3	50.	50.	50.	50.	50.	*	19.68	19.68	19.68	19.68	19.68
DBH1	ND	ND	3.	5.	3.	*	ND	ND	1.18	1.96	1.18
DBH2	ND	ND	5.	8.	8.	*	ND	ND	1.96	3.15	3.15
DBH3	ND	ND	5.	10.	10.	*	ND	ND	1.96	3.93	3.93
DTIME	180.00	180.00	240.00	300.00	300.00	*	3.00	3.00	4.00	5.00	5.00
UMF	.81	.81	.81	.81	.81	*	2.66	2.66	2.66	2.66	2.66
QUAL	B3 CG3	B2-3 CG3	B2 CG2-3	CG2	B2-1 CG1	*	B3 CG3	B2-3 CG3	B2 CG2-3	CG2	B2-1 CG1
QUAL	CG3 E1	CG3 E2	CG3 E3	B2	NA	*	CG3 E1	CG3 E2	CG3 E3	B2	NA

	S. I. UNITS						ENGLISH UNITS				
DATE	2 08 76	2 08 76	2 08 76	2 08 76	2 08 76	*	2 08 76	2 08 76	2 08 76	2 08 76	2 08 76
TUBE ARRAY	C1-S	C1-S	C1-S	C1-S	C1-S	*	C1-S	C1-S	C1-S	C1-S	C1-S
ARRAY LOC	2.5	2.5	2.5	2.5	2.5	*	.98	.98	.98	.98	.98
DPM	569.00	569.00	569.00	569.00	569.00	*	.022	.022	.022	.022	.022
UO	3.05	2.44	1.83	1.22	.61	*	10.01	8.01	6.00	4.00	2.00
P(ATM)	100.71	100.71	100.71	100.71	100.71	*	29.74	29.74	29.74	29.74	29.74
P(ORF)	.78	.72	.53	.36	.19	*	3.13	2.89	2.13	1.45	.75
T(ORF)	318.71	330.37	333.15	331.48	330.37	*	114.00	135.00	140.00	137.00	135.00
DPD	7.47	10.46	5.48	2.49	1.00	*	30.00	42.00	22.00	10.00	4.00
DPB(AV)	3.98	3.98	4.98	5.98	6.48	*	16.00	16.00	20.00	24.00	26.00
DPV(MX)	5.98	5.98	7.47	8.47	6.48	*	24.00	24.00	30.00	34.00	26.00
DPB(MN)	1.49	1.99	2.49	3.98	5.98	*	6.00	8.00	10.00	16.00	24.00
PS	37.23	33.10	26.89	23.44	20.68	*	5.40	4.80	3.90	3.40	3.00
LI	45.00	45.00	45.00	45.00	45.00	*	17.72	17.72	17.72	17.72	17.72
LF	40.00	40.00	45.00	45.00	53.00	*	15.75	15.75	17.72	17.72	20.87
LE	62.	70.	70.	68.	5.	*	24.40	27.55	27.55	26.77	1.96
H1	5.	5.	5.	5.	25.	*	1.96	1.96	1.96	1.96	9.84
H2	25.	25.	25.	25.	50.	*	9.84	9.84	9.84	9.84	19.68
H3	50.	50.	50.	50.	2.	*	19.68	19.68	19.68	19.68	.78
DPH1	10.	5.	3.	3.		*	3.93	1.96	1.18	1.18	
DPH2	10.	7.	8.	8.	4.	*	3.93	2.75	3.15	3.15	1.57
DPH3	15.	15.	15.	10.	8.	*	5.90	5.90	5.90	3.93	3.15
DTIME	300.00	420.00	300.00	420.00	420.00	*	5.00	7.00	5.00	7.00	7.00
UMF	.50	.50	.50	.50	.50	*	1.64	1.64	1.64	1.64	1.64
QUAL	B3 CG3	B3 CG3	B1-2 CG1	B2-B1	B1 F1	*	B3 CG3	B3 CG3	B1-2 CG1	B2-B1	B1 F1
QUAL	CG3E3S1	B3CG3E2	CG1S1E1	B3 S1 F1	NA	*	CG3E3S1	B3CG3E2	CG1S1E1	B3 S1 E1	NA

S. I. UNITS / ENGLISH UNITS

DATE	2 08 76	2 08 76	2 08 76	2 08 76		*	2 08 76	2 08 76	2 08 76	2 08 76	
TUBE ARRAY	C2-S	C2-S	C2-S	C2-S		*	C2-S	C2-S	C2-S	C2-S	
ARRAY LOC	2.5	2.5	2.5	2.5		*	.98	.98	.98	.98	
RPM	569.00	569.00	569.00	569.00	0	*	.022	.022	.022	.022	0
UO	3.05	2.44	1.83	1.22	0	*	10.01	8.01	6.00	4.00	0
P(ATM)	100.71	100.71	100.71	100.71	0	*	29.74	29.74	29.74	29.74	0
P(ORF)	.81	.75	.56	.37	0	*	3.25	3.00	2.25	1.50	0
T(ORF)	310.93	332.04	337.04	334.26	0	*	100.00	138.00	147.00	142.00	0
DPD	14.94	10.46	4.98	2.49	0	*	60.00	42.00	20.00	10.00	0
DPB(AV)	3.49	3.98	5.48	5.98	0	*	14.00	16.00	22.00	24.00	0
DPV(MX)	4.98	7.47	6.97	5.98	0	*	20.00	30.00	28.00	24.00	0
DPB(MN)	1.99	1.49	3.98	5.48	0	*	8.00	6.00	16.00	22.00	0
PS	37.23	31.72	25.51	20.68	0	*	5.40	4.60	3.70	3.00	0
LI	45.00	45.00	45.00	45.00	0	*	17.72	17.72	17.72	17.72	0
LF	40.00	44.00	45.00	45.00	0	*	15.75	17.32	17.72	17.72	0
LE	60.	70.	70.	63.		*	23.62	27.55	27.55	24.80	
H1	5.	5.	5.	5.		*	1.96	1.96	1.96	1.96	
H2	25.	25.	25.	25.		*	9.84	9.84	9.84	9.84	
H3	50.	50.	50.	50.		*	19.68	19.68	19.68	19.68	
DBH1	5.	5.	3.	3.		*	1.96	1.96	1.18	1.18	
DBH2	8.	5.	5.	5.		*	3.15	1.96	1.96	1.96	
DBH3	10.	8.	7.	7.		*	3.93	3.15	2.75	2.75	
DTIME	300.00	300.00	360.00	360.00	0	*	5.00	5.00	6.00	6.00	0
UMF	1.22	1.22	1.22	1.22	0	*	4.00	4.00	4.00	4.00	0
QUAL	B2CG3S1	B2 CG3	B1-2 CG1	B1 F1		*	B2CG3S1	B2 CG3	B1-2 CG1	B1 F1	
QUAL	CG3 E3	B2CG3E2	B3 E1 S1	B3		*	CG3 E3	B2CG3E2	B3 E1 S1	B3	

	S. I. UNITS						ENGLISH UNITS				
DATE	2 08 76	2 08 76	2 08 76	2 08 76		*	2 08 76	2 08 76	2 08 76	2 08 76	
TUBE ARRAY	C3-S	C3-S	C3-S	C3-S		*	C3-S	C3-S	C3-S	C3-S	
ARRAY LOC	2.5	2.5	2.5	2.5		*	.98	.98	.98	.98	
DPM	569.00	569.00	569.00	569.00	0	*	.022	.022	.022	.022	0
UO	3.05	2.44	1.83	1.22	0	*	10.01	8.01	6.00	4.00	0
P(ATM)	100.71	100.71	100.71	100.71	0	*	29.74	29.74	29.74	29.74	0
P(ORF)	.78	.72	.53	.35	0	*	3.13	2.88	2.13	1.40	0
T(ORF)	309.26	319.26	319.26	327.04	0	*	97.00	115.00	115.00	129.00	0
DPD	21.42	16.44	6.97	3.49	0	*	86.00	66.00	28.00	14.00	0
DPB(AV)	2.49	3.98	4.48	4.98	0	*	10.00	16.00	18.00	20.00	0
DPV(MX)	3.98	5.98	4.98	4.98	0	*	16.00	24.00	20.00	20.00	0
DPR(MN)	1.49	1.99	3.98	4.98	0	*	6.00	8.00	16.00	20.00	0
PS	42.06	35.35	26.20	22.06	0	*	6.10	5.20	3.80	3.20	0
LI	45.00	45.00	43.00	45.00	0	*	17.72	17.72	16.93	17.72	0
LF	39.00	43.00	43.00	45.00	0	*	15.35	16.93	16.93	17.72	0
LE	55.	60.	60.	55.		*	21.65	23.62	23.62	21.65	
H1	5.	5.	5.	5.		*	1.96	1.96	1.96	1.96	
H2	25.	25.	25.	25.		*	9.84	9.84	9.84	9.84	
H3	50.	50.	50.	50.		*	19.68	19.68	19.68	19.68	
DBH1	5.	ND	5.	3.		*	1.96	ND	1.96	1.18	
DBH2	5.	ND	7.	5.		*	1.96	ND	2.75	1.96	
DBH3	5.	ND	15.	7.		*	1.96	ND	5.90	2.75	
DTIME	240.00	240.00	240.00	360.00	0	*	4.00	4.00	4.00	6.00	0
UMF	1.22	1.22	1.22	1.22	0	*	4.00	4.00	4.00	4.00	0
QUAL	B3 CG3	B3 CG3	B3-2 CG2	B2-1 F1		*	B3 CG3	B3 CG3	B3-2 CG2	B2-1 F1	
QUAL	CG3 F3	E2-3 S2	B2 E2	B2		*	CG3 F3	E2-3 S2	B2 E2	B2	

	S. I. UNITS						ENGLISH UNITS				
DATE	2 11 76	2 11 76	2 11 76	2 11 76	2 11 76	*	2 11 76	2 11 76	2 11 76	2 11 76	2 11 76
TUBE ARRAY	A1-T	A1-T	A1-T	A1-T	A1-T	*	A1-T	A1-T	A1-T	A1-T	A1-T
ARRAY LOC	2.5	2.5	2.5	2.5	2.5	*	.98	.98	.98	.98	.98
DPM	569.00	569.00	569.00	569.00	569.00	*	.022	.022	.022	.022	.022
UO	3.05	2.44	1.83	1.22	.61	*	10.01	8.01	6.00	4.00	2.00
P(ATM)	101.83	101.83	101.83	101.83	101.83	*	30.07	30.07	30.07	30.07	30.07
P(ORF)	.75	.75	.56	.34	.19	*	3.00	3.00	2.25	1.38	.75
T(ORF)	310.93	333.15	332.04	330.37	330.37	*	100.00	140.00	138.00	135.00	135.00
DPD	18.43	13.95	5.98	2.99	1.00	*	74.00	56.00	24.00	12.00	4.00
DPB(AV)	4.48	4.98	5.48	5.98	6.48	*	18.00	20.00	22.00	24.00	26.00
DPV(MX)	7.47	9.96	16.93	9.96	7.47	*	30.00	40.00	68.00	40.00	30.00
DPB(MN)	2.49	.50	-3.98	2.99	5.98	*	10.00	2.00	-16.00	12.00	24.00
PS	39.99	33.10	28.96	23.44	21.37	*	5.80	4.80	4.20	3.40	3.10
LT	43.00	42.00	43.00	45.00	45.00	*	16.93	16.54	15.93	17.72	17.72
LF	38.00	38.00	41.00	45.00	45.00	*	14.96	14.96	16.14	17.72	17.72
LE	ND	60.	70.	60.	55.	*	ND	23.62	27.55	23.62	21.65
H1	5.	5.	5.	5.	5.	*	1.96	1.96	1.96	1.96	1.96
H2	25.	25.	25.	25.	25.	*	9.84	9.84	9.84	9.84	9.84
H3	50.	50.	50.	50.	50.	*	19.68	19.68	19.68	19.68	19.68
DBH1	5.	3.	3.	3.	2.	*	1.96	1.18	1.18	1.18	.78
DBH2	10.	7.	8.	5.	4.	*	3.93	2.75	3.15	1.96	1.57
DBH3	12.	10.	15.	10.	10.	*	4.72	3.93	5.90	3.93	3.93
DTIME	300.00	300.00	300.00	300.00	480.00	*	5.00	5.00	5.00	5.00	8.00
UMF	.41	.41	.41	.41	.41	*	1.35	1.35	1.35	1.35	1.35
QUAL	B2-3 CG2	B2 CG2-3	CG1-CG2	B2-B1 S1	B1-B2	*	B2-3 CG2	B2 CG2-3	CG1-CG2	B2-B1 S1	B1-B2
QUAL	B2 CG2E3	CG2-3 E2	CG1 E2S1	S1-S2	NA	*	B2 CG2E3	CG2-3 E2	CG1 E2S1	S1-S2	NA

	S. I. UNITS						ENGLISH UNITS				
DATE	2 12 76	2 12 76	2 12 76	2 12 76	2 12 76	*	2 12 76	2 12 76	2 12 76	2 12 76	2 12 76
TUBE ARRAY	A2-T	A2-T	A2-T	A2-T	A2-T	*	A2-T	A2-T	A2-T	A2-T	A2-T
ARRAY LOC	2.5	2.5	2.5	2.5	2.5	*	.98	.98	.98	.98	.98
DPM	569.00	569.00	569.00	569.00	569.00	*	.022	.022	.022	.022	.022
UO	3.05	2.44	1.83	1.22	.61	*	10.01	8.01	6.00	4.00	2.00
P(ATM)	101.46	101.46	101.46	101.46	101.46	*	29.96	29.96	29.96	29.96	29.96
P(OPE)	.85	.72	.56	.40	.22	*	3.40	2.88	2.25	1.60	.88
T(OPE)	316.48	330.37	333.15	333.15	335.93	*	110.00	135.00	140.00	140.00	145.00
DPD	13.95	9.46	5.48	2.49	1.49	*	56.00	38.00	22.00	10.00	6.00
DPB(AV)	3.98	5.48	5.98	6.48	6.97	*	16.00	22.00	24.00	26.00	28.00
DPV(MX)	7.47	9.96	10.46	10.96	8.97	*	30.00	40.00	42.00	44.00	36.00
DPB(MN)	1.99	1.99	2.49	2.49	4.98	*	8.00	8.00	10.00	10.00	20.00
PS	41.37	34.47	29.65	25.51	23.44	*	6.00	5.00	4.30	3.70	3.40
LI	45.00	45.00	43.00	43.00	43.00	*	17.72	17.72	16.93	16.93	16.93
LF	42.00	43.00	43.00	43.00	43.00	*	16.54	16.93	16.93	16.93	16.93
LF	65.	75.	65.	65.	58.	*	25.59	29.52	25.59	25.59	22.83
H1	5.	5.	5.	5.	5.	*	1.96	1.96	1.96	1.96	1.96
H2	25.	25.	25.	25.	25.	*	9.84	9.84	9.84	9.84	9.84
H3	50.	50.	50.	50.	50.	*	19.68	19.68	19.68	19.68	19.68
DBH1	ND	3.	2.	2.	2.	*	ND	1.18	.78	.78	.78
DBH2	ND	7.	5.	5.	4.	*	ND	2.75	1.96	1.96	1.57
DBH3	ND	12.	8.	8.	6.	*	ND	4.72	3.15	3.15	2.36
DTIME	360.00	420.00	360.00	300.00	300.00	*	6.00	7.00	6.00	5.00	5.00
UMF	.40	.40	.40	.40	.40	*	1.31	1.31	1.31	1.31	1.31
QUAL	B3	B3-B2	B2-B1	B1-B2	B1	*	B3	B3-B2	B2-B1	B1-B2	B1
QUAL	B3 CG1E3	B3 CG1E2	B3 E1 S2	B2-B3 S1	B3 S1	*	B3 CG1E3	B3 CG1E2	B3 E1 S2	B2-B3 S1	B3 S1

	S. I. UNITS						ENGLISH UNITS				
DATE	2 12 76	2 12 76	2 12 76	2 12 76	2 12 76	*	2 12 76	2 12 76	2 12 76	2 12 76	2 12 76
TUBE ARRAY	A3-T	A3-T	A3-T	A3-T	A3-T	*	A3-T	A3-T	A3-T	A3-T	A3-T
ARRAY LOC	2.5	2.5	2.5	2.5	2.5	*	.98	.98	.98	.98	.98
DPM	569.00	569.00	569.00	569.00	569.00	*	.022	.022	.022	.022	.022
UO	2.75	2.44	1.83	1.22	.61	*	9.02	8.01	6.00	4.00	2.00
P(ATM)	101.08	101.08	101.08	101.08	101.08	*	29.85	29.85	29.85	29.85	29.85
P(ORF)	.75	.72	.59	.40	.22	*	3.00	2.88	2.38	1.60	.88
T(ORF)	310.93	322.04	335.93	335.93	333.15	*	100.00	120.00	145.00	145.00	140.00
DPD	20.92	21.92	10.96	4.48	1.99	*	84.00	88.00	44.00	18.00	8.00
DPB(AV)	4.48	4.98	5.98	6.97	6.97	*	18.00	20.00	24.00	28.00	28.00
DPV(MX)	4.98	7.47	7.47	9.46	7.47	*	20.00	30.00	30.00	38.00	30.00
DPB(MN)	2.99	1.00	2.49	2.99	6.48	*	12.00	4.00	10.00	12.00	26.00
PS	42.75	42.75	33.10	29.65	22.06	*	6.20	6.20	4.80	4.30	3.20
LI	45.00	45.00	45.00	45.00	45.00	*	17.72	17.72	17.72	17.72	17.72
LF	41.00	42.00	45.00	45.00	45.00	*	16.14	16.54	17.72	17.72	17.72
LF	60.	70.	65.	62.	58.	*	23.62	27.55	25.59	24.40	22.83
H1	5.	5.	5.	5.	5.	*	1.96	1.96	1.96	1.96	1.96
H2	25.	25.	25.	25.	25.	*	9.84	9.84	9.84	9.84	9.84
H3	50.	50.	50.	50.	50.	*	19.68	19.68	19.68	19.68	19.68
DPH1	5.	5.	3.	3.	2.	*	1.96	1.96	1.18	1.18	.79
DBH2	10.	10.	5.	5.	4.	*	3.93	3.93	1.96	1.96	1.57
DBH3	15.	15.	7.	7.	7.	*	5.90	5.90	2.75	2.75	2.75
DTIME	480.00	300.00	300.00	360.00	300.00	*	8.00	5.00	5.00	6.00	5.00
UMF	.40	.40	.40	.40	.40	*	1.31	1.31	1.31	1.31	1.31
QUAL	33 CG2-3	B2-3 CG3	B2	B2-B1	B1	*	B3 CG2-3	B2-3 CG3	B2	B2-B1	B1
QUAL	33 CG2F2	B3 F3 S2	B3 F1 S1	B2 S1	B1-BI	*	B3 CG2F2	B3 F3 S2	B3 F1 S1	B2 S1	B1-BI

	S. I. UNITS					*	ENGLISH UNITS				
DATE	2 12 76	2 12 76	2 12 76	2 12 76	2 12 76	*	2 12 76	2 12 76	2 12 76	2 12 76	2 12 76
TUBE ARRAY	B1-T	B1-T	B1-T	B1-T	B1-T	*	B1-T	B1-T	B1-T	B1-T	B1-T
ARRAY LOC	2.5	2.5	2.5	2.5	2.5	*	.98	.98	.98	.98	.98
DPM	569.00	569.00	569.00	569.00	569.00	*	.022	.022	.022	.022	.022
UO	2.75	2.44	1.83	1.22	.61	*	9.02	8.01	6.00	4.00	2.00
P(ATM)	101.08	101.08	101.08	101.08	101.08	*	29.85	29.85	29.85	29.85	29.85
P(ORF)	.75	.75	.56	.44	.22	*	3.00	3.00	2.25	1.75	.88
T(ORF)	313.71	335.93	341.48	340.37	338.71	*	105.00	145.00	155.00	153.00	150.00
DPD	17.93	14.44	9.46	3.98	1.49	*	72.00	58.00	38.00	16.00	6.00
DPP(AV)	4.48	4.98	5.98	6.97	6.97	*	18.00	20.00	24.00	28.00	28.00
DPV(MX)	9.96	9.96	10.96	8.97	7.47	*	40.00	40.00	44.00	36.00	30.00
DPP(MN)	-0.50	-0.50	-1.00	4.48	6.48	*	-2.00	-2.00	-4.00	18.00	26.00
PS	39.99	38.61	33.10	27.58	23.44	*	5.80	5.60	4.80	4.00	3.40
LI	45.00	45.00	45.00	45.00	45.00	*	17.72	17.72	17.72	17.72	17.72
LF	40.00	43.00	45.00	45.00	45.00	*	15.75	16.93	17.72	17.72	17.72
LF	75.	70.	70.	60.	57.	*	29.52	27.55	27.55	23.62	22.44
H1	5.	5.	5.	5.	5.	*	1.96	1.96	1.96	1.96	1.96
H2	25.	25.	25.	25.	25.	*	9.84	9.84	9.84	9.84	9.84
H3	50.	50.	50.	50.	50.	*	19.68	19.68	19.68	19.68	19.68
DBH1	3.	5.	5.	3.	2.	*	1.18	1.96	1.96	1.18	.79
DBH2	8.	10.	8.	5.	5.	*	3.15	3.93	3.15	1.96	1.96
DBH3	15.	12.	12.	10.	8.	*	5.90	4.72	4.72	3.93	3.15
DTIME	300.00	300.00	300.00	300.00	300.00	*	5.00	5.00	5.00	5.00	5.00
UMF	.46	.46	.46	.46	.46	*	1.51	1.51	1.51	1.51	1.51
QUAL	B3 CG3S1	B3 CG2	B3-B2	B2	B1	*	B3 CG3S1	B3 CG2	B3-B2	B2	B1
QUAL	CG3 E3S2	E2-E3 S1	CG2 S2-3	S1	B2	*	CG3 E3S2	E2-E3 S1	CG2 S2-3	S1	B2

	S. I. UNITS								ENGLISH UNITS		
DATE	2 13 76	2 13 76	2 13 76	2 13 76	2 13 76	*	2 13 76	2 13 76	2 13 76	2 13 76	2 13 76
TUBE ARRAY	B2-T	B2-T	B2-T	B2-T	B2-T	*	B2-T	B2-T	B2-T	B2-T	B2-T
ARRAY LOC	2.5	2.5	2.5	2.5	2.5	*	.98	.98	.98	.98	.98
DPM	559.00	569.00	569.00	569.00	569.00	*	.022	.022	.022	.022	.022
UO	2.75	2.44	1.83	1.22	.61	*	9.02	8.01	6.00	4.00	2.00
P(ATM)	100.85	100.85	100.85	100.85	100.85	*	29.78	29.78	29.78	29.78	29.78
P(ORF)	.75	.72	.55	.40	.20	*	3.00	2.88	2.20	1.60	.80
T(ORF)	308.15	327.59	333.15	338.71	337.04	*	95.00	130.00	140.00	150.00	147.00
DPD	13.45	9.96	4.98	2.49	1.00	*	54.00	40.00	20.00	10.00	4.00
DPB(AV)	3.98	4.48	5.98	6.48	6.97	*	16.00	18.00	24.00	26.00	28.00
DPV(MX)	5.98	7.47	9.96	9.96	7.47	*	24.00	30.00	40.00	40.00	30.00
DPB(MN)	1.49	1.99	3.98	3.49	6.48	*	6.00	8.00	16.00	14.00	26.00
PS	37.23	34.47	27.58	24.82	22.75	*	5.40	5.00	4.00	3.60	3.30
LT	45.00	45.00	45.00	45.00	45.00	*	17.72	17.72	17.72	17.72	17.72
LF	40.00	43.00	45.00	45.00	45.00	*	15.75	16.93	17.72	17.72	17.72
LE	65.	80.	70.	65.	58.	*	25.59	31.49	27.55	25.59	22.83
H1	5.	5.	5.	5.	5.	*	1.96	1.96	1.96	1.96	1.96
H2	25.	25.	25.	25.	25.	*	9.84	9.84	9.84	9.84	9.84
H3	50.	50.	50.	50.	50.	*	19.58	19.68	19.68	19.68	19.68
DBH1	5.	3.	3.	2.	2.	*	1.96	1.18	1.18	.78	.78
DBH2	10.	7.	5.	5.	5.	*	3.93	2.75	1.96	1.96	1.96
DBH3	15.	10.	7.	10.	5.	*	5.90	3.93	2.75	3.93	1.96
DTIME	240.00	300.00	300.00	300.00	300.00	*	4.00	5.00	5.00	5.00	5.00
UMF	.40	.40	.40	.40	.40	*	1.31	1.31	1.31	1.31	1.31
QUAL	B3 CG1	B3	B2-B3	B1-B2	B1	*	B3 CG1	B3	B2-B3	B1-B2	B1
QUAL	B3 E3 S1	B3 E1 S2	B3 E1 S1	B2-B3 S1	B1 B2	*	B3 E3 S1	B3 E1 S2	B3 E1 S1	B2-B3 S1	B1 B2

	S. I. UNITS						ENGLISH UNITS				
DATE	2 14 76	2 14 76	2 14 76	2 14 76	2 14 76	*	2 14 76	2 14 76	2 14 76	2 14 76	2 14 76
TUBE ARRAY	B3-T	B3-T	B3-T	B3-T	B3-T	*	B3-T	B3-T	B3-T	B3-T	B3-T
ARRAY LOC	2.5	2.5	2.5	2.5	2.5	*	.98	.98	.98	.98	.98
DPM	569.00	569.00	569.00	569.00	569.00	*	.022	.022	.022	.022	.022
UO	2.75	2.44	1.83	1.22	.61	*	9.02	8.01	6.00	4.00	2.00
P(ATM)	101.12	101.12	101.12	101.12	101.12	*	29.86	29.86	29.86	29.86	29.86
P(ORF)	.75	.72	.56	.37	.19	*	3.00	2.88	2.25	1.50	.75
T(ORF)	308.15	333.15	333.15	324.82	331.48	*	95.00	140.00	140.00	125.00	137.00
DPD	9.95	9.46	4.98	2.99	1.00	*	40.00	38.00	20.00	12.00	4.00
DPB(AV)	4.98	4.98	5.48	6.48	6.97	*	20.00	20.00	22.00	26.00	28.00
DPV(MX)	7.47	9.96	7.97	9.96	7.47	*	30.00	40.00	32.00	40.00	30.00
DPB(MN)	2.49	0	2.49	3.98	6.48	*	10.00	0	10.00	16.00	26.00
PS	37.23	34.47	29.65	26.89	24.13	*	5.40	5.00	4.30	3.90	3.50
LI	45.00	45.00	45.00	45.00	45.00	*	17.72	17.72	17.72	17.72	17.72
LF	40.00	42.00	45.00	45.00	45.00	*	15.75	16.54	17.72	17.72	17.72
LF	70.	70.	67.	60.	52.	*	27.55	27.55	26.37	23.62	20.47
H1	5.	5.	5.	5.	5.	*	1.96	1.96	1.96	1.96	1.96
H2	25.	25.	25.	25.	25.	*	9.84	9.84	9.84	9.84	9.84
H3	50.	50.	50.	50.	50.	*	19.58	19.68	19.68	19.68	19.68
DPH1	5.	3.	3.	2.	2.	*	1.96	1.18	1.18	.78	.78
DBH2	5.	5.	5.	3.	3.	*	1.96	1.96	1.96	1.18	1.18
DBH3	15.	8.	8.	5.	5.	*	5.90	3.15	3.15	1.96	1.96
DTIME	300.00	240.00	360.00	480.00	360.00	*	5.00	4.00	6.00	8.00	6.00
UMF	.61	.61	.61	.61	.61	*	2.00	2.00	2.00	2.00	2.00
QUAL	B3	B3 CG1	B2	B1-B2	B1 F1	*	B3	B3 CG1	B2	B1-B2	B1 F1
QUAL	B3 CG2F3	B3F3-2S1	B3 S1-S2	B3 S1	NA	*	B3 CG2F3	B3F3-2S1	B3 S1-S2	B3 S1	NA

	S. I. UNITS						ENGLISH UNITS				
DATE	2 14 76	2 14 76	2 14 76	2 14 76	2 14 76	*	2 14 76	2 14 76	2 14 76	2 14 76	2 14 76
TUBE ARRAY	C1-T	C1-T	C1-T	C1-T	C1-T	*	C1-T	C1-T	C1-T	C1-T	C1-T
ARRAY LOC	2.5	2.5	2.5	2.5	2.5	*	.98	.98	.98	.98	.98
DPM	569.00	569.00	569.00	569.00	569.00	*	.022	.022	.022	.022	.022
UO	2.75	2.44	1.83	1.22	.61	*	9.02	8.01	6.00	4.00	2.00
P(ATM)	101.12	101.12	101.12	101.12	101.12	*	29.86	29.86	29.86	29.86	29.86
P(ORF)	.75	.78	.59	.44	.22	*	3.00	3.13	2.38	1.75	.89
T(ORF)	322.04	341.49	347.04	344.26	338.71	*	120.00	155.00	165.00	160.00	150.00
DPD	9.96	9.46	6.48	2.99	1.00	*	40.00	38.00	26.00	12.00	4.00
DPB(AV)	4.99	4.98	5.48	6.48	6.48	*	20.00	20.00	22.00	26.00	26.00
DPV(MX)	7.47	7.97	9.96	8.97	6.97	*	30.00	32.00	40.00	36.00	28.00
DPB(MN)	2.99	2.49	.50	3.49	5.98	*	12.00	10.00	2.00	14.00	24.00
PS	35.16	67.57	30.34	25.51	22.75	*	5.10	9.80	4.40	3.70	3.30
LI	45.00	45.00	45.00	44.00	44.00	*	17.72	17.72	17.72	17.32	17.32
LF	43.00	43.00	45.00	44.00	44.00	*	16.93	16.93	17.72	17.32	17.32
LE	70.	70.	65.	65.	53.	*	27.55	27.55	25.59	25.59	20.86
H1	5.	5.	5.	5.	5.	*	1.96	1.96	1.96	1.96	1.96
H2	25.	25.	25.	25.	25.	*	9.84	9.84	9.84	9.84	9.84
H3	50.	50.	50.	50.	50.	*	19.68	19.68	19.68	19.68	19.68
DBH1	5.	3.	3.	2.	2.	*	1.96	1.18	1.18	.78	.78
DBH2	5.	8.	5.	5.	5.	*	1.96	3.15	1.96	1.96	1.96
DBH3	5.	5.	8.	5.	7.	*	1.96	1.96	3.15	1.96	2.75
DTIME	420.00	360.00	300.00	300.00	360.00	*	7.00	6.00	5.00	5.00	6.00
UMF	.40	.40	.40	.40	.40	*	1.31	1.31	1.31	1.31	1.31
QUAL	B3 CG1	B3-2 CG1	B3-2 CG1	B2-B1	B1	*	B3 CG1	B3-2 CG1	B3-2 CG1	B2-B1	B1
QUAL	B3 CG2E3	CG1 E1S2	B3 CG1S1	B3 S1	B1	*	B3 CG2E3	CG1 E1S2	B3 CG1S1	B3 S1	B1

	S. I. UNITS						ENGLISH UNITS				
DATE	2 14 76	2 14 76	2 14 76	2 14 76		*	2 14 76	2 14 76	2 14 76	2 14 76	
TUBE ARRAY	C2-T	C2-T	C2-T	C2-T		*	C2-T	C2-T	C2-T	C2-T	
ARRAY LOC	2.5	2.5	2.5	2.5		*	.98	.98	.98	.98	
DPM	569.00	569.00	569.00	569.00	0	*	.022	.022	.022	.022	0
UO	2.75	2.44	1.83	1.22	0	*	9.02	8.01	6.00	4.00	0
P(ATM)	101.12	101.12	101.12	101.12	0	*	29.86	29.85	29.86	29.86	0
P(ORF)	.75	.72	.59	.44	0	*	3.00	2.88	2.38	1.75	0
T(ORF)	316.48	326.48	338.71	341.48	0	*	110.00	128.00	150.00	155.00	0
DPD	14.94	6.97	6.48	2.99	0	*	60.00	28.00	26.00	12.00	0
DPB(AV)	4.98	5.48	5.98	5.98	0	*	20.00	22.00	24.00	24.00	0
DPV(MX)	6.97	5.98	5.98	5.98	0	*	28.00	24.00	24.00	24.00	0
DPP(MN)	2.99	4.48	5.98	5.98	0	*	12.00	18.00	24.00	24.00	0
PS	36.54	28.96	28.96	24.13	0	*	5.30	4.20	4.20	3.50	0
LI	45.00	47.00	47.00	47.00	0	*	17.72	18.50	18.50	18.50	0
LF	42.00	47.00	47.00	47.00	0	*	16.54	18.50	18.50	18.50	0
LE	70.	72.	70.	62.		*	27.55	28.34	27.55	24.40	
H1	5.	5.	5.	5.		*	1.96	1.95	1.96	1.95	
H2	25.	25.	25.	25.		*	9.84	9.84	9.84	9.84	
H3	50.	50.	50.	50.		*	19.68	19.68	19.68	19.68	
DBH1	5.	3.	2.	2.		*	1.96	1.18	.78	.79	
DBH2	5.	5.	6.	4.		*	1.96	1.95	2.36	1.57	
DBH3	5.	7.	8.	5.		*	1.96	2.75	3.15	1.96	
DTIME	420.00	420.00	480.00	360.00	0	*	7.00	7.00	8.00	6.00	0
UMF	.45	.95	.95	.95	0	*	1.48	3.12	3.12	3.12	0
QUAL	33 CG2	B2-B3	B2-1 CG1	B1		*	B3 CG2	B2-B3	B2-1 CG1	B1	
QUAL	B3 CG1	B3 S1	B3 S1	B2-B3		*	B3 CG1	B3 S1	B3 S1	B2-B3	

	S. I. UNITS					*	ENGLISH UNITS				
DATE	2 14 76	2 14 76	2 14 76	2 14 76	2 14 76	*	2 14 76	2 14 76	2 14 76	2 14 76	2 14 76
TUBE ARRAY	C3-T	C3-T	C3-T	C3-T	C3-T	*	C3-T	C3-T	C3-T	C3-T	C3-T
ARRAY LOC	2.5	2.5	2.5	2.5	2.5	*	.98	.98	.98	.98	.98
DPM	569.00	569.00	569.00	569.00	569.00	*	.022	.022	.022	.022	.022
UO	2.75	2.44	1.83	1.22	.61	*	9.02	8.01	6.00	4.00	2.00
P(ATM)	101.12	101.12	101.12	101.12	101.12	*	29.86	29.86	29.86	29.86	29.86
P(ORF)	.78	.72	.56	.41	.22	*	3.13	2.88	2.25	1.63	.88
T(ORF)	319.26	327.59	333.15	338.71	338.71	*	115.00	130.00	140.00	150.00	150.00
DPD	17.93	8.47	7.97	3.49	1.49	*	72.00	34.00	32.00	14.00	6.00
DPB(AV)	4.48	4.98	5.48	5.98	6.48	*	18.00	20.00	22.00	24.00	26.00
DPV(MX)	4.98	7.47	6.48	6.48	6.48	*	20.00	30.00	26.00	26.00	26.00
DPB(MN)	3.98	2.99	2.49	5.98	6.48	*	16.00	12.00	10.00	24.00	26.00
PS	37.23	31.03	28.96	24.82	22.06	*	5.40	4.50	4.20	3.60	3.20
LT	45.00	45.00	45.00	45.00	45.00	*	17.72	17.72	17.72	17.72	17.72
LF	42.00	43.00	43.00	45.00	45.00	*	16.54	16.93	16.93	17.72	17.72
LF	70.	60.	65.	60.	58.	*	27.55	23.62	25.59	23.62	22.83
H1	5.	5.	5.	5.	5.	*	1.96	1.96	1.96	1.96	1.96
H2	25.	25.	25.	25.	25.	*	9.84	9.84	9.84	9.84	9.84
H3	50.	50.	50.	50.	50.	*	19.68	19.68	19.68	19.68	19.68
DBH1	3.	3.	3.	2.	2.	*	1.18	1.18	1.18	.78	.78
DBH2	5.	5.	4.	4.	4.	*	1.96	1.96	1.57	1.57	1.57
DBH3	10.	7.	6.	6.	5.	*	3.93	2.75	2.36	2.36	1.96
DTIME	240.00	300.00	300.00	300.00	360.00	*	4.00	5.00	5.00	5.00	6.00
UMF	.41	.40	.40	.40	.40	*	1.35	1.31	1.31	1.31	1.31
QUAL	B3-2 CG1	B2-B3	B2-B3	B1	B1 F1	*	B3-2 CG1	B2-B3	B2-B3	B1	B1 F1
QUAL	B3 E3CG2	B3 E2 S1	B3 E2 S2	B3 S2	B2	*	B3 E3CG2	B3 E2 S1	B3 E2 S2	B3 S2	B2

	S. I. UNITS						ENGLISH UNITS				
DATE	2 16 76	2 16 76	2 16 76	2 16 76	2 16 76	*	2 16 76	2 16 76	2 16 76	2 16 76	2 16 76
TUBE ARRAY	EMPT	EMPT	EMPT	EMPT	EMPT	*	EMPT	EMPT	EMPT	EMPT	EMPT
ARRAY LOC	NA	NA	NA	NA	NA	*	NA	NA	NA	NA	NA
DPM	1379.00	1379.00	1379.00	1379.00	1379.00	*	.054	.054	.054	.054	.054
UC	2.75	2.44	1.83	1.22	.91	*	9.02	8.01	6.00	4.00	2.99
P(ATM)	100.75	100.75	100.75	100.75	100.75	*	29.75	29.75	29.75	29.75	29.75
P(ORF)	.87	.78	.59	.41	.28	*	3.50	3.13	2.38	1.63	1.13
T(ORF)	333.15	341.48	341.48	342.59	338.71	*	140.00	155.00	155.00	157.00	150.00
DPD	15.94	10.46	6.97	2.99	3.98	*	64.00	42.00	28.00	12.00	16.00
DPR(AV)	3.98	3.98	3.49	3.49	3.49	*	16.00	16.00	14.00	14.00	14.00
DPV(MX)	5.48	6.97	4.98	3.98	3.49	*	22.00	28.00	20.00	16.00	14.00
DPR(MN)	1.99	1.49	1.99	2.99	3.49	*	8.00	6.00	8.00	12.00	14.00
PS	37.23	31.03	26.20	20.68	19.31	*	5.40	4.50	3.80	3.00	2.80
LI	27.00	27.00	27.00	27.00	27.00	*	10.63	10.63	10.63	10.63	10.63
LF	27.00	27.00	27.00	27.00	27.00	*	10.63	10.63	10.63	10.63	10.63
LF	40.	40.	3.5	30.	29.	*	15.74	15.74	1.37	11.81	11.41
H1	5.	5.	5.	5.	5.	*	1.96	1.96	1.96	1.96	1.96
H2	25.	15.	15.	15.	15.	*	9.84	5.90	5.90	5.90	5.90
H3	50.	30.	30.	30.	25.	*	19.68	11.81	11.81	11.81	9.84
DPH1	5.	3.	3.	2.	2.	*	1.96	1.18	1.18	.78	.78
DPH2	15.	10.	7.	6.	3.	*	5.90	3.93	2.75	2.36	1.18
DPH3	NO	20.	15.	12.	5.	*	NO	7.87	5.90	4.72	1.96
DTIME	300.00	180.00	180.00	180.00	240.00	*	5.00	3.00	3.00	3.00	4.00
UMF	.91	.91	.91	.91	.91	*	2.99	2.99	2.99	2.99	2.99
QUAL	S3	S2-S3	S2	S2-S3	S1 F1	*	S3	S2-S3	S2	S2-S3	S1 F1
QUAL	NA	NA	NA	NA	NA	*	NA	NA	NA	NA	NA

	S. I. UNITS						ENGLISH UNITS				
DATE	2 16 76	2 16 76	2 16 76	2 16 76	2 16 76	*	2 16 76	2 16 76	2 16 76	2 16 76	2 15 76
TUBE ARRAY	EMPT	EMPT	EMPT	EMPT	EMPT	*	EMPT	EMPT	EMPT	EMPT	EMPT
ARRAY LOC	NA	NA	NA	NA	NA	*	NA	NA	NA	NA	NA
DPM	1379.00	1379.00	1379.00	1379.00	1379.00	*	.054	.054	.054	.054	.054
UO	2.75	2.44	1.83	1.22	.91	*	9.02	8.01	6.00	4.00	2.99
P(ATM)	100.75	100.75	100.75	100.75	100.75	*	29.75	29.75	29.75	29.75	29.75
P(ORF)	.87	.81	.62	.44	.28	*	3.50	3.25	2.50	1.75	1.13
T(ORF)	338.71	344.26	344.26	344.26	344.26	*	150.00	160.00	160.00	160.00	160.00
DPD	13.45	13.45	7.47	3.49	1.99	*	54.00	54.00	30.00	14.00	8.00
DPB(AV)	7.47	6.48	5.48	5.98	6.48	*	30.00	26.00	25.00	24.00	26.00
DPV(MX)	19.92	14.94	18.93	9.96	6.48	*	80.00	60.00	76.00	40.00	26.00
DPB(MN)	-6.23	-4.98	-2.49	2.99	6.48	*	-25.00	-20.00	-10.00	12.00	26.00
PS	39.99	35.35	29.65	24.13	22.06	*	5.80	5.20	4.30	3.50	3.20
LI	43.00	46.00	46.00	46.00	46.00	*	16.93	18.11	18.11	18.11	18.11
LF	46.00	46.00	46.00	46.00	46.00	*	18.11	18.11	18.11	18.11	18.11
LF	60.	60.	55.	55.	48.	*	23.62	23.62	21.65	21.65	18.89
H1	5.	5.	5.	5.	5.	*	1.96	1.96	1.96	1.96	1.96
H2	25.	25.	25.	25.	25.	*	9.84	9.84	9.84	9.84	9.84
H3	50.	50.	50.	50.	45.	*	19.68	19.68	19.68	19.68	17.71
DBH1	5.	7.	5.	3.	2.	*	1.96	2.75	1.96	1.18	.78
DBH2	12.	30.	12.	15.	12.	*	4.72	11.81	4.72	5.90	4.72
DBH3	30.	40.	30.	20.	10.	*	11.81	15.74	11.81	7.87	3.93
DTIME	120.00	180.00	180.00	240.00	360.00	*	2.00	3.00	3.00	4.00	6.00
UMF	.91	.91	.91	.91	.91	*	2.99	2.99	2.99	2.99	2.99
QUAL	S3 F2	S3	S2-S3	S1-S2	S1 F1	*	S3 F2	S3	S2-S3	S1-S2	S1 F1
QUAL	NA	NA	NA	NA	NA	*	NA	NA	NA	NA	NA

	S. I. UNITS						ENGLISH UNITS				
DATE	2 16 76	2 16 76	2 16 76	2 16 76	2 16 76	*	2 16 76	2 16 76	2 16 76	2 16 76	2 16 76
TUBE ARRAY	C2-T	C2-T	C2-T	C2-T	C2-T	*	C2-T	C2-T	C2-T	C2-T	C2-T
ARRAY LOC	15.	15.	15.	15.	15.	*	5.90	5.90	5.90	5.90	5.90
DPM	569.00	569.00	569.00	569.00	569.00	*	.022	.022	.022	.022	.022
UO	2.75	2.44	1.83	1.22	.61	*	9.02	8.01	6.00	4.00	2.00
P(ATM)	100.88	100.88	100.88	100.75	100.88	*	29.79	29.79	29.79	29.75	29.79
P(ORF)	.78	.72	.59	.41	.22	*	3.13	2.88	2.38	1.63	.88
T(ORF)	309.26	324.82	335.93	335.93	335.93	*	97.00	125.00	145.00	145.00	145.00
DPD	14.94	11.46	5.98	3.49	1.00	*	60.00	46.00	24.00	14.00	4.00
DPB(AV)	1.49	2.49	2.99	3.98	3.49	*	6.00	10.00	12.00	16.00	14.00
DPV(MX)	1.49	2.49	2.99	3.98	3.98	*	6.00	10.00	12.00	16.00	16.00
DPB(MN)	1.49	2.49	2.99	3.98	3.49	*	6.00	10.00	12.00	16.00	14.00
PS	33.10	28.96	24.13	22.06	18.62	*	4.80	4.20	3.50	3.20	2.70
LI	23.00	23.00	23.00	23.00	23.00	*	9.06	9.06	9.06	9.06	9.06
LF	19.00	21.00	23.00	23.00	23.00	*	7.48	8.27	9.06	9.06	9.06
LE	ND	ND	45.	42.	32.	*	ND	ND	17.71	16.53	12.59
H1	5.	5.	5.	5.	5.	*	1.96	1.96	1.96	1.96	1.96
H2	25.	25.	25.	25.	20.	*	9.84	9.84	9.84	9.84	7.87
H3	50.	50.	40.	40.	30.	*	19.68	19.68	15.74	15.74	11.81
DPH1	ND	ND	3.	3.	2.	*	ND	ND	1.18	1.18	.79
DPH2	ND	ND	5.	5.	4.	*	ND	ND	1.96	1.96	1.57
DPH3	ND	ND	6.	5.	3.	*	ND	ND	2.36	1.96	1.18
DTIME	300.00	300.00	420.00	360.00	240.00	*	5.00	5.00	7.00	6.00	4.00
UMF	.50	.50	.50	.50	.50	*	1.64	1.64	1.64	1.64	1.64
QUAL	33	33 CG1	32 S1	32 S1	31 S1	*	33	33 CG1	32 S1	32 S1	31 S1
QUAL	31 S3	NA	NA	NA	NA	*	31 S3	NA	NA	NA	NA

	S. I. UNITS						ENGLISH UNITS				
DATE	2 16 76	2 16 76	2 16 76	2 56 76	2 16 76	*	2 16 76	2 16 76	2 16 76	2 56 76	2 16 76
TUBE ARRAY	C2-T	C2-T	C2-T	C2-T	C2-T	*	C2-T	C2-T	C2-T	C2-T	C2-T
ARRAY LOC	15.	15.	15.	15.	15.	*	5.90	5.90	5.90	5.90	5.90
DPM	569.00	569.00	569.00	569.00	569.00	*	.022	.022	.022	.022	.022
UO	2.75	2.44	1.83	1.22	.61	*	9.02	8.01	6.00	4.00	2.00
P(ATM)	100.88	100.88	100.88	100.88	100.88	*	29.79	29.79	29.79	29.79	29.79
P(ORF)	.84	.77	.59	.41	.22	*	3.38	3.10	2.38	1.63	.88
T(ORF)	335.93	332.04	338.71	344.26	338.71	*	145.00	138.00	150.00	160.00	150.00
DPD	14.94	13.45	6.97	2.99	1.00	*	60.00	54.00	28.00	12.00	4.00
DPB(AV)	2.49	3.49	4.98	5.98	6.97	*	10.00	14.00	20.00	24.00	28.00
DPV(MX)	2.99	3.98	5.48	7.97	7.47	*	12.00	16.00	22.00	32.00	30.00
DPB(MN)	2.49	2.99	4.48	3.49	6.48	*	10.00	12.00	18.00	14.00	26.00
PS	37.92	365.42	282.69	24.82	22.06	*	5.50	53.00	41.00	3.60	3.20
LI	45.00	45.00	45.00	45.00	45.00	*	17.72	17.72	17.72	17.72	17.72
LF	39.00	43.00	45.00	45.00	45.00	*	15.35	16.93	17.72	17.72	17.72
LE	90.	85.	80.	70.	60.	*	35.43	33.46	31.49	27.55	23.62
H1	5.	5.	5.	5.	5.	*	1.96	1.96	1.96	1.96	1.96
H2	25.	25.	25.	25.	25.	*	9.84	9.84	9.84	9.84	9.84
H3	50.	50.	50.	50.	50.	*	19.68	19.68	19.68	19.68	19.68
DBH1	ND	ND	3.	5.	7.	*	ND	ND	1.18	1.96	2.75
DBH2	ND	ND	5.	8.	5.	*	ND	ND	1.96	3.15	1.96
DBH3	ND	ND	8.	5.	7.	*	ND	ND	3.15	1.96	2.75
DTIME	240.00	240.00	300.00	360.00	360.00	*	4.00	4.00	5.00	6.00	6.00
UMF	.48	.48	.48	.48	.48	*	1.57	1.57	1.57	1.57	1.57
QUAL	B3	B3	B2	B2-B1 S1	B1 S1	*	B3	B3	B2	B2-B1 S1	B1 S1
QUAL	E3 S3	E3 S1-S3	B3 E1 S1	B2-B3 S1	NA	*	E3 S3	E3 S1-S3	B3 E1 S1	B2-B3 S1	NA

	S. I. UNITS						ENGLISH UNITS				
DATE	2 16 76	2 16 76	2 16 76	2 16 76		*	2 16 76	2 16 76	2 16 76	2 16 76	
TUBE ARRAY	C2-T	C2-T	C2-T	C2-T		*	C2-T	C2-T	C2-T	C2-T	
ARRAY LOC	15.	15.	15.	15.		*	5.90	5.90	5.90	5.90	
DPM	1379.00	1379.00	1379.00	1379.00	0	*	.054	.054	.054	.054	0
UO	2.75	2.44	1.83	1.22	0	*	9.02	8.01	6.00	4.00	0
P(ATM)	100.88	100.88	100.88	100.88	0	*	29.79	29.79	29.79	29.79	0
P(ORF)	.78	.81	.62	.37	0	*	3.13	3.25	2.50	1.50	0
T(ORF)	330.93	338.71	347.04	330.37	0	*	136.00	150.00	165.00	135.00	0
DPO	12.95	11.46	5.98	2.99	0	*	52.00	46.00	24.00	12.00	0
DPB(AV)	2.99	2.99	2.99	3.49	0	*	12.00	12.00	12.00	14.00	0
DPV(MX)	2.99	2.99	3.49	3.49	0	*	12.00	12.00	14.00	14.00	0
DPB(MN)	2.99	2.99	2.99	2.99	0	*	12.00	12.00	12.00	12.00	0
PS	31.03	296.48	26.20	20.68	0	*	4.50	43.00	3.80	3.00	0
LI	23.00	23.00	23.00	23.00	0	*	9.06	9.06	9.06	9.06	0
LF	22.00	23.00	23.00	23.00	0	*	8.66	9.06	9.06	9.06	0
LE	48.	60.	41.	31.		*	18.89	23.62	16.14	12.20	
H1	5.	5.	5.	5.		*	1.96	1.96	1.96	1.96	
H2	30.	30.	20.	20.		*	11.81	11.81	7.87	7.87	
H3	40.	50.	40.	30.		*	15.74	19.68	15.74	11.81	
DBH1	3.	5.	5.	8.		*	1.18	1.96	1.96	3.15	
DBH2	9.	7.	6.	5.		*	3.54	2.75	2.36	1.96	
DBH3	7.	7.	5.	5.		*	2.75	2.75	1.96	1.96	
DTIME	360.00	300.00	240.00	180.00	0	*	6.00	5.00	4.00	3.00	0
UMF	1.00	1.00	1.00	1.00	0	*	3.28	3.28	3.28	3.28	0
QUAL	B2-B3	B2	B1-B2	B1 F1		*	B2-B3	B2	B1-B2	B1 F1	
QUAL	NA	NA	NA	NA		*	NA	NA	NA	NA	

	S. I. UNITS						ENGLISH UNITS				
DATE	2 16 76	2 16 76	2 16 76	2 16 76	2 16 76	*	2 16 76	2 16 76	2 16 76	2 16 76	2 16 76
TUBE ARRAY	C2-T	C2-T	C2-T	C2-T	C2-T	*	C2-T	C2-T	C2-T	C2-T	C2-T
ARRAY LOC	25.	25.	25.	25.	25.	*	9.84	9.84	9.84	9.84	9.84
DPM	569.00	569.00	569.00	569.00	569.00	*	.022	.022	.022	.022	.022
UO	29.79	2.44	1.83	1.22	.61	*	97.74	8.01	6.00	4.00	2.00
P(ATM)	10.60	100.88	100.88	100.88	100.88	*	3.13	29.79	29.79	29.79	29.79
P(ORF)	32.38	.78	.56	.41	.20	*	130.00	3.13	2.25	1.63	.80
T(ORF)	286.48	333.15	335.93	344.26	341.48	*	56.00	140.00	145.00	160.00	155.00
DPD	3.98	11.95	5.98	2.99	1.49	*	16.00	48.00	24.00	12.00	6.00
DPB(AV)	4.48	3.49	5.98	6.48	6.97	*	18.00	14.00	24.00	26.00	28.00
DPV(MX)	4.48	4.48	7.97	9.96	8.47	*	18.00	18.00	32.00	40.00	34.00
DPB(MN)	2.99	3.49	2.49	2.99	4.48	*	12.00	14.00	10.00	12.00	18.00
PS	37.23	35.16	27.58	24.82	23.44	*	5.40	5.10	4.00	3.60	3.40
LI	45.00	45.00	45.00	45.00	45.00	*	17.72	17.72	17.72	17.72	17.72
LF	40.00	42.00	45.00	45.00	45.00	*	15.75	16.54	17.72	17.72	17.72
LE	90.	90.	80.	70.	62.	*	35.43	35.43	31.49	27.55	24.40
H1	5.	5.	5.	5.	5.	*	1.96	1.96	1.96	1.96	1.96
H2	25.	25.	30.	30.	30.	*	9.84	9.84	11.81	11.81	11.81
H3	50.	50.	50.	50.	50.	*	19.68	19.68	19.68	19.68	19.68
DBH1	10.	8.	7.	10.	7.	*	3.93	3.15	2.75	3.93	2.75
DBH2	ND	ND	5.	7.	5.	*	ND	ND	1.96	2.75	1.96
DBH3	ND	ND	7.	6.	5.	*	ND	ND	2.75	2.36	1.96
DTIME	360.00	240.00	240.00	360.00	300.00	*	6.00	4.00	4.00	6.00	5.00
UMF	.40	.40	.40	.40	.40	*	1.31	1.31	1.31	1.31	1.31
QUAL	B3	B3	B3-B2	B2	B1-B2 S1	*	B3	B3	B3-B2	B2	B1-B2 S1
QUAL	B3 E3 S1	B3 E2 S2	B2 S1	NA	NA	*	B3 E3 S1	B3 E2 S2	B2 S1	NA	NA

	S. I. UNITS						ENGLISH UNITS				
DATE	2 16 76	2 16 76	2 16 76	2 16 76	2 16 76	*	2 16 76	2 16 76	2 16 76	2 16 76	2 16 76
TUBE ARRAY	C2-T	C2-T	C2-T	C2-T	C2-T	*	C2-T	C2-T	C2-T	C2-T	C2-T
ARRAY LOC	25.	25.	25.	25.	25.	*	9.84	9.84	9.84	9.84	9.84
DPM	569.00	569.00	569.00	569.00	569.00	*	.022	.022	.022	.022	.022
UO	2.75	2.44	1.83	1.22	.61	*	9.02	8.01	6.00	4.00	2.00
P(ATM)	101.52	101.52	101.52	101.52	101.52	*	29.98	29.98	29.98	29.98	29.98
P(ORF)	.75	.72	.59	.41	.20	*	3.00	2.88	2.38	1.63	.80
T(ORF)	310.93	327.59	335.93	338.71	335.93	*	100.00	130.00	145.00	150.00	145.00
DPD	12.95	8.97	6.97	2.99	1.00	*	52.00	36.00	28.00	12.00	4.00
DPB(AV)	2.99	2.99	3.49	4.48	3.98	*	12.00	12.00	14.00	18.00	16.00
DPV(MX)	2.99	3.49	4.48	4.98	4.48	*	12.00	14.00	18.00	20.00	18.00
DPB(MN)	2.99	2.99	2.99	3.98	3.49	*	12.00	12.00	12.00	16.00	14.00
PS	32.41	30.34	27.58	23.44	20.68	*	4.70	4.40	4.00	3.40	3.00
LI	23.00	23.00	23.00	23.00	23.00	*	9.06	9.06	9.06	9.06	9.06
LF	23.00	23.00	23.00	23.00	23.00	*	9.06	9.06	9.06	9.06	9.06
LE	ND	70.	60.	42.	36.	*	ND	27.55	23.62	16.53	14.17
H1	5.	5.	10.	10.	10.	*	1.96	1.96	3.93	3.93	3.93
H2	30.	30.	30.	30.	25.	*	11.81	11.81	11.81	11.81	9.84
H3	50.	50.	50.	40.	30.	*	19.68	19.68	19.68	15.74	11.81
DBH1	ND	12.	10.	15.	5.	*	ND	4.72	3.93	5.90	1.96
DBH2	ND	7.	6.	8.	8.	*	ND	2.75	2.36	3.15	3.15
DBH3	ND	ND	8.	5.	5.	*	ND	ND	3.15	1.96	1.96
DTIME	180.00	240.00	240.00	240.00	240.00	*	3.00	4.00	4.00	4.00	4.00
UMF	.48	.48	.48	.48	.48	*	1.57	1.57	1.57	1.57	1.57
QUAL	B3 S1	B3 S1	B3-B2 S2	B2 S2	B1 S1	*	B3 S1	B3 S1	B3-B2 S2	B2 S2	B1 S1
QUAL	E2	E1		NA	NA	*	E2	E1		NA	NA

S. I. UNITS

DATE		2 16 76	2 17 76	2 17 76	2 17 76	*
TUBE ARRAY		C2-T	C2-T	C2-T	C2-T	*
ARRAY LOC		25.	25.	25.	25.	*
DPM	0	1379.00	1379.00	1379.00	1379.00	*
UO	0	2.44	1.83	1.22	.91	*
P(ATM)	0	101.52	100.64	100.64	100.64	*
P(ORF)	0	.84	.57	.37	.28	*
T(ORF)	0	347.04	316.48	330.37	330.37	*
DPD	0	13.95	8.47	2.99	1.99	*
DPB(AV)	0	3.49	4.48	5.98	5.98	*
DPV(MX)	0	4.98	5.98	6.48	5.98	*
DPB(MN)	0	2.99	2.99	5.48	5.98	*
PS	0	37.23	30.34	24.13	22.75	*
LI	0	45.00	45.00	45.00	45.00	*
LF	0	43.00	45.00	45.00	45.00	*
LF		80.	84.	60.	51.	*
H1		5.	10.	10.	10.	*
H2		30.	40.	30.	30.	*
H3		50.	60.	50.	50.	*
DBH1		8.	15.	7.	2.	*
DBH2		ND	7.	5.	3.	*
DBH3		ND	7.	4.	5.	*
DTIME	0	360.00	360.00	360.00	360.00	*
UMF	0	.91	.91	.91	.91	*
QUAL		B3 S1	B2-B3	B1-B2	B1 F1	*
QUAL		B3 S1	B3 S1	NA	NA	*

ENGLISH UNITS

DATE		2 16 76	2 17 76	2 17 76	2 17 76
TUBE ARRAY		C2-T	C2-T	C2-T	C2-T
ARRAY LOC		9.84	9.84	9.84	9.84
DPM	0	.054	.054	.054	.054
UO	0	8.01	6.00	4.00	2.99
P(ATM)	0	29.98	29.72	29.72	29.72
P(ORF)	0	3.38	2.30	1.50	1.13
T(ORF)	0	165.00	110.00	135.00	135.00
DPD	0	56.00	34.00	12.00	8.00
DPB(AV)	0	14.00	18.00	24.00	24.00
DPV(MX)	0	20.00	24.00	26.00	24.00
DPB(MN)	0	12.00	12.00	22.00	24.00
PS	0	5.40	4.40	3.50	3.30
LI	0	17.72	17.72	17.72	17.72
LF	0	16.93	17.72	17.72	17.72
LF		31.49	33.07	23.62	20.07
H1		1.96	3.93	3.93	3.93
H2		11.81	15.74	11.81	11.81
H3		19.68	23.62	19.68	19.68
DBH1		3.15	5.90	2.75	.78
DBH2		ND	2.75	1.96	1.18
DBH3		ND	2.75	1.57	1.96
DTIME	0	6.00	6.00	6.00	6.00
UMF	0	2.99	2.99	2.99	2.99
QUAL		B3 S1	B2-B3	B1-B2	B1 F1
QUAL		B3 S1	B3 S1	NA	NA

	S. I. UNITS						ENGLISH UNITS				
DATE	2 17 76	2 17 76	2 17 76	2 17 76		*	2 17 76	2 17 76	2 17 76	2 17 76	
TUBE ARRAY	C2-T	C2-T	C2-T	C2-T		*	C2-T	C2-T	C2-T	C2-T	
ARRAY LOC	25.	25.	25.	25.		*	9.84	9.84	9.84	9.84	
DPM	1379.00	1379.00	1379.00	1379.00	0	*	.054	.054	.054	.054	0
UO	2.75	2.44	1.83	1.22	0	*	9.02	8.01	6.00	4.00	0
P(ATM)	100.64	100.64	100.64	100.64	0	*	29.72	29.72	29.72	29.72	0
P(ORF)	.78	.81	.59	.41	0	*	3.13	3.25	2.38	1.63	0
T(ORF)	319.26	338.71	341.48	340.37	0	*	115.00	150.00	155.00	153.00	0
DPD	11.46	11.46	5.98	2.99	0	*	46.00	46.00	24.00	12.00	0
DPB(AV)	2.99	3.49	3.49	3.49	0	*	12.00	14.00	14.00	14.00	0
DPV(MX)	2.99	3.98	4.98	3.98	0	*	12.00	16.00	20.00	16.00	0
DPB(MN)	2.99	2.49	2.99	3.49	0	*	12.00	10.00	12.00	14.00	0
PS	35.85	33.78	27.58	22.75	0	*	5.20	4.90	4.00	3.30	0
LI	23.00	23.00	23.00	23.00	0	*	9.06	9.06	9.06	9.06	0
LF	23.00	23.00	23.00	23.00	0	*	9.06	9.06	9.06	9.06	0
LE	50.	60.	45.	35.		*	19.68	23.62	17.71	13.78	
H1	10.	10.	10.	10.		*	3.93	3.93	3.93	3.93	
H2	30.	30.	30.	25.		*	11.81	11.81	11.81	9.84	
H3	50.	40.	40.	50.		*	19.68	15.74	15.74	19.68	
DPH1	8.	10.	12.	8.		*	3.15	3.93	4.72	3.15	
DPH2	5.	5.	5.	ND		*	1.96	1.96	1.96	ND	
DBH3	ND	7.	4.	ND		*	ND	2.75	1.57	ND	
DTIME	240.00	180.00	240.00	180.00	0	*	4.00	3.00	4.00	3.00	0
UMF	.98	.98	.98	.98	0	*	3.22	3.22	3.22	3.22	0
QUAL	B3-B2	B3-B2 S1	B2 S1	B1 B2		*	B3-B2	B3-B2 S1	B2 S1	B1 B2	
QUAL	E1	NA	NA	NA		*	E1	NA	NA	NA	

	S. I. UNITS						ENGLISH UNITS				
DATE	2 17 76	2 17 76	2 17 76	2 17 76		*	2 17 76	2 17 76	2 17 76	2 17 76	
TUBE ARRAY	C2-T	C2-T	C2-T	C2-T		*	C2-T	C2-T	C2-T	C2-T	
ARRAY LOC	25.	25.	25.	25.		*	9.84	9.84	9.84	9.84	
DPM	1379.00	1379.00	1379.00	1379.00	0	*	.054	.054	.054	.054	0
UO	2.75	2.44	1.83	1.22	0	*	9.02	8.01	6.00	4.00	0
P(ATM)	100.64	100.64	100.64	100.64	0	*	29.72	29.72	29.72	29.72	0
P(ORF)	.78	.78	.59	.41	0	*	3.13	3.13	2.38	1.63	0
T(ORF)	338.71	344.26	345.37	344.26	0	*	150.00	160.00	162.00	160.00	0
DPC	13.45	10.96	5.48	2.49	0	*	54.00	44.00	22.00	10.00	0
DPB(AV)	2.99	3.49	3.98	3.98	0	*	12.00	14.00	16.00	16.00	0
DPV(MX)	3.49	4.48	4.98	4.48	0	*	14.00	18.00	20.00	18.00	0
DPB(MN)	2.49	2.99	2.99	3.49	0	*	10.00	12.00	12.00	14.00	0
PS	35.85	31.03	27.58	22.06	0	*	5.20	4.50	4.00	3.20	0
LI	30.00	30.00	30.00	30.00	0	*	11.81	11.81	11.81	11.81	0
LF	29.00	30.00	30.00	30.00	0	*	11.42	11.81	11.81	11.81	0
LE	65.	55.	50.	40.		*	25.59	21.65	19.68	15.74	
H1	10.	10.	10.	15.		*	3.93	3.93	3.93	5.90	
H2	35.	40.	30.	30.		*	13.78	15.74	11.81	11.81	
H3	50.	50.	45.	50.		*	19.68	19.68	17.71	19.68	
DBH1	15.	10.	7.	10.		*	5.90	3.93	2.75	3.93	
DBH2	7.	5.	5.	5.		*	2.75	1.96	1.96	1.96	
DBH3	ND	ND	4.	ND		*	ND	ND	1.57	ND	
DTIME	360.00	180.00	240.00	300.00	0	*	6.00	3.00	4.00	5.00	0
UMF	.97	.97	.97	.97	0	*	3.18	3.18	3.18	3.18	0
QUAL	B3	B3-B2 S1	B2-B1	B1-B2		*	B3	B3-B2 S1	B2-B1	B1-B2	
QUAL	E1	NA	NA	NA		*	E1	NA	NA	NA	

	S. I. UNITS						ENGLISH UNITS				
DATE	2 17 76	2 17 76	2 17 76	2 17 76	2 17 76	*	2 17 76	2 17 76	2 17 76	2 17 76	2 17 76
TUBE ARRAY	B2-S	B2-S	B2-S	B2-S	B2-S	*	B2-S	B2-S	B2-S	B2-S	B2-S
ARRAY LOC	15.	15.	15.	15.	15.	*	5.90	5.90	5.90	5.90	5.90
DPM	1379.00	1379.00	1379.00	1379.00	1379.00	*	.054	.054	.054	.054	.054
UO	2.75	2.44	1.83	1.22	.81	*	9.02	8.01	6.00	4.00	2.66
P(ATM)	100.64	100.64	100.64	100.64	100.64	*	29.72	29.72	29.72	29.72	29.72
P(ORF)	.78	.78	.59	.41	.28	*	3.13	3.13	2.38	1.63	1.13
T(ORF)	319.26	341.48	341.48	341.48	341.48	*	115.00	155.00	155.00	155.00	155.00
DPD	8.97	6.97	4.48	2.49	1.49	*	36.00	28.00	18.00	10.00	6.00
DPB(AV)	4.98	5.48	5.48	6.48	5.48	*	20.00	22.00	22.00	26.00	22.00
DPV(MX)	5.98	6.97	5.98	8.97	5.48	*	24.00	28.00	24.00	36.00	22.00
DPB(MN)	3.98	3.98	4.98	4.98	5.48	*	16.00	16.00	20.00	20.00	22.00
PS	33.10	30.34	26.20	24.13	22.06	*	4.80	4.40	3.80	3.50	3.20
LI	43.00	43.00	43.00	43.00	43.00	*	16.93	16.93	16.93	16.93	16.93
LF	43.00	43.00	43.00	43.00	43.00	*	16.93	16.93	16.93	16.93	16.93
LE	72.	65.	58.	60.	50.	*	28.34	25.59	22.83	23.62	19.68
H1	10.	10.	10.	10.	10.	*	3.93	3.93	3.93	3.93	3.93
H2	25.	25.	30.	30.	25.	*	9.84	9.84	11.81	11.81	9.84
H3	50.	50.	50.	50.	50.	*	19.68	19.68	19.68	19.68	19.68
DBH1	5.	ND	10.	8.	3.	*	1.96	ND	3.93	3.15	1.18
DBH2	7.	5.	5.	5.	5.	*	2.75	1.96	1.96	1.96	1.96
DBH3	7.	4.	5.	5.	3.	*	2.75	1.57	1.96	1.96	1.18
DTIME	360.00	300.00	240.00	240.00	300.00	*	6.00	5.00	4.00	4.00	5.00
UMF	.81	.81	.81	.81	.81	*	2.66	2.66	2.66	2.66	2.66
QUAL	B2 CG2	B2 CG2-1	B2-1 CG1	B1-2 CG1	B1 F1	*	B2 CG2	B2 CG2-1	B2-1 CG1	B1-2 CG1	B1 F1
QUAL	B2-B3	NA	NA	NA	NA	*	B2-B3	NA	NA	NA	NA

	S. I. UNITS						ENGLISH UNITS				
DATE	2 17 76	2 17 76	2 20 76	2 20 76	2 20 76	*	2 17 76	2 17 76	2 20 76	2 20 76	2 20 76
TUBE ARRAY	B2-S	B2-S	B2-S	B2-S	B2-S	*	B2-S	B2-S	B2-S	B2-S	B2-S
ARRAY LOC	15.	15.	15.	15.	15.	*	5.90	5.90	5.90	5.90	5.90
DPM	1379.00	1379.00	1379.00	1379.00	1379.00	*	.054	.054	.054	.054	.054
UO	2.75	2.44	1.83	1.22	.91	*	9.02	8.01	6.00	4.00	2.99
P(ATM)	100.64	100.64	100.64	100.64	102.40	*	29.72	29.72	29.72	29.72	30.24
P(ORF)	.87	.81	.45	.31	.25	*	3.50	3.25	1.80	1.25	1.00
T(ORF)	338.71	347.04	305.37	305.37	322.04	*	150.00	165.00	90.00	90.00	120.00
DPD	9.96	7.97	3.98	1.99	2.99	*	40.00	32.00	16.00	8.00	12.00
DPB(AV)	2.99	2.99	3.49	2.99	2.99	*	12.00	12.00	14.00	12.00	12.00
DPV(MX)	2.99	3.98	4.48	3.49	2.99	*	12.00	16.00	18.00	14.00	12.00
DPB(MN)	2.49	2.49	2.49	2.99	2.99	*	10.00	10.00	10.00	12.00	12.00
PS	33.10	31.03	23.44	20.68	19.99	*	4.80	4.50	3.40	3.00	2.90
LI	23.00	23.00	23.00	23.00	23.00	*	9.06	9.06	9.06	9.06	9.06
LF	23.00	23.00	23.00	23.00	23.00	*	9.06	9.06	9.06	9.06	9.06
LE	60.	50.	40.	33.	29.	*	23.62	19.68	15.74	12.99	11.41
H1	10.	10.	10.	10.	10.	*	3.93	3.93	3.93	3.93	3.93
H2	30.	25.	25.	25.	25.	*	11.81	9.84	9.84	9.84	9.84
H3	50.	50.	50.	50.	50.	*	19.68	19.68	19.68	19.68	19.68
DPH1	ND	8.	5.	2.	2.	*	ND	3.15	1.96	.78	.78
DPH2	7.	5.	4.	4.	3.	*	2.75	1.96	1.57	1.57	1.18
DPH3	ND	ND	3.	ND	ND	*	ND	ND	1.18	ND	ND
DTIME	240.00	240.00	240.00	240.00	300.00	*	4.00	4.00	4.00	4.00	5.00
UMF	.91	.91	.91	.91	.91	*	2.99	2.99	2.99	2.99	2.99
QUAL	B3 CG3	B3-2 CG2	B1-2 CG1	B1	B1 F1	*	B3 CG3	B3-2 CG2	B1-2 CG1	B1	B1 F1
QUAL	E1	NA	NA	NA	NA	*	E1	NA	NA	NA	NA

	S. I. UNITS						ENGLISH UNITS				
DATE	2 20 76	2 20 76	2 20 76	2 20 76	2 20 76	*	2 20 76	2 20 76	2 20 76	2 20 76	2 20 76
TUBE ARRAY	B2-S	B2-S	B2-S	B2-S	B2-S	*	B2-S	B2-S	B2-S	B2-S	B2-S
ARRAY LOC	15.	15.	15.	15.	15.	*	5.90	5.90	5.90	5.90	5.90
DPM	569.00	569.00	569.00	569.00	569.00	*	.022	.022	.022	.022	.022
UO	2.75	2.44	1.83	1.22	.61	*	9.02	8.01	6.00	4.00	2.00
P(ATM)	102.40	102.40	102.40	102.40	102.40	*	30.24	30.24	30.24	30.24	30.24
P(ORF)	.78	.75	.60	.39	.19	*	3.13	3.00	2.40	1.55	.75
T(ORF)	322.04	335.93	338.71	335.93	335.93	*	120.00	145.00	150.00	145.00	145.00
DPD	8.97	6.48	4.98	1.99	1.00	*	36.00	26.00	20.00	8.00	4.00
DPB(AV)	2.99	3.98	4.98	6.97	2.49	*	12.00	16.00	20.00	28.00	10.00
DPV(MX)	3.49	4.48	5.98	9.96	3.98	*	14.00	18.00	24.00	40.00	16.00
DPB(MN)	2.49	3.49	4.48	4.48	1.99	*	10.00	14.00	18.00	18.00	8.00
PS	33.10	30.34	29.65	25.51	24.13	*	4.80	4.40	4.30	3.70	3.50
LI	45.00	43.00	45.00	45.00	45.00	*	17.72	16.93	17.72	17.72	17.72
LF	42.00	40.00	45.00	45.00	45.00	*	16.54	15.75	17.72	17.72	17.72
LE	86.	80.	80.	70.	62.	*	33.85	31.49	31.49	27.55	24.40
H1	10.	10.	10.	10.	10.	*	3.93	3.93	3.93	3.93	3.93
H2	25.	25.	25.	25.	25.	*	9.84	9.84	9.84	9.84	9.84
H3	50.	50.	50.	50.	50.	*	19.68	19.68	19.68	19.68	19.68
DBH1	ND	ND	5.	5.	3.	*	ND	ND	1.96	1.96	1.18
DBH2	ND	ND	7.	7.	5.	*	ND	ND	2.75	2.75	1.96
DBH3	ND	ND	8.	10.	7.	*	ND	ND	3.15	3.93	2.75
DTIME	180.00	180.00	300.00	300.00	240.00	*	3.00	3.00	5.00	5.00	4.00
UMF	.41	.41	.41	.41	.41	*	1.35	1.35	1.35	1.35	1.35
QUAL	B3 CG3S1	B3 CG3	B3-2 CG2	B2-B1	B1-B2	*	B3 CG3S1	B3 CG3	B3-2 CG2	B2-B1	B1-B2
QUAL	B3 E3CG3	CG3 E2	CG2 E1S1	B2 S1	NA	*	B3 E3CG3	CG3 E2	CG2 E1S1	B2 S1	NA

S. I. UNITS | ENGLISH UNITS

	S. I. UNITS						ENGLISH UNITS				
DATE	2 20 76	2 20 76	2 20 76	2 20 76	2 20 76	*	2 20 76	2 20 76	2 20 76	2 20 76	2 20 76
TUBE ARRAY	B2-S	B2-S	B2-S	B2-S	B2-S	*	B2-S	B2-S	B2-S	B2-S	B2-S
ARRAY LOC	15.	15.	15.	15.	15.	*	5.90	5.90	5.90	5.90	5.90
DPM	569.00	569.00	569.00	569.00	569.00	*	.022	.022	.022	.022	.022
UO	2.75	2.44	1.83	1.22	.41	*	9.02	8.01	6.00	4.00	1.35
P(ATM)	102.40	102.40	102.40	102.40	102.40	*	30.24	30.24	30.24	30.24	30.24
P(ORF)	.78	.72	.60	.42	.22	*	3.13	2.90	2.40	1.70	.88
T(ORF)	322.04	342.04	341.48	344.26	338.71	*	120.00	156.00	155.00	160.00	150.00
DPD	8.97	5.98	4.48	1.99	1.00	*	36.00	24.00	18.00	8.00	4.00
DPB(AV)	2.49	2.99	3.49	3.98	3.98	*	10.00	12.00	14.00	16.00	16.00
DPV(MX)	2.49	3.49	4.48	4.98	4.48	*	10.00	14.00	18.00	20.00	18.00
DPB(MN)	2.49	2.99	2.99	2.99	2.99	*	10.00	12.00	12.00	12.00	12.00
PS	30.34	27.58	26.20	23.44	20.68	*	4.40	4.00	3.80	3.40	3.00
LT	23.00	23.00	23.00	23.00	23.00	*	9.06	9.06	9.06	9.06	9.06
LF	23.00	23.00	23.00	23.00	23.00	*	9.06	9.06	9.06	9.06	9.06
LE	70.	62.	50.	39.	33.	*	27.55	24.40	19.68	15.35	12.99
H1	10.	10.	10.	10.	10.	*	3.93	3.93	3.93	3.93	3.93
H2	25.	25.	25.	25.	25.	*	9.84	9.84	9.84	9.84	9.84
H3	50.	50.	50.	50.	50.	*	19.68	19.68	19.68	19.68	19.68
DBH1	ND	5.	3.	5.	7.	*	ND	1.96	1.18	1.96	2.75
DBH2	ND	8.	5.	8.	5.	*	ND	3.15	1.96	3.15	1.96
DBH3	ND	ND	5.	ND	ND	*	ND	ND	1.96	ND	ND
DTIME	420.00	300.00	180.00	300.00	240.00	*	7.00	5.00	3.00	5.00	4.00
UMF	.41	.41	.41	.41	.41	*	1.35	1.35	1.35	1.35	1.35
QUAL	B3 CG3	B3-2 CG2	B2-1 CG2	B2-B1 S1	B1-B2	*	B3 CG3	B3-2 CG2	B2-1 CG2	B2-B1 S1	B1-B2
QUAL	CG3 E2	CG2 E1	NA	NA	NA	*	CG3 E2	CG2 E1	NA	NA	NA

	S. I. UNITS						ENGLISH UNITS				
DATE	2 20 76	2 20 76	2 20 76	2 20 76	2 20 76	*	2 20 76	2 20 76	2 20 76	2 20 76	2 20 76
TUBE ARRAY	B2-S	B2-S	B2-S	B2-S	B2-S	*	B2-S	B2-S	B2-S	B2-S	B2-S
ARRAY LOC	25.	25.	25.	25.	25.	*	9.84	9.84	9.84	9.84	9.84
DPM	1379.00	1379.00	1379.00	1379.00	1379.00	*	.054	.054	.054	.054	.054
UO	2.75	2.44	1.83	1.22	.91	*	9.02	8.01	6.00	4.00	2.99
P(ATM)	102.40	102.40	102.40	102.40	102.40	*	30.24	30.24	30.24	30.24	30.24
P(ORF)	.75	.75	.59	.41	.28	*	3.00	3.00	2.38	1.63	1.13
T(ORF)	316.48	338.71	344.26	344.26	341.48	*	110.00	150.00	160.00	160.00	155.00
DPD	7.47	7.47	4.48	6.97	1.25	*	30.00	30.00	18.00	28.00	5.00
DPB(AV)	4.98	4.48	5.98	6.48	5.98	*	20.00	18.00	24.00	26.00	24.00
DPV(MX)	7.97	9.96	9.46	6.97	5.98	*	32.00	40.00	38.00	28.00	24.00
DPB(MN)	1.99	0	2.49	4.98	5.98	*	8.00	0	10.00	20.00	24.00
PS	33.10	32.41	28.27	24.13	22.75	*	4.80	4.70	4.10	3.50	3.30
LI	45.00	45.00	45.00	45.00	45.00	*	17.72	17.72	17.72	17.72	17.72
LF	43.00	45.00	45.00	45.00	45.00	*	16.93	17.72	17.72	17.72	17.72
LE	80.	85.	75.	58.	50.	*	31.49	33.46	29.52	22.83	19.68
H1	15.	10.	20.	10.	20.	*	5.90	3.93	7.87	3.93	7.87
H2	40.	40.	40.	40.	30.	*	15.74	15.74	15.74	15.74	11.81
H3	60.	60.	60.	50.	50.	*	23.62	23.62	23.62	19.68	19.68
DBH1	20.	20.	12.	3.	2.	*	7.87	7.87	4.72	1.18	.78
DBH2	8.	10.	5.	7.	3.	*	3.15	3.93	1.96	2.75	1.18
DBH3	10.	5.	7.	10.	5.	*	3.93	1.96	2.75	3.93	1.96
DTIME	480.00	420.00	300.00	300.00	600.00	*	8.00	7.00	5.00	5.00	10.00
UMF	.91	.91	.91	.91	.91	*	2.99	2.99	2.99	2.99	2.99
QUAL	B3 CG3S1	B3 CG2S2	B2 CG1S1	B1 S1	B1 F1	*	B3 CG3S1	B3 CG2S2	B2 CG1S1	B1 S1	B1 F1
QUAL	B3 CG2	CG2 S2	NA	NA	NA	*	B3 CG2	CG2 S2	NA	NA	NA

	S. I. UNITS						ENGLISH UNITS				
DATE	2 20 76	2 20 76	2 20 76	2 20 76		*	2 20 76	2 20 76	2 20 76	2 20 76	
TUBE ARRAY	B2-S	B2-S	B2-S	B2-S		*	B2-S	B2-S	B2-S	B2-S	
ARRAY LOC	25.	25.	25.	25.		*	9.84	9.84	9.84	9.84	
DPM	1379.00	1379.00	1379.00	1379.00	0	*	.054	.054	.054	.054	0
UO	2.75	2.44	1.83	1.22	0	*	9.02	8.01	6.00	4.00	0
P(ATM)	102.40	102.40	102.40	102.40	0	*	30.24	30.24	30.24	30.24	0
P(ORF)	.84	.80	.59	.41	0	*	3.38	3.20	2.38	1.63	0
T(ORF)	335.93	341.48	347.04	344.26	0	*	145.00	155.00	165.00	160.00	0
DPD	8.97	6.97	3.98	1.99	0	*	36.00	28.00	16.00	8.00	0
DPB(AV)	3.49	3.49	3.98	3.49	0	*	14.00	14.00	16.00	14.00	0
DPV(MX)	3.98	4.98	4.98	3.98	0	*	16.00	20.00	20.00	16.00	0
DPB(MN)	2.99	1.99	2.49	2.99	0	*	12.00	8.00	10.00	12.00	0
PS	31.03	28.96	26.20	22.06	0	*	4.50	4.20	3.80	3.20	0
LI	23.00	23.00	23.00	23.00	0	*	9.06	9.06	9.06	9.06	0
LF	23.00	23.00	23.00	23.00	0	*	9.06	9.06	9.06	9.06	0
LE	55.	50.	45.	35.		*	21.65	19.68	17.71	13.78	
H1	20.	20.	20.	10.		*	7.87	7.87	7.87	3.93	
H2	40.	40.	40.	20.		*	15.74	15.74	15.74	7.87	
H3	50.	50.	50.	30.		*	19.68	19.68	19.68	11.81	
DBH1	15.	12.	12.	2.		*	5.90	4.72	4.72	.78	
DBH2	8.	6.	5.	8.		*	3.15	2.36	1.96	3.15	
DBH3	ND	ND	ND	5.		*	ND	ND	ND	1.96	
DTIME	240.00	240.00	180.00	240.00	0	*	4.00	4.00	3.00	4.00	0
UMF	1.00	1.00	1.00	1.00	0	*	3.28	3.28	3.28	3.28	0
QUAL	B3 CG3S1	B2-B3 S1	B2-B1 S1	B1 S1		*	B3 CG3S1	B2-B3 S1	B2-B1 S1	B1 S1	
QUAL	NA	NA	NA	NA		*	NA	NA	NA	NA	

	S. I. UNITS						ENGLISH UNITS				
DATE	2 20 76	2 20 76	2 20 76	2 20 76	2 20 76	*	2 20 76	2 20 76	2 20 76	2 20 76	2 20 76
TUBE ARRAY	B2-S	B2-S	B2-S	B2-S	B2-S	*	B2-S	B2-S	B2-S	B2-S	B2-S
ARRAY LOC	25.	25.	25.	25.	25.	*	9.84	9.84	9.84	9.84	9.84
DPM	569.00	569.00	569.00	569.00	569.00	*	.022	.022	.022	.022	.022
UO	2.75	2.44	1.83	1.22	.61	*	9.02	8.01	6.00	4.00	2.00
P(ATM)	102.40	102.40	102.40	102.40	102.40	*	30.24	30.24	30.24	30.24	30.24
P(ORF)	.84	.78	.59	.41	.19	*	3.38	3.13	2.38	1.63	.75
T(ORF)	338.71	341.48	341.48	335.937500255.37		*	150.00	155.00	155.00	145.00	500000.0*
DPD	7.47	7.47	2.99	1.99	1.49	*	30.00	30.00	12.00	8.00	6.00
DPB(AV)	3.49	3.98	5.48	6.48	6.97	*	14.00	16.00	22.00	25.00	28.00
DPV(MX)	2.49	4.98	9.96	9.96	8.97	*	10.00	20.00	40.00	40.00	36.00
DPB(MN)	2.99	2.99	0	2.49	5.48	*	12.00	12.00	0	10.00	22.00
PS	33.10	32.41	26.20	0	0	*	4.80	4.70	3.80	0	0
LI	45.00	45.00	45.00	45.00	45.00	*	17.72	17.72	17.72	17.72	17.72
LF	43.00	45.00	45.00	45.00	45.00	*	16.93	17.72	17.72	17.72	17.72
LE	90.	88.	80.	75.	63.	*	35.43	34.64	31.49	29.52	24.80
H1	10.	10.	20.	20.	20.	*	3.93	3.93	7.87	7.87	7.87
H2	25.	40.	40.	40.	40.	*	9.84	15.74	15.74	15.74	15.74
H3	50.	60.	70.	60.	60.	*	19.58	23.62	27.55	23.62	23.62
DBH1	ND	10.	10.	8.	5.	*	ND	3.93	3.93	3.15	1.96
DBH2	ND	8.	7.	6.	5.	*	ND	3.15	2.75	2.36	1.96
DBH3	ND	8.	8.	5.	5.	*	ND	3.15	3.15	1.96	1.96
DTIME	180.00	240.00	240.00	240.00	300.00	*	3.00	4.00	4.00	4.00	5.00
UMF	.42	.42	.42	.42	.42	*	1.38	1.38	1.38	1.38	1.38
QUAL	B3 CG3	B3 CG3S2	B2-3 CG2	B2 CG1S1	B1 S1	*	B3 CG3	B3 CG3S2	B2-3 CG2	B2 CG1S1	B1 S1
QUAL	B3 E3CG3	CG3 E3S2	B3 E1CG1	S1	NA	*	B3 E3CG3	CG3 E3S2	B3 E1CG1	S1	NA

	S. I. UNITS						ENGLISH UNITS				
DATE	2 20 76	2 20 76	2 20 76	2 20 76	2 20 76	*	2 20 76	2 20 76	2 20 76	2 20 76	2 20 76
TUBE ARRAY	B2-S	B2-S	B2-S	B2-S	B2-S	*	B2-S	B2-S	B2-S	B2-S	B2-S
ARRAY LOC	25.	25.	25.	25.	25.	*	9.84	9.84	9.84	9.84	9.84
DPM	569.00	569.00	569.00	569.00	569.00	*	.022	.022	.022	.022	.022
UO	2.75	2.44	1.83	1.22	.61	*	9.02	8.01	6.00	4.00	2.00
P(ATM)	101.76	101.76	101.76	101.76	101.76	*	30.05	30.05	30.05	30.05	30.05
P(ORF)	.75	.72	.59	.40	.20	*	3.00	2.88	2.38	1.60	.80
T(ORF)	310.93	327.59	335.93	337.04	335.37	*	100.00	130.00	145.00	147.00	144.00
DPD	8.97	6.48	3.98	1.99	1.00	*	36.00	26.00	16.00	8.00	4.00
DPB(AV)	2.49	3.49	3.98	4.48	3.98	*	10.00	14.00	16.00	18.00	16.00
DPV(MX)	2.99	6.48	6.97	6.48	4.48	*	12.00	26.00	28.00	26.00	18.00
DPB(MN)	2.49	.50	1.99	3.49	3.98	*	10.00	2.00	8.00	14.00	16.00
PS	30.34	27.58	26.20	22.06	20.68	*	4.40	4.00	3.80	3.20	3.00
LI	23.00	23.00	23.00	23.00	23.00	*	9.06	9.06	9.06	9.06	9.06
LF	23.00	23.00	23.00	23.00	23.00	*	9.06	9.06	9.06	9.06	9.06
LE	70.	60.	50.	43.	35.	*	27.55	23.62	19.68	16.92	13.78
H1	10.	20.	20.	10.	5.	*	3.93	7.87	7.87	3.93	1.96
H2	25.	40.	40.	25.	20.	*	9.84	15.74	15.74	9.84	7.87
H3	50.	50.	60.	40.	30.	*	19.68	19.68	23.62	15.74	11.81
DBH1	ND	12.	15.	5.	2.	*	ND	4.72	5.90	1.96	.78
DBH2	ND	8.	8.	17.	8.	*	ND	3.15	3.15	6.69	3.15
DBH3	ND	ND	ND	8.	5.	*	ND	ND	ND	3.15	1.96
DTIME	240.00	240.00	300.00	300.00	240.00	*	4.00	4.00	5.00	5.00	4.00
UMF	.50	.50	.50	.50	.50	*	1.64	1.64	1.64	1.64	1.64
QUAL	B3 CG3S1	B3 CG3S1	B3 CG2S2	B2-B1 S1	B1	*	B3 CG3S1	B3 CG3S1	B3 CG2S2	B2-B1 S1	B1
QUAL	CG3 E3	E1	NA	NA	NA	*	CG3 E3	E1	NA	NA	NA

	S. I. UNITS						ENGLISH UNITS				
DATE		3 04 76	3 04 76	3 04 76	3 04 76	*		3 04 76	3 04 76	3 04 76	3 04 76
TUBE ARRAY		B2-S	B2-S	B2-S	B2-S	*		B2-S	B2-S	B2-S	B2-S
ARRAY LOC		2.5	2.5	2.5	2.5	*		.98	.98	.98	.98
DPM	0	1379.00	1379.00	1379.00	1379.00	*	0	.054	.054	.054	.054
UO	0	2.44	1.83	1.22	.91	*	0	8.01	6.00	4.00	2.99
P(ATM)	0	101.63	101.63	101.63	101.63	*	0	30.01	30.01	30.01	30.01
P(ORF)	0	.72	.59	.41	.28	*	0	2.88	2.38	1.63	1.13
T(ORF)	0	322.04	335.93	338.15	335.93	*	0	120.00	145.00	149.00	145.00
DPD	0	5.98	3.49	6.97	3.49	*	0	24.00	14.00	28.00	14.00
DPB(AV)	0	4.98	4.98	4.98	4.48	*	0	20.00	20.00	20.00	18.00
DPV(MX)	0	5.48	5.98	5.48	4.98	*	0	22.00	24.00	22.00	20.00
DPB(MN)	0	3.98	4.48	4.48	4.48	*	0	16.00	18.00	18.00	18.00
PS	0	26.20	23.44	24.82	21.37	*	0	3.80	3.40	3.60	3.10
LI	0	45.00	45.00	45.00	43.00	*	0	17.72	17.72	17.72	16.93
LF	0	45.00	45.00	45.00	43.00	*	0	17.72	17.72	17.72	16.93
LF		63.	55.	50.	43.	*		24.80	21.65	19.68	16.92
H1		10.	10.	10.	10.	*		3.93	3.93	3.93	3.93
H2		25.	25.	25.	25.	*		9.84	9.84	9.84	9.84
H3		50.	50.	50.	40.	*		19.68	19.68	19.68	15.74
DBH1		3.	3.	2.	3.	*		1.18	1.18	.78	1.18
DBH2		5.	5.	3.	3.	*		1.96	1.96	1.18	1.18
DBH3		5.	5.	5.	5.	*		1.96	1.96	1.96	1.96
DTIME	0	180.00	180.00	300.00	240.00	*	0	3.00	3.00	5.00	4.00
UMF	0	.91	.91	.91	.91	*	0	2.99	2.99	2.99	2.99
QUAL		B2 CG1	B1-2 CG1	B2-B1	B1 F1	*		B2 CG1	B1-2 CG1	B2-B1	B1 F1
QUAL		NA	NA	NA	NA	*		NA	NA	NA	NA

APPENDIX B

Unit Conversions

Unit conversions, necessary in the manipulation of the raw data into the desired form are provided below for the convenience of the reader.

Length

a. $(\text{inches}) \times (2.54 \frac{\text{centimeters}}{\text{inch}}) = \text{centimeters} = 10^{-2}\ \text{meters}$

b. $(\text{feet}) \times (0.3048 \frac{\text{meters}}{\text{foot}}) = \text{meters}$

c. $(\text{inches}) \times (2.54 \times 10^{4} \frac{\mu\text{m}}{\text{inch}} = \text{micrometers, } \mu\text{m}$

Pressure

a. $(\text{inches of } H_2O) \times (\text{o}.2490 \frac{\text{kPa}}{\text{in } H_2O}) = \text{kilo-pascals, kPa}$

b. $(\text{PSI}) \times (6.8948 \frac{\text{kPa}}{\text{PSI}} = \text{kilo-pascals, kPa}$

c. $(\text{inches of Hg}) \times (3.3864 \frac{\text{kPa}}{\text{in Hg}}) = \text{kilo-pascals, kPa}$

Temperature

a. $\frac{(F) + 459.67}{1.8} = \text{Kelvin, K}$

<u>Heat Transfer Coefficient</u>

a. $\left(\frac{\text{Btu}}{\text{hr} \cdot \text{ft}^2 \cdot {}^\circ\text{F}}\right) \times \left(5.675 \frac{\text{W}}{\text{m}^2 \cdot {}^\circ\text{K}} \Big/ \frac{\text{Btu}}{\text{hr} \cdot \text{ft}^2 \cdot {}^\circ\text{F}}\right) = \frac{\text{W}}{\text{m}^2 \cdot {}^\circ\text{K}}$

APPENDIX C

Sample Calculations

The following information and calculations are typical, though not all inclusive, of those necessary in the initial design phase of a fluidized bed system, and follow the development found in Kunii and Levenspiel (4). It should be noted that the values used here are representative only, and are strongly particle size dependent.

Solids

Name: Commercial	Name: Chemical	Molecular Formula	Formula Weight bm/gmole	Specific Gravity	Bulk Density lb_m/ft^3
LIMESTONE	CALCIUM CARBONATE (CALCITE)	$CaCO_3$	100.09	2.711	95
DOLOMITE	MAGNESIUM CARBONATE	$CaCO_3MgCO_3$	184.42	2.872	100

Voidage, ϵ_{mf}: The fraction of voids per unit volume of bed.

$$\epsilon_{mf} = 1 - \frac{\gamma\ bulk}{\gamma\ solid}$$

assume: T = 100 F

thus: $\rho = 62.1\ lb_m/ft^3$ and $\gamma_{bulk} = \frac{100}{62.1} = 1.61$

$$\epsilon_{mf} = 1 - \frac{1.61}{2.87} = 0.439$$

Sphericity, ϕ_s: The ratio of the surface area of a sphere to that of a particle of equal volume.

$\phi_s = 0.75$ (from graphed data in Kunii and Levenspiel)

Mean Particle Diameter, $\bar{d}_{sv}$: The mean specific particle size is approximated by the following equation (3).

$$\bar{d}_{sv} = \frac{1}{\Sigma \frac{x}{d_P}}$$

where: x = weight fraction of a particle size.

d_p = particle size, as sieved.

d_{sv} = particle diameter of a sphere having the same surface area as a particle of d_P.

For the data, in Table 1, for 20 mesh dolomite:

$\bar{d}_{sv} = 581.57\ \mu m$ (0.0229 in. ≈ 28 mesh.)

Minimum Fluidization Velocity, U_{mf}:

for: Reynolds Number, $Re_p < 20$

and: T = 100 F = 311 K

and: For the known Voidage and Sphericity.

$$U_{mf} = \frac{(\phi_s \bar{d}_p)^2}{150} \quad \frac{(\rho_s - \rho_g)}{\mu} \; g \; \frac{(\epsilon_{mf}^{\;3})}{1 - \epsilon_{mf}} \tag{4}$$

where:

ϕ_s = sphericity, dimensionless

ϵ_{mf} = void fraction

d_p = particle diameter, cm.

ρ_s = density of solids, gm/cm^3.

ρ_g = density of gas (air), gm/cm^3.

g = acceleration due to gravity, cm/s^2.

μ = viscosity, $gm/cm \cdot s$.

$$U_{mf} = \frac{((0.75)\ (0.0841\ cm))^2}{150} \times \frac{2.871\ gm/cm^3)}{(1.905 \times 10^4\ gm/cm \cdot s)}$$

$$\times\ (980.66\ cm/s^2) \times \frac{(0.439)^3}{1 - 0.439}$$

$$U_{mf} = 0.591\ m/s\ (1.94\ ft/sec.)$$

Reynolds Number Check:

$$Re_p = \frac{d_p \rho_g U_{mf}}{\mu}$$

$$Re_p = \frac{(0.0841\ cm)\ (1.137 \times 10^{-3}\ gm/cm^3)\ (59.12\ cm/s)}{(1.905 \times 10^4\ gm/cm \cdot s)}$$

$$Re_p^{\cdot} = 29.68 \approx 20$$

Since the calculated value is approximately equal to the suggested value of 20, compared to that of 1000 for the alternative equation for U_{mf}, this calculation is considered the valid one to use.

System Pressures

A. Pressure drop across the bed at minimum fluidization velocity is calculated from the following equation:

$$\Delta P_b \approx \Delta P_{b_{mf}} = L_{mf} (1 - \epsilon_{mf}) (\rho_s - \rho_g) \frac{g}{g_c}$$

where: L_{mf} = bed height at minimum fluidization.

$$\Delta P_b = (50 \text{ cm}) (1-0.439) (2.871 \text{ gm/cm}^3) \frac{(980.66 \text{ cm/s}^2)}{(1 \text{ gm}\cdot\text{cm/dyne}\cdot\text{s}^2)}$$

$$(0.1 \text{ Pa}/\frac{\text{dyne}}{\text{cm}^2})$$

$$\Delta P_{b_{mf}} = 7897.41 \text{ Pa} \quad (1.145 \text{ PSI})$$

B. Pressure drop across the distributor plate, according to Kunii and Levenspiel, should be at least one-tenth that across the bed. ($\Delta P_d \geq 0.1\ \Delta P_b$); but not less than 35 cm H_2O of 3431.1 pa. This is to insure a sufficient distribution of fluidizing gas to uniformly fluidize the entire bed.

Thus the lower design limit is: P_d = 3431.1 Pa (0.497 PSI).

Design of the Distributor Plate

The primary decision required in the design of the distributor plate was the number of holes which were necessary to achieve the desired fluidization quality. This decision necessarily included the effect of sandwiching a copper wire screen, of approximately 44 mesh, between two mild steel plates, in which the holes were drilled. The screen was used to prevent solids from falling through the holes into the air inlet plenum below.

For this design, an optimum fluidizing velocity range of 1.83 to 2.44 m/s (6 to 8 ft/sec) was chosen, on which to base the calculations. The overall velocity range was 0.61 to 3.05 m/s (2 to 10 ft/sec). The assumptions made for the design were:

1. Operating temperature of T=328 K (130 F).

2. Pressure drop across the distributor plate was

$$\Delta P_d = 3.735 \text{ kPa } (15.0 \text{ in } H_2O).$$

3. Hole diameter in the distributor plate d_{or} = 0.4763 cm (0.1875 in.).

4. Number of drilled holes was based upon 64 without a wire screen.

5. Orifice coefficient of 0.61.

The procedure followed that presented in Kunii and Levenspiel (4) and resulted in a plate with 102 holes drilled in it, which allowed for the 60% reduction in open area contributed by the wire screen, and an effective open area for the plate of 4.4%.

APPENDIX D

Table of size distribution of used solids.

Tyler Screen Number	Weight fractions after 4.0 hours use — Mean starting size: 569 μm (28 mesh)	Weight fractions after 4.0 hours use — Mean starting size: 1379 μm (9 mesh)	Weight fractions of cyclone effluent of 569 μm (28 mesh) solids — After 5.0 hours cumulative	Weight fractions of cyclone effluent of 569 μm (28 mesh) solids — After 10.0 hours cumulative
6	--	0	--	--
10	0	0.3726	--	--
12	0	0.1263	--	--
14	0.0130	0.1178	0	0
20	0.1967	0.2034	0.0833	0.0325
28	0.5389	0.1199	0.1389	0.2175
48	0.2435	0.0471	0.444	0.4708
$\geq$60	0.0077	0.0129	0.3333	0.2792
	0.9998	1.0000	1.0000	1.0000
Final mean size	d_{sv} = 499.6 μm	d_{sv} = 940.0 μm	d_{sv} = 316.3 μm	d_{sv} = 321.9 μm
	≈ 32 mesh	≈ 18 mesh	≈ 46 mesh	≈ 46 mesh

APPENDIX E

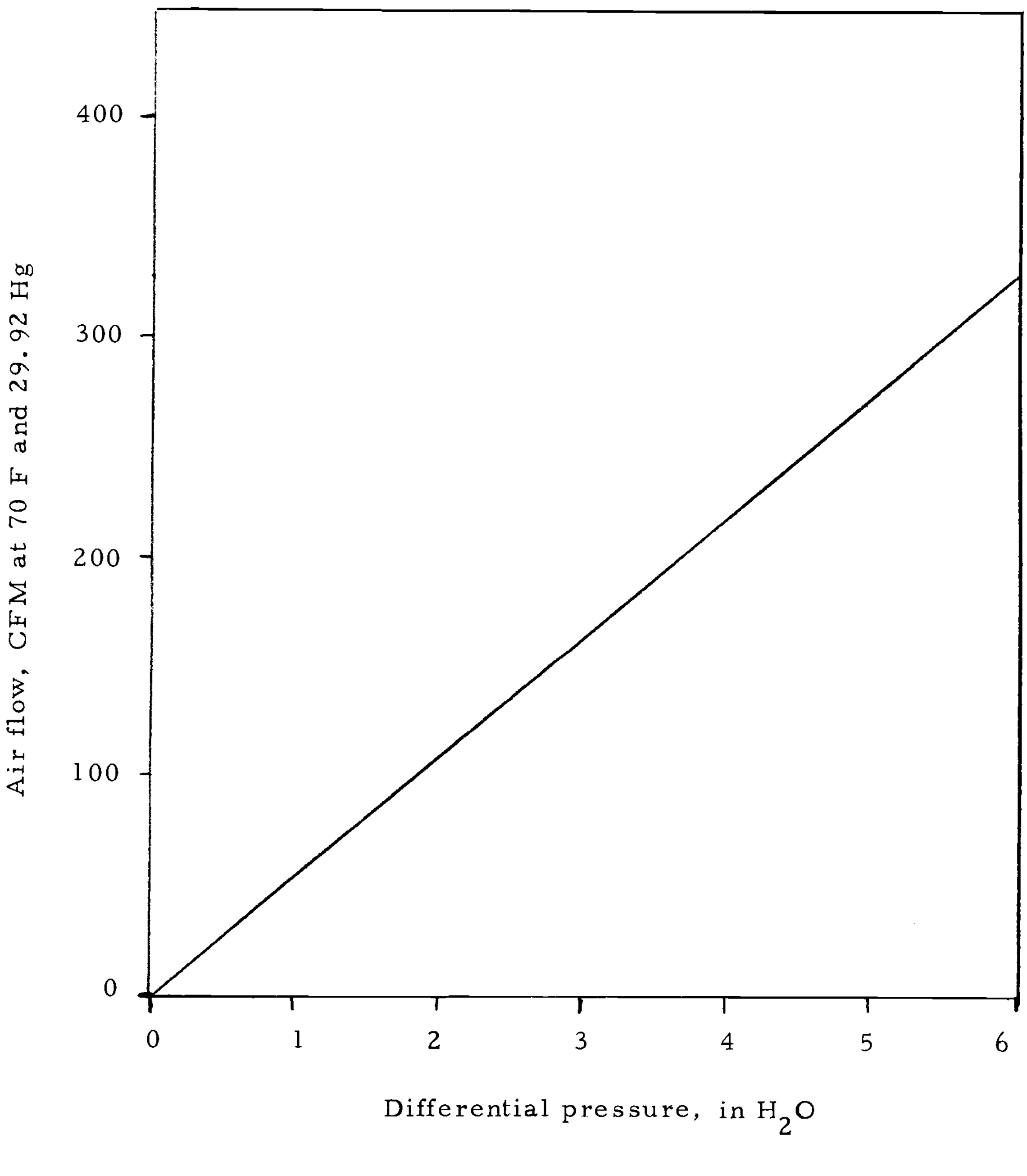
List of Tyler Sieve Sizes and Equivalents

	Aperature	
Mesh	μm	in.
3	6370	0.265
4	4760	0.187
6	3360	0.132
8	2380	0.0937
10	1680	0.0661
12	1410	0.0555
14	1190	0.0469
20	841	0.0331
28	595	0.0234
48	297	0.0117
60	250	0.0098

APPENDIX F

Orifice (Laminar Flow Element) Calibration Curve

Calibration curve reproduction for Meriam Laminar Flow Element Model 50 MC2-4F, Serial No. G-58821T



APPENDIX G

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