DOE/PC/89806--T4

DOE/PC/89806--T4

DE92 007760

CONFINED VORTEX SCRUBBER

QUARTERLY TECHNICAL PROGRESS REPORT

for the period

April 1, 1990 - June 30, 1990

Date Prepared

July 1990

Prepared by

AVCO RESEARCH LABORATORY

2385 Revere Beach Parkway
Everett, Massachusetts 02149

Prepared for

U.S. DEPARTMENT OF ENERGY

Pittsburgh Energy Technology Center
Pittsburgh, Pennsylvania 15236

Under Contract No. DE-AC22-89PC89806

28

TABLE OF CONTENTS

1.0 SUMMARY 1

2.0 TECHNICAL PROGRESS 4

2.1 BACKGROUND 4

2.1.1 Program Objective and Device Concept 4

2.1.2 Progress Prior to This Reporting Period 4

2.2 MARK I CVS CLEANUP TESTS 7

2.2.1 Shakedown Tests 9

2.2.2 Fly Ash Cleanup Tests 15

2.2.3 Fly Ash Size Changes 21

2.3 MARK II CVS 25

2.3.1 Two-Phase Flow Tests 25

2.3.2 Cleanup Tests 28

2.4 MARK III CVS 30

2.4.1 Two-Phase Flow Tests 30

2.4.2 Fly Ash Cleanup Tests 34

2.4.3 Effect of Liquid Layer Type 36

2.4.4 Sub-Micron Alumina Cleanup Tests 38

3.0 CONCLUSIONS AND PLANS FOR FUTURE WORK 40

REFERENCES 42

1.0 SUMMARY

The program objective is to demonstrate efficient removal of fine particulates to sufficiently low levels to meet proposed small scale coal combustor emission standards using a cleanup technology appropriate to small scale coal combustors. This is to be accomplished using a novel particulate removal device, the Confined Vortex Scrubber (CVS), which consists of a cylindrical vortex chamber with tangential flue gas inlets. The clean gas exit is via two vortex finder outlets, one at either end of the tube. Liquid is introduced into the chamber and is confined within the vortex chamber by the centrifugal force generated by the gas flow itself. This confined liquid forms a layer through which the flue gas is then forced to bubble, producing a strong gas/liquid interaction, high inertial separation forces and efficient particulate cleanup. In effect, each of the sub-millimeter diameter gas bubbles in the liquid layer acts as a micro-cyclone, inertially separating particles into the surrounding liquid. The CVS thus obtains efficient particle removal by forcing intimate and vigorous interaction between the particle laden flue gas and the liquid scrubbing medium.

In order to demonstrate and optimize the cleanup performance of the CVS, a twelve month experimental program supported by analytical efforts is being carried out. Tests are being conducted on a model CVS at a mass flow equivalent to the exhaust gas flow of a 1 MM BTU/hr combustor. The test gas is essentially at ambient temperature and pressure. Prior to this reporting period a CVS design was developed and number of CVS models fabricated. A proof of concept experimental arrangement was assembled and a comprehensive series of two-phase flow experiments were conducted. This work led to the choice of an optimum CVS configuration from the point of view of pressure drop and two-phase flow field characteristics.

This is the third quarterly technical progress report in the program. During this quarter a comprehensive series of cleanup experiments have been made for three CVS configurations. The test arrangement was modified to include two water knockout chambers and a filter section downstream of

the CVS. The purpose of the knockout chambers is to collect any water which is entrained into the clean air leaving the CVS. The purpose of the filter section is to allow the mass of dust passed by the CVS to be determined in order to obtain measurements of cleanup efficiency. A series of shakedown tests of the new experimental hardware were conducted. In addition, calibration experiments were conducted for the fluidized bed dust feeder.

A variety of dust size distributions and materials have been tested. Shakedown experiments were made using fine silica and alumina dusts. Most of the tests have been made with ultra-fine fly ash for which d_{10}, d_{50}, d_{90} = 1, 3, 8 microns as fed (10 percent of the mass of the dust is contained in particles of diameter d_{10} or smaller, 50 percent in particles of diameter d_{50} or smaller and 90 percent in particles of diameter d_{90} or smaller). This ultra-fine fly ash is generated by classifying fly ash in a cyclone separator. All three CVS configurations have demonstrated extremely efficient capture of this ash: typical collection efficiencies are greater than 99 percent and have been measured at up to 99.8 percent. Tests have also been made with fine silica and alumina dust, as well as larger grinds of fly ash (200 and 325 mesh). The CVS is also extremely efficient at capturing sub-micron particles: 98 percent collection for 0.3 micron alumina particles has been demonstrated.

The first CVS configuration tested gave very efficient fine particulate removal at the design air mass flow rate (1 MM BTU/hr combustor exhaust flow), but had over 20"WC pressure drop. The first CVS configuration was then re-designed to produce the same very efficient particulate collection performance at a lower pressure drop. The current CVS configuration produces 99.4 percent cleanup of ultra-fine fly ash at the design air mass flow at a pressure drop of 12 "WC with a liquid/air flow ratio of 0.3 l/m^3. Unlike venturi scrubbers, the collection performance of the CVS is insensitive to dust loading and to liquid/air flow ratio.

Results to date indicate that the size distributions of the ash entering the CVS, the ash collected in the water and the ash collected in the downstream filter are very similar. This suggests that the CVS does not have a classic inertial separator type grade efficiency curve, with high collection efficiency for larger particles and progressively lower collection efficiency for smaller particles. Rather, it suggests that the CVS has a uniformly high collection efficiency for particles of all sizes (in the range exhibited by the fly ash used) and the mechanism by which a very small fraction of the inlet ash is passed through the CVS is connected with either failure to contact all the inlet air with the water or with re-release of a small fraction of the separated ash from the water. At present there is insufficient evidence to determine the precise mechanisms involved.

The collection efficiency data for three CVS chambers of different sizes has been successfully correlated by a simple exponential relationship between the collection efficiency and the radial acceleration in the CVS chamber.

Outstanding issues include the problem of ash deposition in the annular plenum feeding the squirrel cage slots. The deposits appear to start building up in the plenum corners and to be growing counter to the main flow in the plenum, probably in secondary flow regimes. The overall collection efficiency remains very high (> 99 percent) for long duration tests in which deposition is noticeable and inlet slot plugging occurs. Future tests will address this issue, as well as the effects of liquid properties on collection performance. In addition, a liquid filtration system will be added to enable a complete dust mass closure to be made for each test.

In summary, a comprehensive series of simulated flue gas cleanup experiments made with a confined vortex scrubber have demonstrated greater than 99 percent capture of extremely fine fly ash at low pressure drops and liquid flow rates. 98 percent collection has been demonstrated for 0.3 micron particles. Projected particulate emissions from a small scale coal combustor equipped with a confined vortex scrubber would be well below the proposed emissions limit of 0.02 lbs/MM BTU.

2.0 TECHNICAL PROGRESS

2.1 BACKGROUND

2.1.1 Program Objective and Device Concept

The program objective is to demonstrate efficient removal of fine particulates to sufficiently low levels to meet proposed small scale coal combustor emission standards. This is to be accomplished using a novel particulate removal device, the Confined Vortex Scrubber (CVS), which consists of a cylindrical vortex chamber with tangential flue gas inlets and is illustrated schematically in Figure 2-1. The clean gas exit is via two vortex finder outlets, one at each end of the chamber. Liquid is introduced into the chamber and is confined within the vortex chamber by the centrifugal force generated by the gas flow itself. This confined liquid forms a layer through which the flue gas is then forced to bubble, producing a strong gas/liquid interaction, high inertial separation forces and efficient particulate cleanup. In effect, each of the sub-millimeter diameter gas bubbles in the liquid layer acts as a micro-cyclone, inertially separating particles into the surrounding liquid. The CVS thus obtains efficient particle removal by forcing intimate and vigorous interaction between the particle laden flue gas and the liquid scrubbing medium.

2.1.2 Progress Prior to This Reporting Period

During the reporting period previous to this one a comprehensive series of two phase flow experiments were conducted on a variety of CVS configurations. An optimum design, from the point of view of the two-phase flow field in the device, was arrived at as a result of experimentation. The optimum design has 24 tangential slot inlets as opposed to the two in the initial CVS design. The design is illustrated schematically in Figure 2-2. Preliminary tests of the new design (the "squirrel cage" design) indicated that the flow field in the squirrel cage CVS chamber was very different from that in the initial, two-inlet design. The inlet air jets were clearly submerged beneath a much thicker liquid layer than had been observed for the initial design. There was an extremely vigorous interaction between the air and

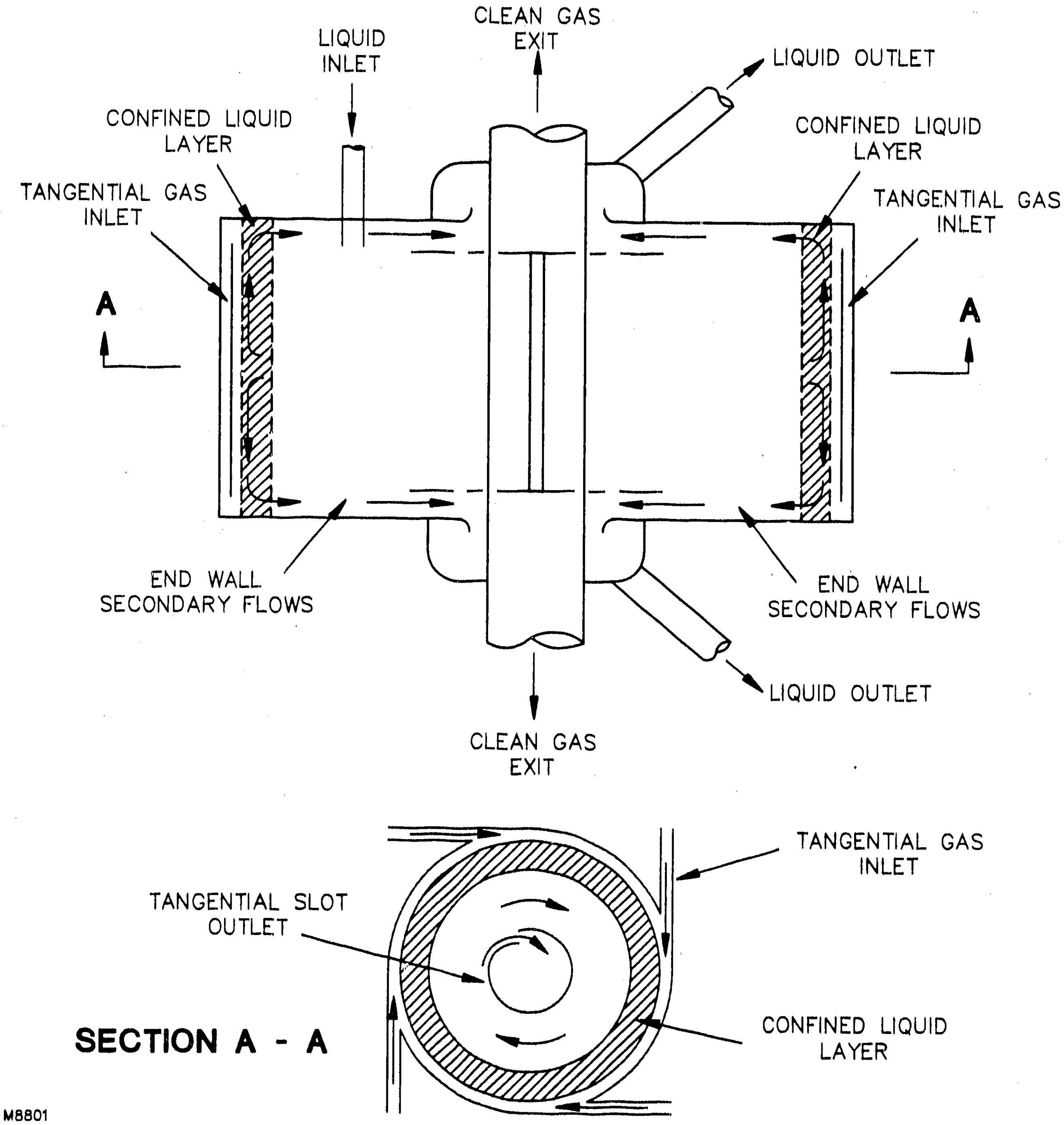

Figure 2-1 Schematic Diagram of Confined Vortex Scrubber

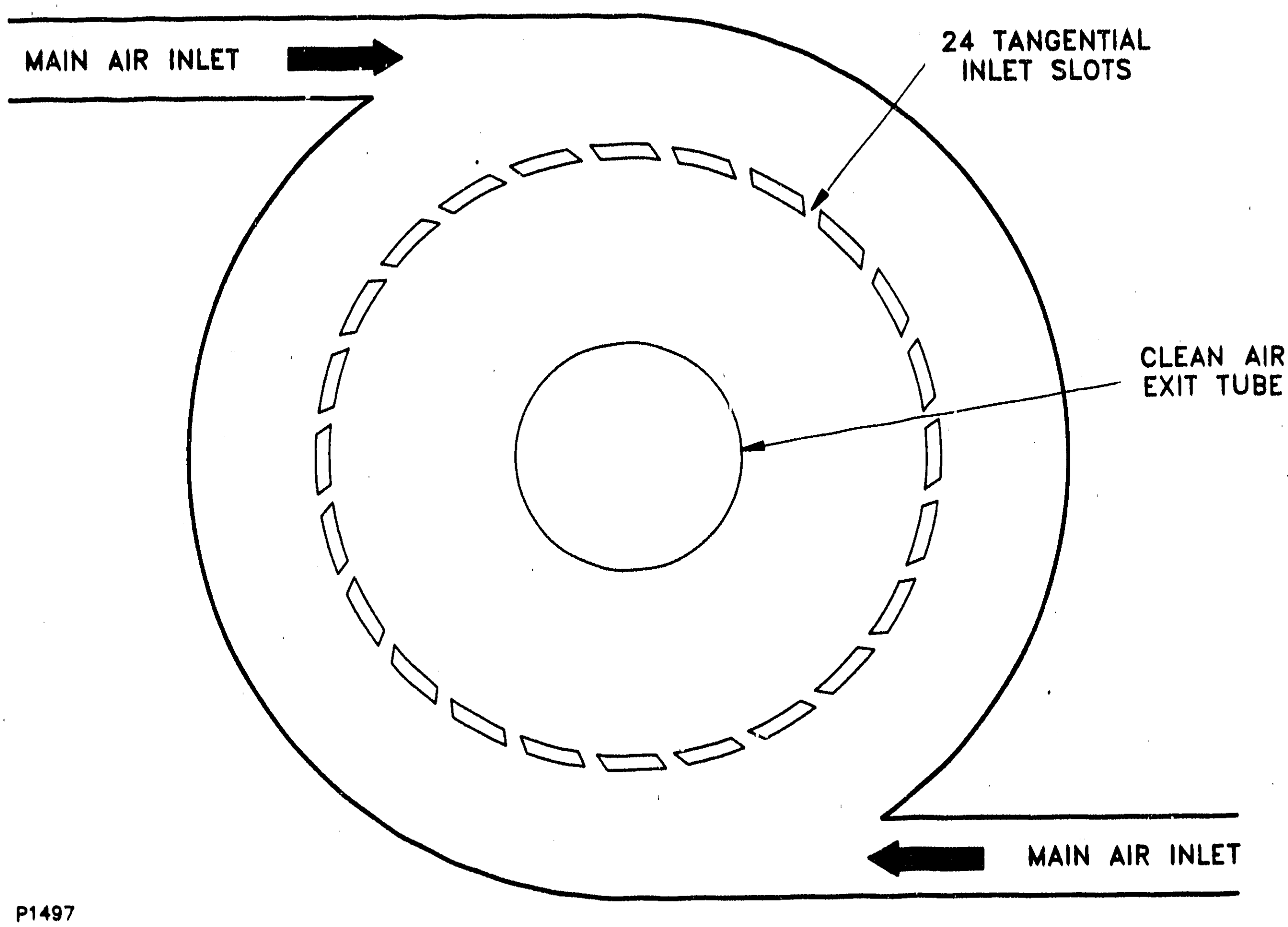

Figure 2-2 Schematic Diagram Showing Squirrel Cage CVS Design Concept

the liquid: the liquid layer appeared thick and frothy in nature. The liquid mass contained increased dramatically to a maximum of approximately 20 percent of chamber volume. The pressure drop was a minimum when a stable liquid layer was established. Other significant differences observed with the squirrel cage CVS design compared to the initial design were that the vortex finder outlet appeared to give superior performance to the flow guide slot outlet and the fact that a spray cloud was visible at the outer edges of the liquid layer, indicating some atomization and entrainment of liquid in this region.

In summary, results obtained for a 4.25" ID CVS of squirrel cage design (hereinafter referred to as the Mark I squirrel cage CVS) indicated effective liquid containment and extremely vigorous air/liquid interaction at a reasonable pressure drop. The vortex finder exit was found to be clearly superior to the slot exit in all areas of concern: pressure drop, liquid containment, liquid mass flow to establish liquid layer, level of air/liquid interaction and rate of liquid loss via clean gas exit.

2.2 MARK I CVS CLEANUP TESTS

The first cleanup experiments were carried out with the same squirrel cage CVS configuration as was described in the previous quarterly technical progress report. This configuration has been designated the Mark I Squirrel Cage CVS, and its geometric parameters are given in Table 2-1. A photograph of the Mark I CVS as installed is shown in Figure 2-3.

TABLE 2-1

MARK I SQUIRREL CAGE CVS CONFIGURATION

Chamber Internal Diameter	4.25"
Aspect Ratio (L/D)	1.53
Air Inlet Type	Slots
No. of Slots	24
Inlet Slot Height	0.040"
Air Outlet Type	Vortex Finder
Air Outlet Diameter (D_e/D)	0.41
Water Outlet Type	Single Tube, 0.372" ID

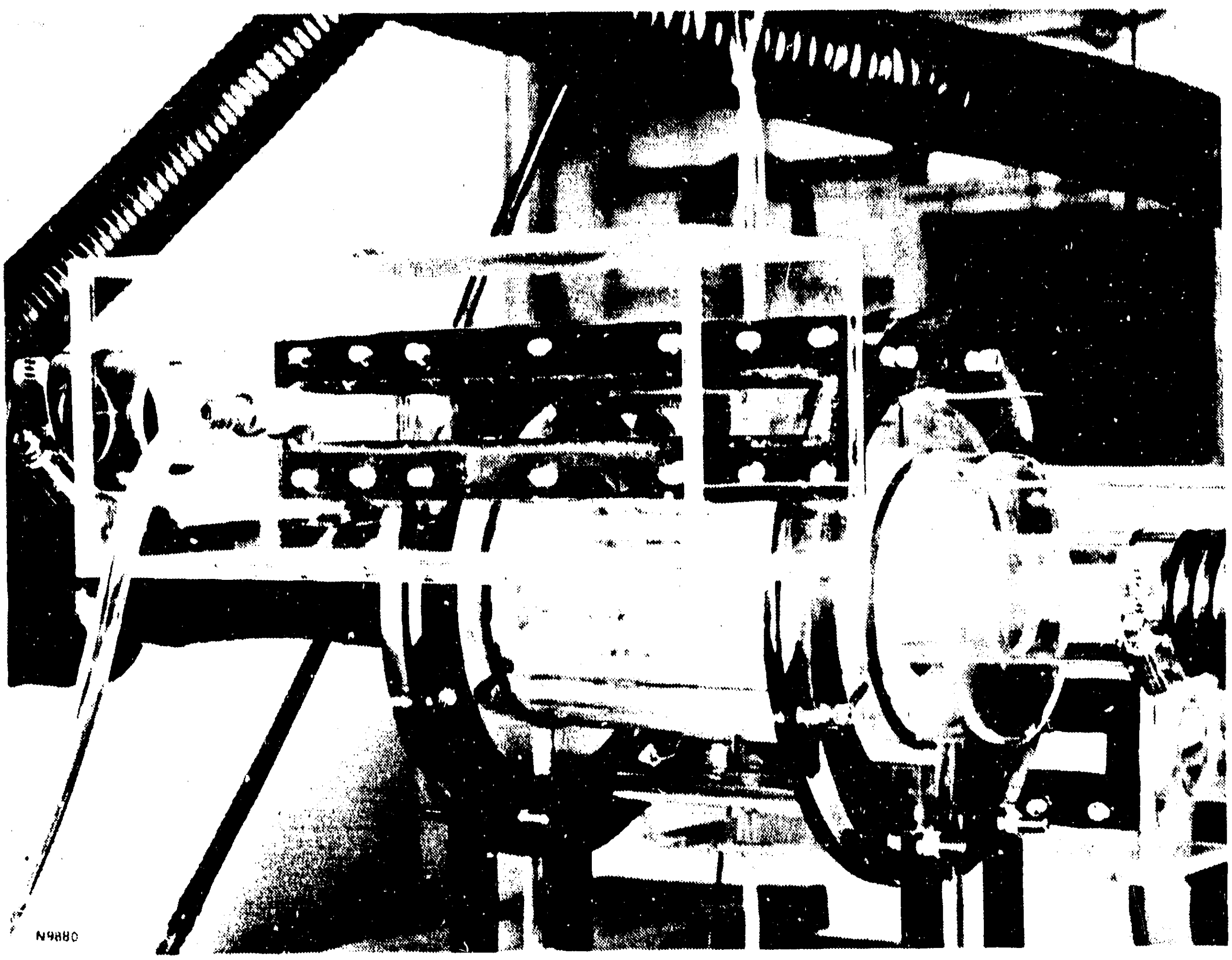

Figure 2-3 Photograph of Mark I Squirrel Cage CVS Installation

2.2.1 Shakedown Tests

A number of modifications were made to the experimental hardware before commencing the cleanup tests. These included adding two water knockout chambers and a filter section downstream of the CVS. The purpose of the knockout chambers is to collect any water which is entrained into the clean air leaving the CVS. The purpose of the filter section is to allow the mass of dust passed by the CVS to be determined in order to obtain measurements of cleanup efficiency. A schematic diagram of the revised arrangement is given in Figure 2-4. Figure 2-5 is a photograph of the complete experimental installation for the cleanup tests.

Shakedown of New Test Rig. Shakedown tests were conducted with the new experimental installation in order to evaluate the efficiency of the water removal arrangement in the clean air exits. A known quantity of water was introduced into the CVS and the mass of water collected from the both the CVS water out-take chambers and the water knockout chambers was recorded. Complete recovery was made, within the measurement accuracy. The outlet filter weight change was also monitored. This showed a very small and consistent increase of approximately 0.1 g (in approximately 100 g). This increase was independent of the length of time the test was run and of the quantity of water flowed through the CVS. After approximately half an hour at room temperature, the filters consistently returned to their original weights, indicating that the weight gain was due to humidification of the filter material.

Fluidized Bed Feeder Tests. Fluidized bed feeder calibration tests were also made. A schematic diagram of the fluidized bed feeder used in these experiments is shown in Figure 2-6. The CVS nominal design airflow simulates the exhaust flow from a 1 MM BTU/hr combustor. Assuming that a 2 percent ash coal is burned, the exhaust ash mass flow rate is approximately 13 g/min. Tests were made to ensure that a stable dust feed in the range 10-15 g/min could be obtained. In this report, dust size distributions will be given in terms of d_{10}, d_{50} and d_{90}, where 10 percent of the mass of the dust is contained in particles of diameter d_{10} or smaller, 50 percent in particles of diameter d_{50} or smaller and 90 percent in particles of diameter d_{90} or smaller. First tests were made with a silica dust for which d_{10}, d_{50} and d_{90} were 8, 19 and 34 microns respectively. The overall size distribution for the silica dust is shown in Figure 2-7.

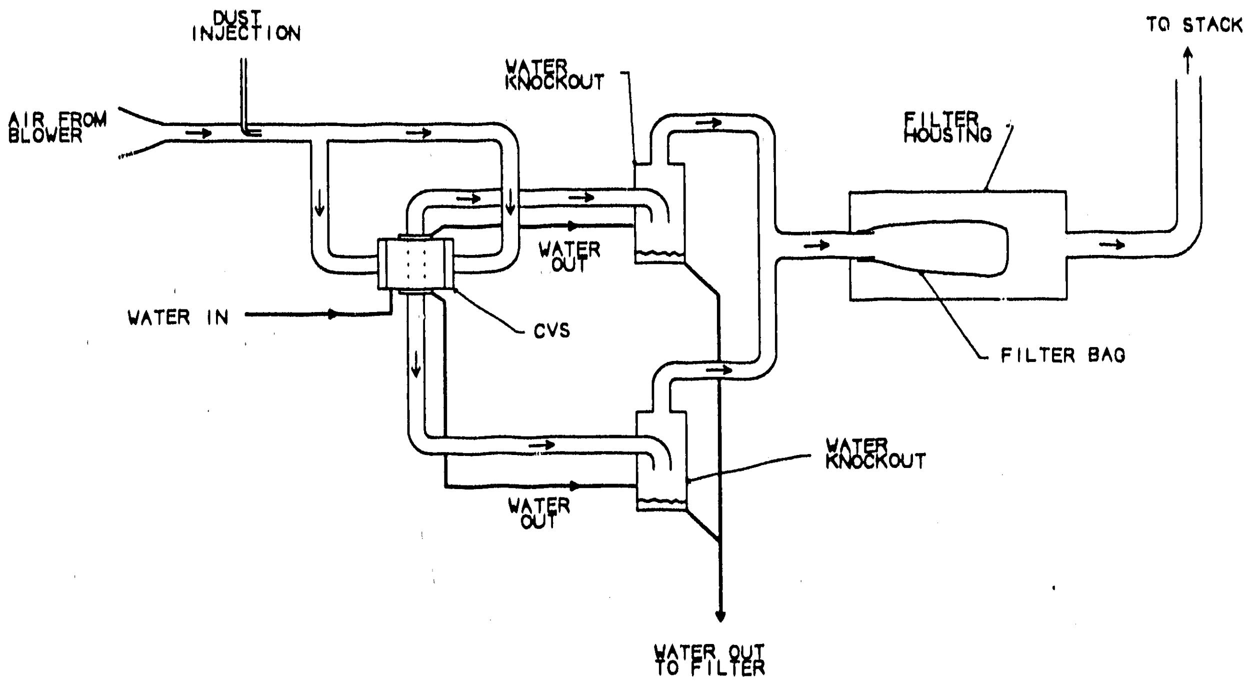

Figure 2-4 Schematic Diagram of Experimental Arrangement for Cleanup Experiments

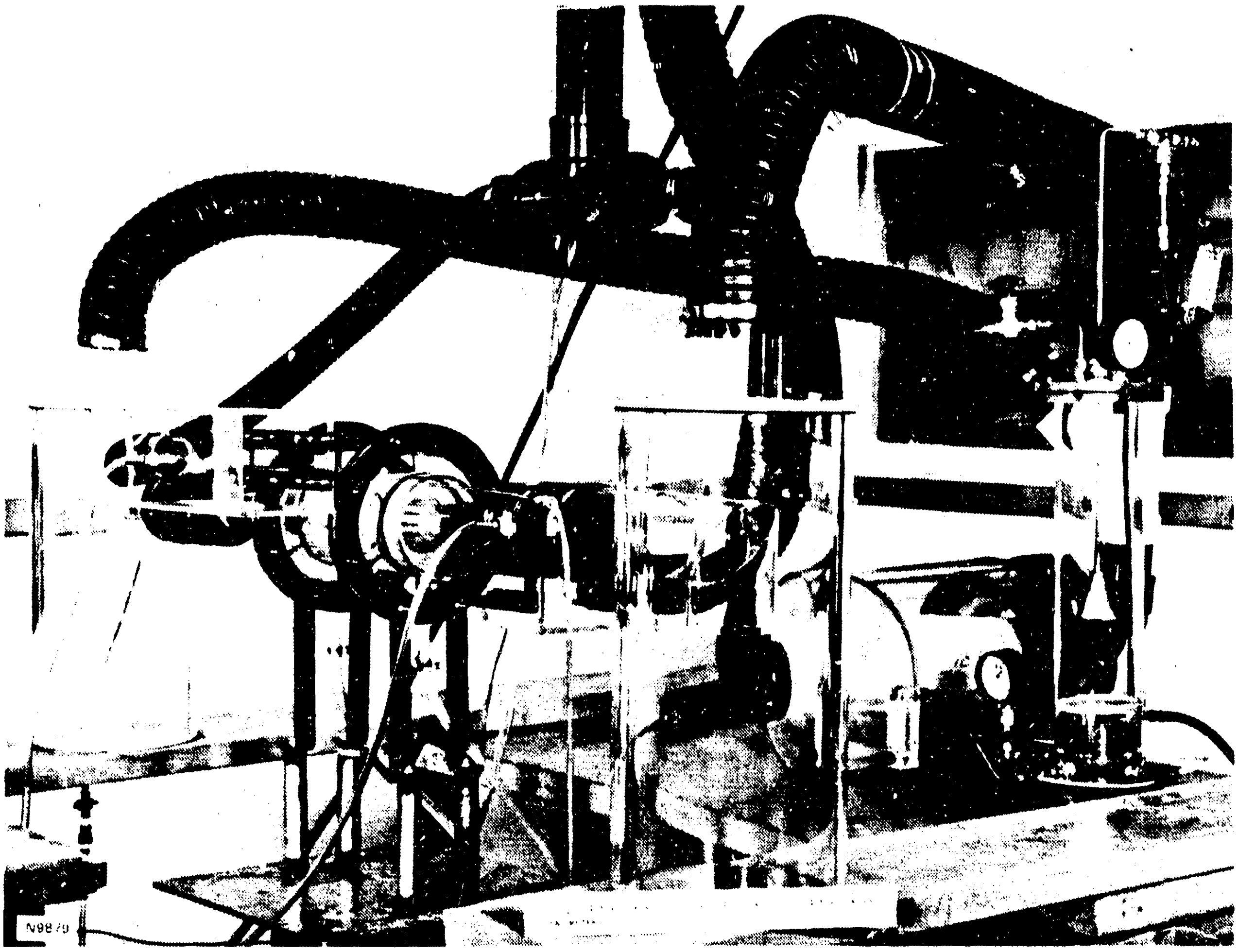

Figure 2-5 Photograph of Experimental Installation for Cleanup Experiments

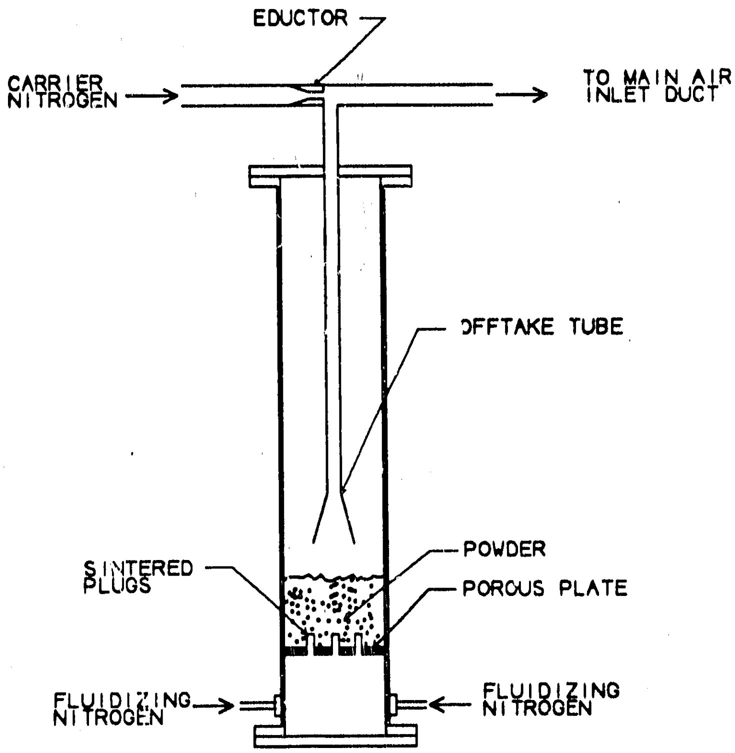

Figure 2-6 Schematic Diagram of Fluidized Bed Dust Feeder

Satisfactory feed was obtained for this dust.

Preliminary Cleanup Tests. A preliminary cleanup test was conducted with the silica dust. The CVS airflow was set to the design mass flow rate and 218 g of silica dust were introduced into the main air inlet pipe over a period of 20 minutes. After the test the filter unit was disassembled and the filter weight gain was recorded. A gain of 0.1 g was measured, indicating a CVS collection efficiency of 99.95 percent.

Subsequently, further shakedown tests were conducted with much finer alumina dust, for which d_{10}, d_{50} and d_{90} = 2, 5 and 8 microns respectively, see Figure 2-7. Some difficulty was experienced in feeding this dust. In order to obtain reliable feed of this very fine material at the desired flow rates, a greater nitrogen flow rate through the fluidized bed was required than for the silica dust used previously. The feeder was modified so as to provide a greater bed flow and the carrier flow was dispensed with. The powder was thus fed directly through the bed offtake tube into the main air inlet and the bed nitrogen flow was used as the dust carrier flow.

Four cleanup tests were then made with the fine alumina dust, in the same manner as was described above. At the design air mass flow, collection efficiencies of 99.75, 99.87 and 99.82 percent were measured. One test was made with no water addition: a collection efficiency of 77.27 percent was measured. Thus with no water present the CVS chamber acts as a high efficiency cyclone separator, with separation due only to centrifugal forces. With a confined liquid layer present, however, the intimate and vigorous air/liquid interaction provides for extremely high collection efficiencies.

During the last of the tests with fine alumina powder, the fluidized bed feeder was damaged by a chamber overpressure.[1] This caused the porous plate to become detached from the main feeder vessel. Once the feeder was repaired it proved impossible to successfully fluidize the fine alumina powder. It transpired that before the feeder failure the bulk of the nitrogen flow through the bed was via leaks at

[1] This caused an extremely high transient dust flow rate of 200 g in 1 - 2 seconds, some 500 times the design dust mass flow rate, yet the CVS collection efficiency was still measured at 99.82 percent for this test.

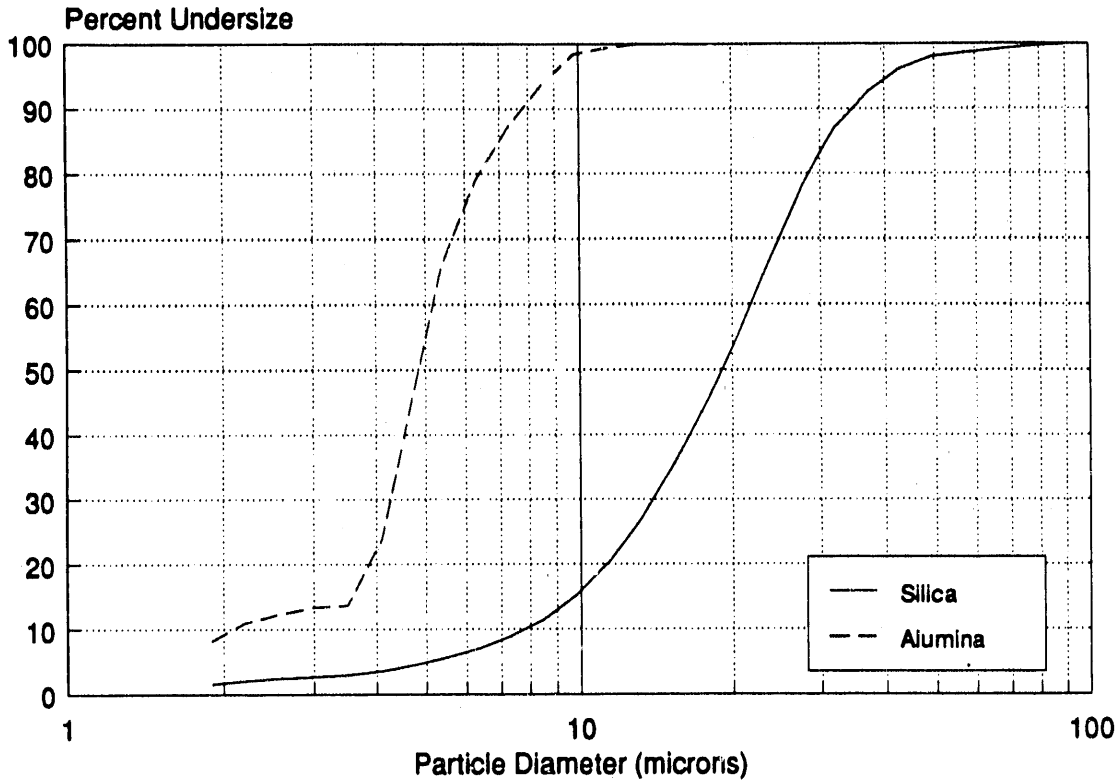

Figure 2-7 Size Distributions of Silica and Alumina Dusts Used in Shakedown Experiments

the junction of the porous plate and the feeder vessel wall. When the feeder was re-built the leaks were fixed and it no longer proved possible to obtain sufficient fluidizing nitrogen flow through the porous plate to fluidize the fine powder. In order to overcome this problem five sintered plugs were installed in the feeder. The fluidizing nitrogen was then supplied through the sintered plugs. A small vibrator was also attached to the feeder wall, below the top of the bed. This proved to be an effective method of feeding the fine dust at a reasonable nitrogen mass flow rate and feeder chamber pressure.

The filter material used to filter the CVS outlet flow in these experiments is rated at 99.8 percent collection down to 1 micron particles. This was checked by feeding a known quantity of the fine alumina dust directly into the CVS outlet piping and hence into the filter, in order to determine the suitability of the filter material collection of these fine dusts. Greater than 99 percent collection was measured, with the discrepancy probably due to very small amounts of deposition in the lines.

2.2.2 Fly Ash Cleanup Tests

The nominal design dust to be cleaned in these experiments is fly ash sieved to below 20 microns in size. Sieving to such a fine size proved to be extremely time-consuming, so in order to generate such fine fly ash a cyclone based classifier was developed. This system is illustrated in Figure 2-8. Fly ash (Pozzolanic Fly Ash Class C & F, meets ASTM C-618, obtained from the Quality Concrete Co., Billings, Montana) is first sieved to below 80 mesh and then loaded into a screw feeder. Air is supplied to the cyclone by a fan. The ash is fed by the screw feeder into the cyclone inlet flow. The cyclone inlet velocity was reduced by opening the bypass air valve until the size distribution of the ash that passed the cyclone was as desired: 100 percent below 20 microns. The cyclone outlet dust was collected in a large filter bag. This proved to be a much more efficient way of generating quantities of sub-20 micron fly ash than sieving. For the purposes of this report, the sub-20 micron fly ash produced by cyclone classification will be referred to as "ultra-fine fly ash."

While the ash classifier system was being commissioned, a number of cleanup tests were made with larger grinds of fly ash. Two tests were made with 200 mesh fly ash (d_{10}, d_{50} d_{90} = 4, 11, 41 microns) and seven were made with 325 mesh fly ash (d_{10}, d_{50} d_{90} = 3, 10, 26 microns). Subsequently five tests were

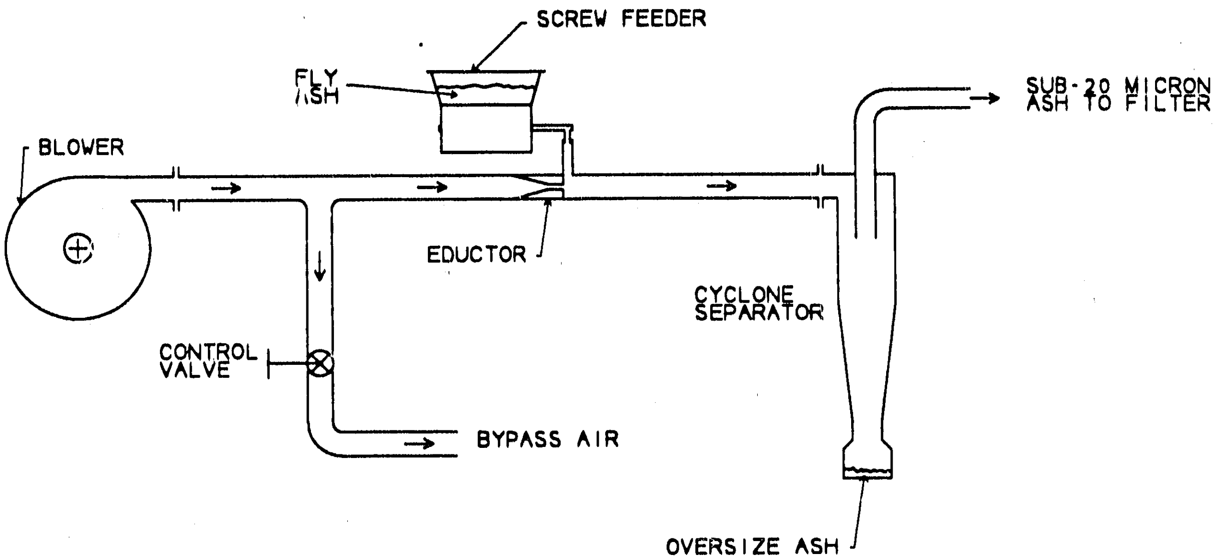

Figure 2-8 Schematic Diagram of Fly Ash Classification System

made with ultra-fine fly ash (d_{10}, d_{50}, d_{90} = 3, 8, 12 microns as generated in ash classifier). Size distributions for the three sizes of fly ash used are shown in Figure 2-9. Downstream filter tests were also conducted for all three fly ash size distributions in the same manner as that described above. Better than 99 percent collection in the filter was measured for all three sizes of fly ash.

The measured Mark I cleanup performance is plotted as a function of the inlet air mass flow rate in Figure 2-10. The nominal design air mass flow rate is approximately 0.1 kg/s. At or above this flow rate the measured collection efficiencies are greater than 99.5 percent. There is a very weak dependence of efficiency on fly ash size: at the same air mass flow the collection efficiency for ultra-fine ash is only approximately 0.1 percent lower than that for the 325 mesh ash. The dependence of efficiency on air mass flow is much more pronounced. This is to be expected, since for a given geometry the inlet air mass flow rate sets the inlet tangential velocity, which sets the radial acceleration produced and hence the particle separation forces generated.

Figure 2-11 shows the effect of liquid/air flow ratio on measured collection efficiency. For two different dust sizes, 325 mesh and ultra-fine, the collection efficiency is almost independent of liquid air/ratio. It should be noted that the liquid/air ratios in the CVS are in the range 0.1 to 0.3 l/m^3, approximately 10 percent of those typically employed in venturi scrubbers (Martin, 1981).

It was noted during the shakedown testing with fine alumina powder that the CVS performance seemed insensitive to dust loading. This was examined systematically using fly ash. The results are shown in Figure 2-12. The measured collection efficiency shows only a very slight increase over the range of a factor of 50 in dust flow (from ~3 to ~150 g/min). This is in contrast to the strong dependence of venturi scrubber performance on dust loading (Roeck and Dennis, 1979). The CVS data is compared to that for venturi scrubbers operated on various coal-fired industrial boilers in Figure 2-13. The venturi scrubber data was obtained from Roeck and Dennis (1979). Performance is expressed in terms of penetration, a penetration of 1 percent corresponding to a collection efficiency of 99 percent, and so on. As the dust loading is reduced the venturi performance falls off rapidly. This is because dust removal in a venturi scrubber relies on collisions between dust particles and water droplets. The lower the particle

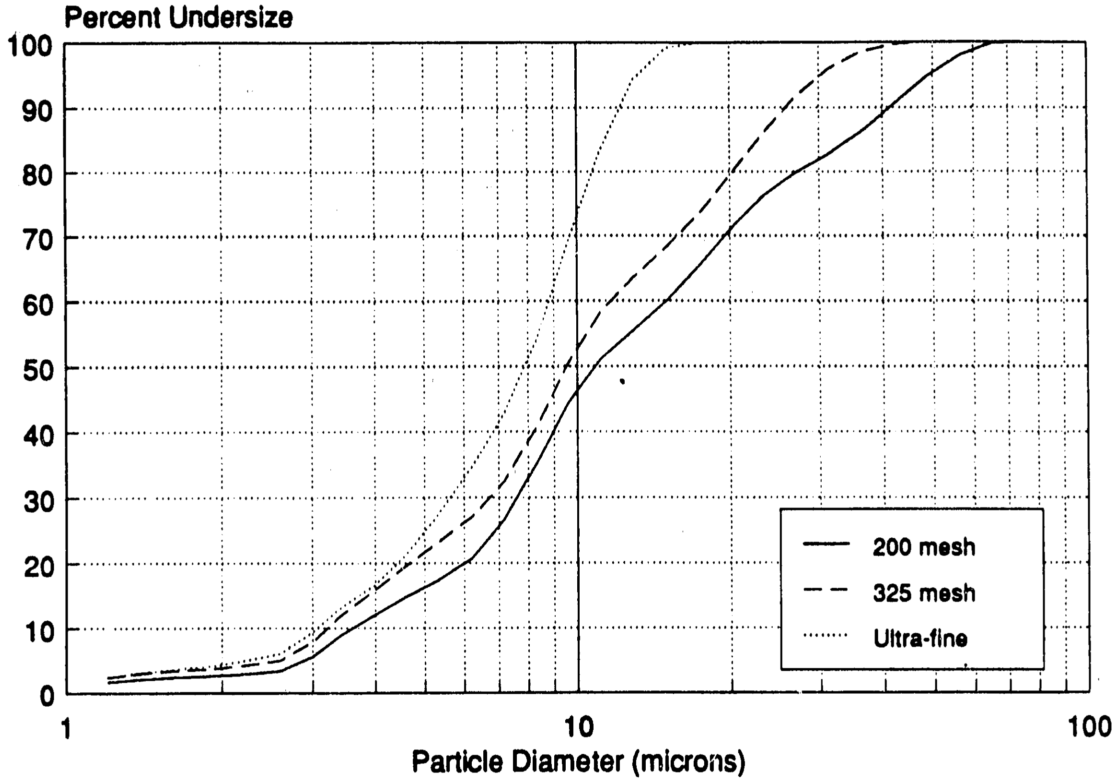

Figure 2-9 Size Distributions of Three Fly Ash Grinds Used in Cleanup Experiments

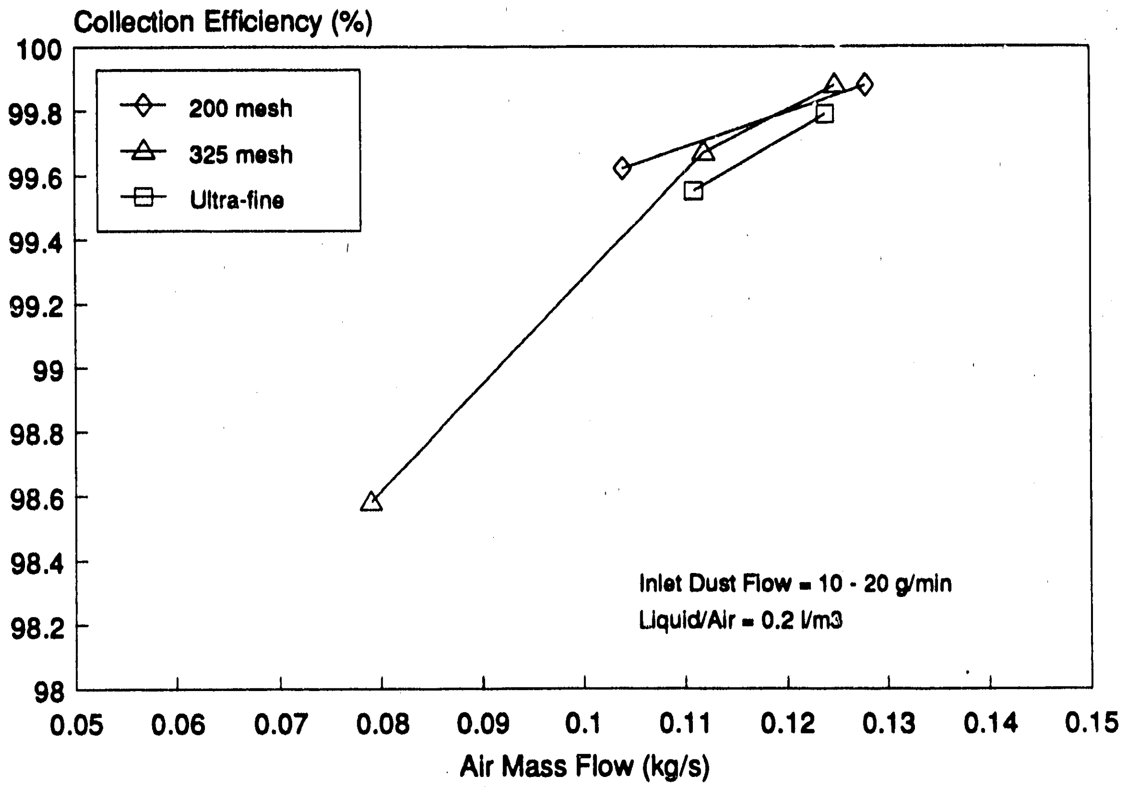

Figure 2-10 Measured Cleanup Performance for Mark I CVS as a Function of CVS Inlet Air Mass Flow Rate for Three Fly Ash Sizes

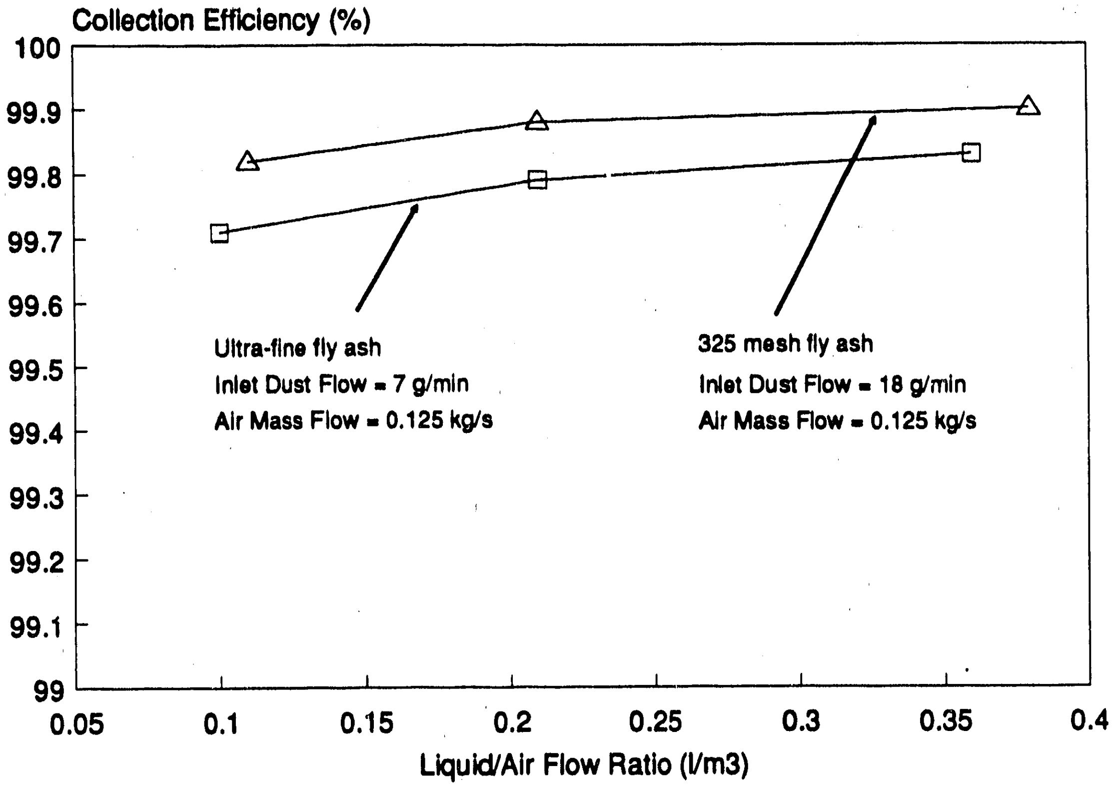

Figure 2-11 Measured Cleanup Performance for Mark I CVS as a Function of Liquid/Air Flow Ratio for Two Fly Ash Sizes

concentration, the lower the collisional frequency and the poorer the collection performance. The CVS, on the other hand, shows a very weak dependence on dust loading.

Figure 2-14 shows outlet emissions in grains per standard cubic foot as a function of pressure drop, again comparing the CVS and venturi scrubbers. The Mark I CVS has pressure drops in the range 10-30 inches of water column ("WC), which is the same range as that for venturi scrubbers. However at the same pressure drop the CVS gives superior cleanup performance, even for very fine fly ash.

Based on the measured inlet ash flows and ash removals, particulate emissions from a small scale coal combustor equipped with a CVS may be projected. This projection is shown in Figure 2-15, for the three ash sizes tested. The proposed small scale combustor emissions limit of 0.02 lb/MM BTU is also shown for reference. The projected emissions are plotted as a function of the equivalent coal ash content, derived from the measured ash flow rate in the cleanup tests. For 1-2 percent ash coals, the projected emissions are approximately 0.002 lb/MM BTU, well below the proposed limit of 0.02 lb/MM BTU.

2.2.3 Fly Ash Size Changes

From the data generated to date, there is considerable evidence that the fly ash size distribution changes as it is fed from the fluidized bed feeder and then changes again in the liquid in the CVS. The ash as sieved or classified is agglomerated: its size distribution changes quite considerably after being treated in an ultrasonic bath for about 30 minutes. This was found to be true for all three ash sizes. For the ultra-fine ash the values of d_{10}, d_{50} and d_{90} change from 4, 8 and 13 microns to 1, 3 and 8 microns as the ash is ultrasonically treated, see Figure 2-16. The dust size distribution was also measured as fed from the fluidized bed feeder. This result is also shown in Figure 2-16: the ash size distribution as fed reflects the de-agglomerated size distribution rather than the as-classified size distribution.[2]

Figure 2-17 shows various ash size distributions from Test #62, which was made with the ultra-fine fly ash. The size distribution of the ash in the water leaving the CVS is also very different to that of the as-classified fly ash. Considerable agglomeration is observed, with the mean size of the ash in the

[2] There exists the possibility that only fines are being fed from the fluidized bed. The fact that the size distribution of the ash as fed was independent of the duration of the feed, the position of the offtake tube above the bed and of the fluidizing gas flow rate would suggest that this is not the case.

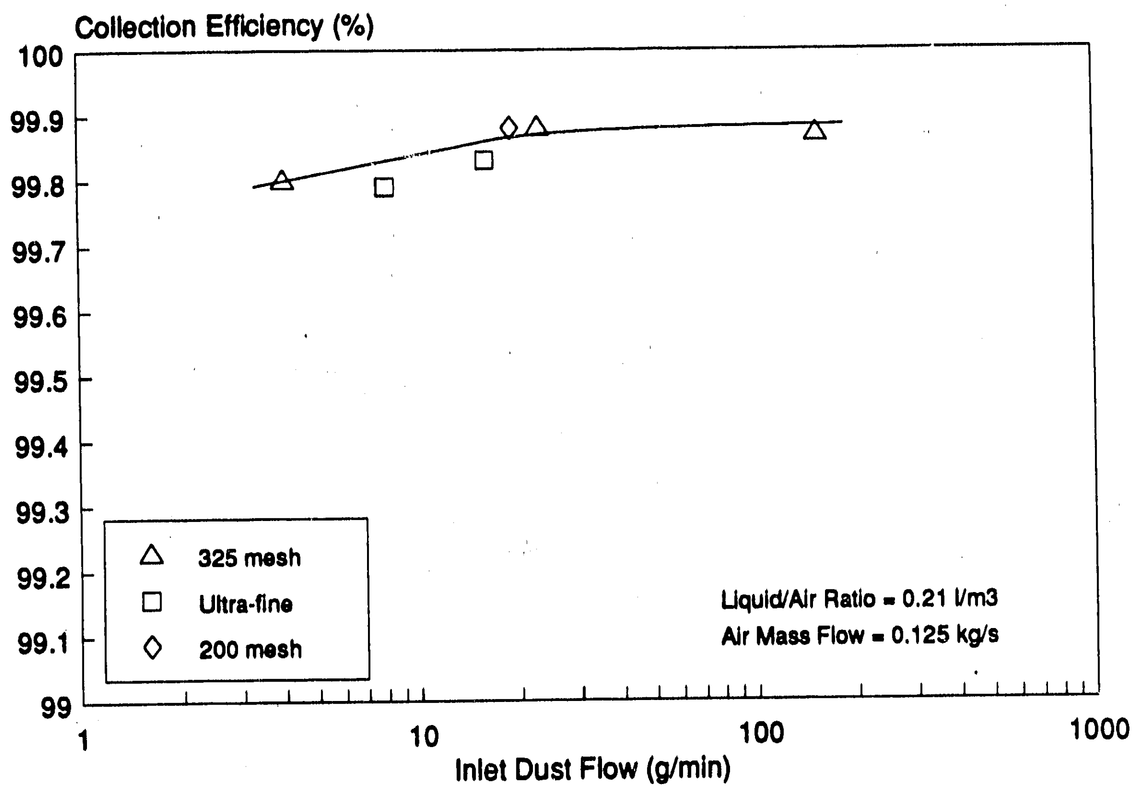

Figure 2-12 Measured Cleanup Performance for Mark I CVS as a Function of Inlet Dust Flow Rate for Three Fly Ash Sizes

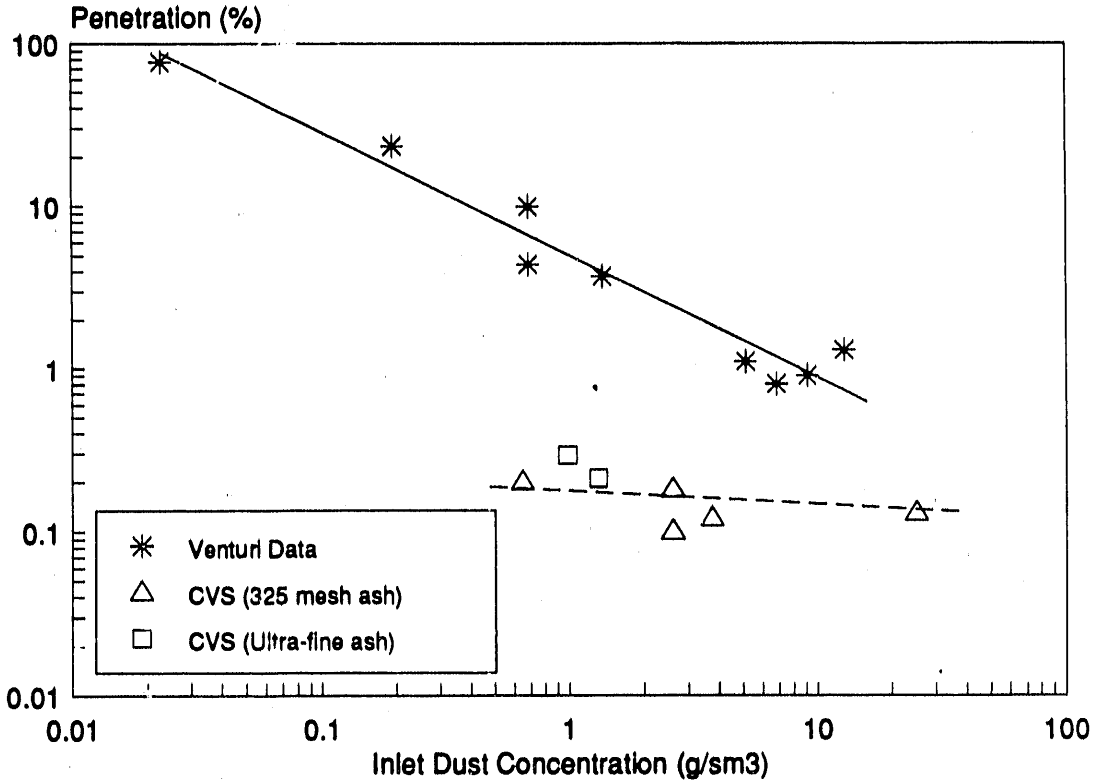

Figure 2-13 Comparison of Mark I CVS Fly Ash Cleanup Performance with Published Venturi Scrubber Data for Industrial Coal-Fired Boilers. (Venturi Data from Roeck and Dennis, 1979).

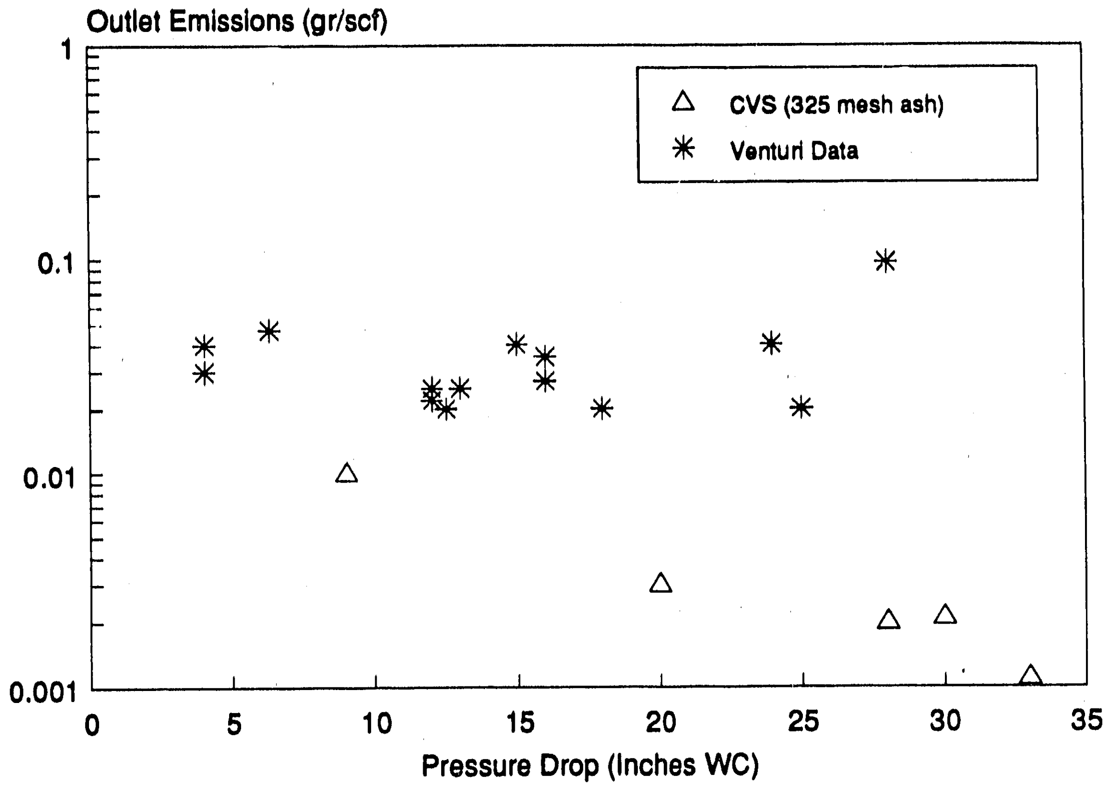

Figure 2-14 Comparison of Mark I CVS Fly Ash Outlet Emissions and Pressure Drop with Published Venturi Scrubber Data for Industrial Coal-Fired Boilers. (Venturi Data from Roeck and Dennis, 1979).

water approaching 20 microns. Ultrasonic treatment, however, results in a size distribution which is very close to that of the de-agglomerated ultra-fine fly ash feed, see Figure 2-16. For most tests not enough fly ash is passed by the CVS to allow a size distribution analysis to be made of the ash collected in the filter. Test #62 was made at a low air mass flow rate and hence at a lower CVS efficiency, and such an analysis was possible. The results are also shown in Figure 2-17: the ash from the downstream filter is also considerably smaller in size than the feed, but is also very similar to the de-agglomerated fly ash feed.

Thus it can be concluded that (1) the size distribution of the ash entering the CVS is considerably smaller than the size distribution measured for the sieved or classified ash; and (2) the size distributions of the ash entering the CVS, the ash collected in the water and the ash collected in the downstream filter are very similar. The latter suggests that the CVS does not have a classic inertial separator type grade efficiency curve, with high efficiency for larger particles and significantly lower efficiency for smaller particles. Rather, it suggests that the CVS has a uniformly high collection efficiency for particles of all sizes (in the range exhibited by the fly ash used) and the mechanism by which a very small fraction of the inlet ash is passed through the CVS is connected with either failure to contact all the inlet air with the water or with re-release of a small fraction of the separated ash from the water. At present there is insufficient evidence to determine the precise mechanisms involved.

2.3 MARK II CVS

The squirrel cage CVS was re-designed in order to retain the same excellent fine particulate collection performance that had been demonstrated by the Mark I CVS, but at a lower pressure drop. The key geometric parameters of the Mark II CVS are given in Table 2-2

2.3.1 Two-Phase Flow Tests

A series of two-phase flow experiments were made to assess the performance of the Mark II CVS. Initial results were encouraging: non-dimensional pressure drops for the Mark II CVS were considerably lower than those for the Mark I CVS. The dry and wet non-dimensional pressure drops (wet pressure drop is for stable liquid layer in CVS) for the Mark II CVS with vortex finder outlets were 7 and 4.5 inlet

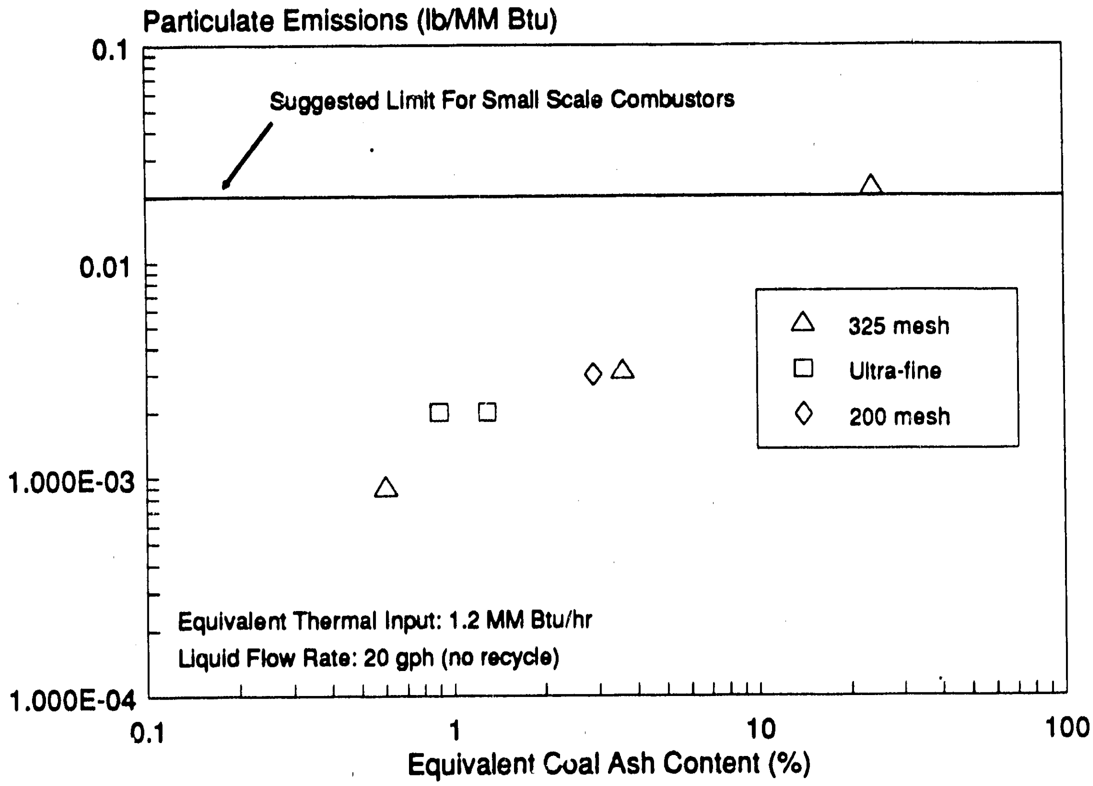

Figure 2-15 Projected Particulate Emissions from a Small Scale Coal Combustor Equipped With a Confined Vortex Scrubber. (Based on Mark I CVS Data for Ultra-Fine Fly Ash.)

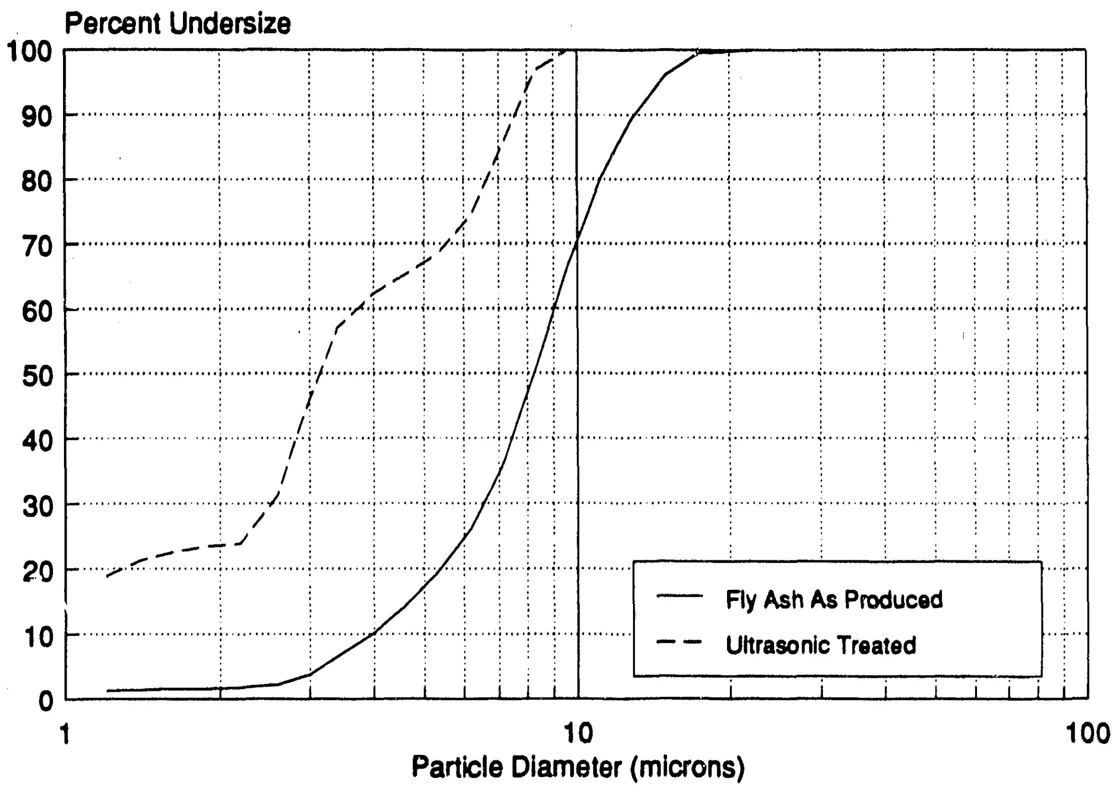

Figure 2-16 Size Distributions of Ultra-Fine Fly Ash As Produced and After Ultrasonic Treatment

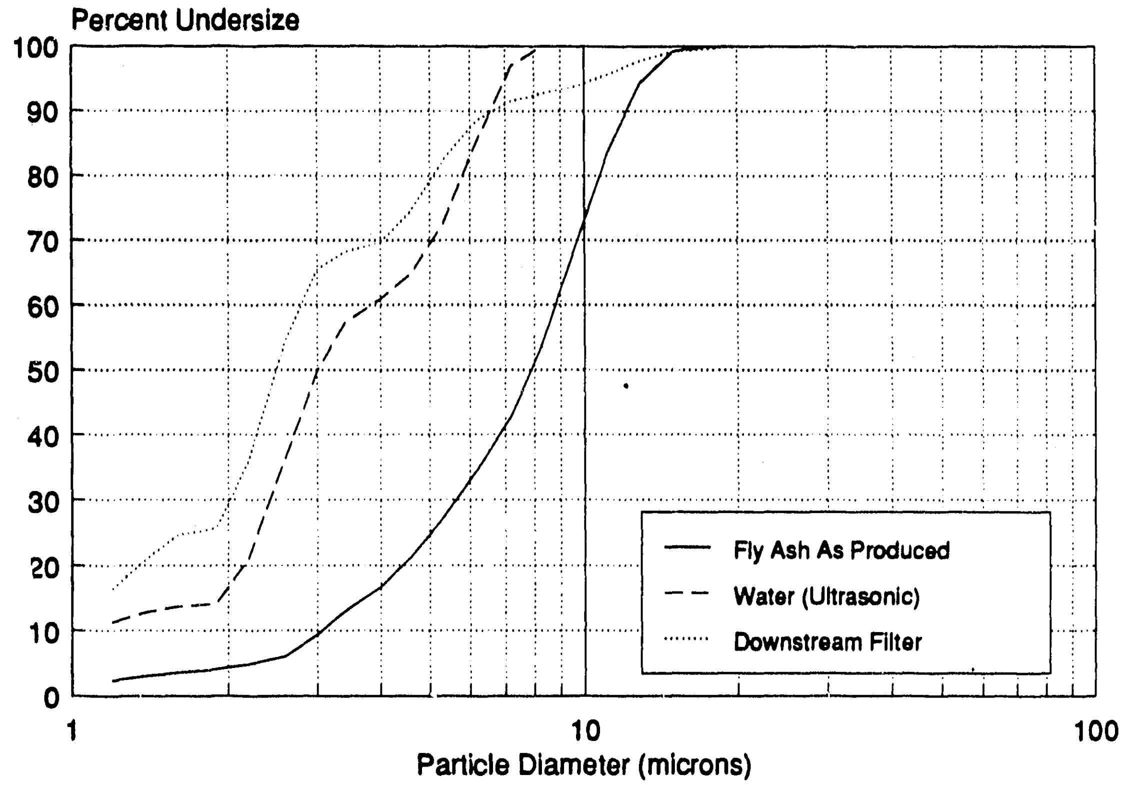

Figure 2-17 Comparison of Fly Ash Size Distributions From Test #62 (1) As Produced; (2) From Recycle Water After Ultrasonic Treatment; and (3) From Downstream Air Filter

dynamic heads, respectively. The corresponding values for the Mark I CVS were 22 and 9 dynamic heads. Once again, the vortex finder exit was superior to the slot exit: the dry and wet non-dimensional pressure drops for the Mark II CVS with slot outlets were 10 and 15 inlet dynamic heads, respectively. The corresponding values for the Mark I CVS were 22 and 28 dynamic heads.

TABLE 2-2

MARK II SQUIRREL CAGE CVS CONFIGURATION

Chamber Internal Diameter	6.50"
Aspect Ratio (L/D)	1.00
Air Inlet Type	Slots
No. of Slots	24
Inlet Slot Height	0.040"
Air Outlet Type	Vortex Finder
Air Outlet Diameter (D_e/D)	0.50
Water Outlet Type	Single Tube, 0.372" ID

The liquid layer was not as stable in the Mark II CVS as in the Mark I, and considerably higher liquid flow rates were required in order to establish an acceptable liquid layer in the chamber. Consequently, the liquid injection velocity in the Mark II CVS was much higher than in the Mark I CVS. The high liquid inlet momentum led to a disruption of the liquid layer in the vicinity of liquid injectors. The diameter of the liquid inlet tubes was increased from 0.125" to 0.250" in order to decrease the liquid inlet momentum at a given flow rate. This change resulted in a much more stable liquid layer, but once again the water flow required (60-120 gph) was significantly higher than that for the Mark I CVS (10-30 gph).

It was also noticed that the airflow in the annular plenum feeding the squirrel cage slots was asymmetric. This was due to the fact the two plenums feeding this annulus were only fed from one side each. In order to rectify the situation, the inlet air supply was further split and each main inlet plenum was fed from both sides. This eliminated the asymmetric flow in the annular plenum.

A further change was made to the fluidized bed feeder in order to increase the stability of the feed of the ultra-fine fly ash. As ash is fed from the feeder the bed tended to settle and an increasingly large nitrogen flow was required in order to obtain the desired ash flow. An electrically driven stirring bar which rotates at 1 rpm was installed within the powder bed. The interaction between the nitrogen flow and the stirrer successfully prevented the bed from settling.

2.3.2 Cleanup Tests

Six cleanup tests were made with the Mark II CVS using the ultra-fine fly ash. The measured collection efficiencies of the Mark I and Mark II CVSs are compared in Figure 2-18. At the same inlet air flow the smaller diameter CVS (Mark I) has a slightly higher collection efficiency, but at a 50 percent higher pressure drop. Measured penetration (1 - efficiency) is plotted as a function of pressure drop for the two designs in Figure 2-19. Thus at the same collection efficiency the Mark II CVS has a substantially lower pressure loss, as desired.

Considerably ash deposition occurred in the annular plenum feeding the squirrel cage slots. After some 15 minutes of testing the deposits had begun to obstruct some of the inlet slots. This problem did not occur in the Mark I CVS tests. The deposits started in strong re-circulation zones which were established in the annulus just upstream of each main air slot inlet. The CVS was re-designed to eliminate this problem.

2.4 MARK III CVS

The re-designed CVS was designated the Mark III CVS. Its principal geometric parameters are given in Table 2-3. The squirrel cage diameter was reduced, while keeping the annular plenum and outlet tube diameters fixed. The annular plenum velocities were thus reduced by a factor of four.

2.4.1 Two-Phase Flow Tests

Non-dimensional pressure drops for the Mark III CVS were similar to those for the Mark II CVS and were again considerably lower than those for the Mark I design. The Mark III CVS was tested only with vortex finder outlets. The dry and wet pressure drops for the Mark III CVS were very similar to those for the Mark II design. Pressure drops for all three CVS designs are plotted against the square of the tangential inlet velocity in Figure 2-20. The liquid flow rates required to obtain a stable, thick and

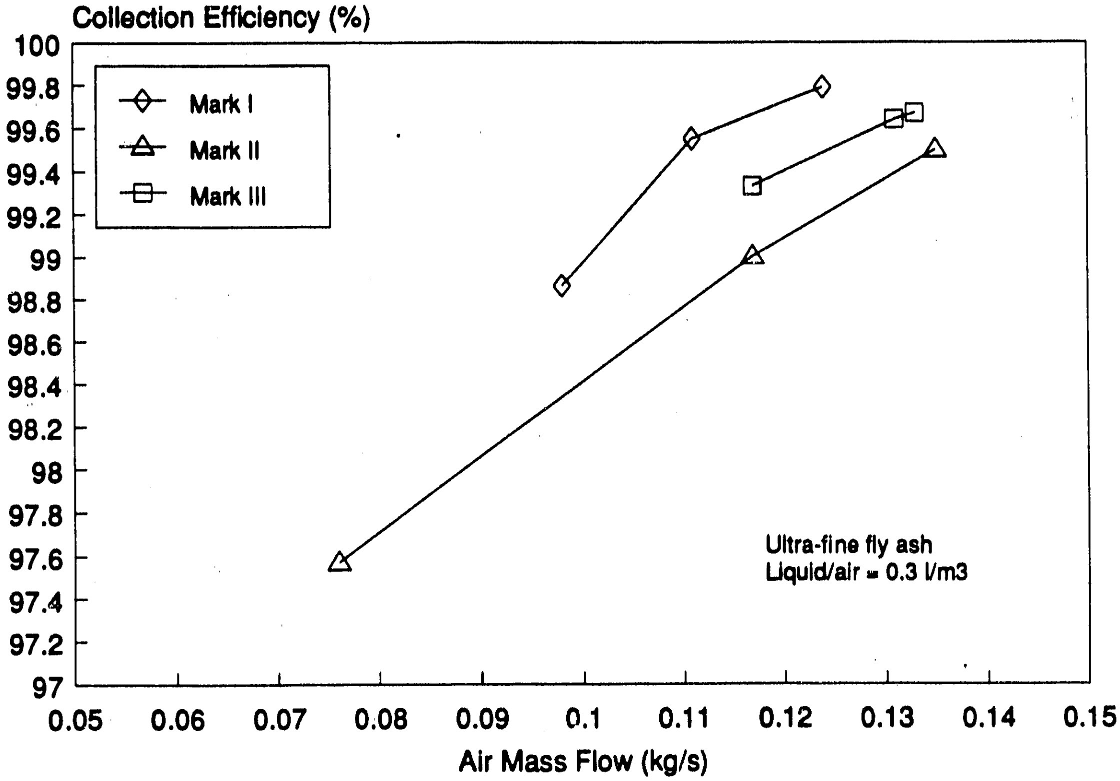

Figure 2-18 Comparison of Cleanup Performance for Three CVS Designs With Ultra-Fine Fly Ash as a Function of Air Mass Flow Rate

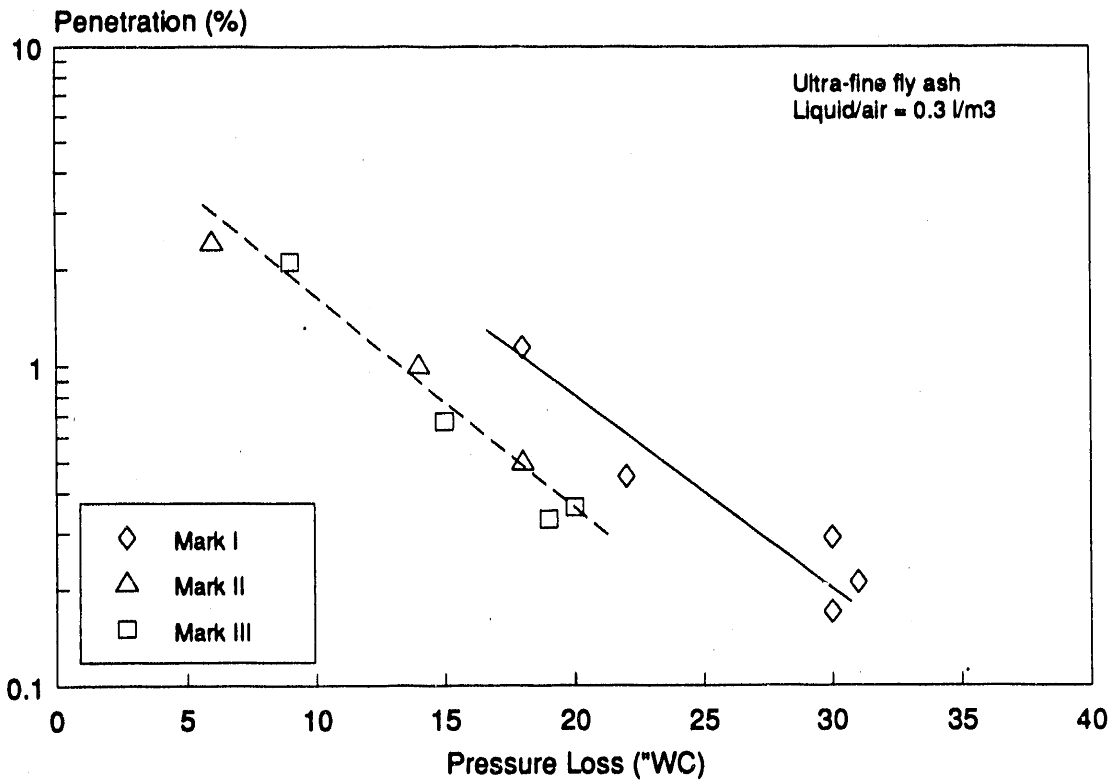

Figure 2-19 Comparison of Cleanup Performance for Three CVS Designs With Ultra-Fine FLy Ash as a Function of Pressure Drop

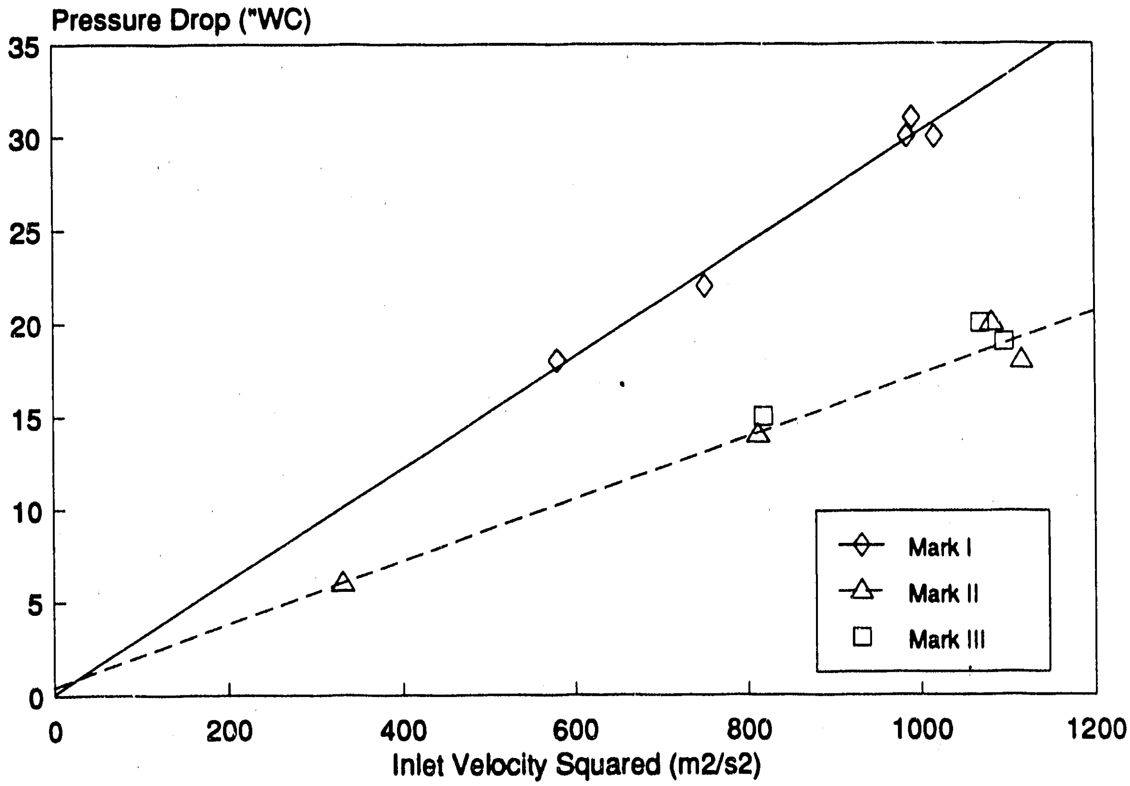

Figure 2-20 Comparison of Pressure Drop With Liquid Layer Present For Three CVS Designs as a Function of Inlet Velocity Squared

frothy liquid layer in the Mark III design were comparable to those for the Mark I CVS and were considerably lower than those required for the Mark II design. The re-circulation zones in the annular plenum feeding the squirrel cage inlet slots were much smaller and less intense than in the Mark II design, as intended.

TABLE 2-3

MARK III SQUIRREL CAGE CVS CONFIGURATION

Chamber Internal Diameter	5.50"
Aspect Ratio (L/D)	1.18
Air Inlet Type	Slots
No. of Slots	24
Inlet Slot Height	0.040"
Air Outlet Type	Vortex Finder
Air Outlet Diameter (D_e/D)	0.59
Water Outlet Type	Single Tube, 0.372" ID

2.4.2 Fly Ash Cleanup Tests

A comprehensive series of cleanup tests were made with the ultra-fine fly ash. The collection performance of all three CVS designs for ultra-fine fly ash is shown in Figure 2-18 as a function of air flow rate and in Figure 2-19 as a function of pressure drop. The data indicates that for a given air mass flow rate an increase in collection efficiency is obtained as the squirrel cage diameter is decreased. This trend is confirmed in Figure 2-21, which is a semi-log plot of penetration against the inlet radial acceleration. The radial acceleration used here is based on the nominal tangential inlet velocity (obtained from mass flow considerations) and the squirrel cage radius. The penetration data for all three CVS designs collapse well when plotted in this manner, indicating an exponential relationship between collection efficiency and radial acceleration of the form:

$$\eta(\%)=100-A\exp(-\frac{a_r}{B})$$

where η is the collection efficiency in percent, A and B are constants and a_r is the radial acceleration defined as above. If the radial acceleration is calculated in m/s^2 the values of A and B for the ultra-fine

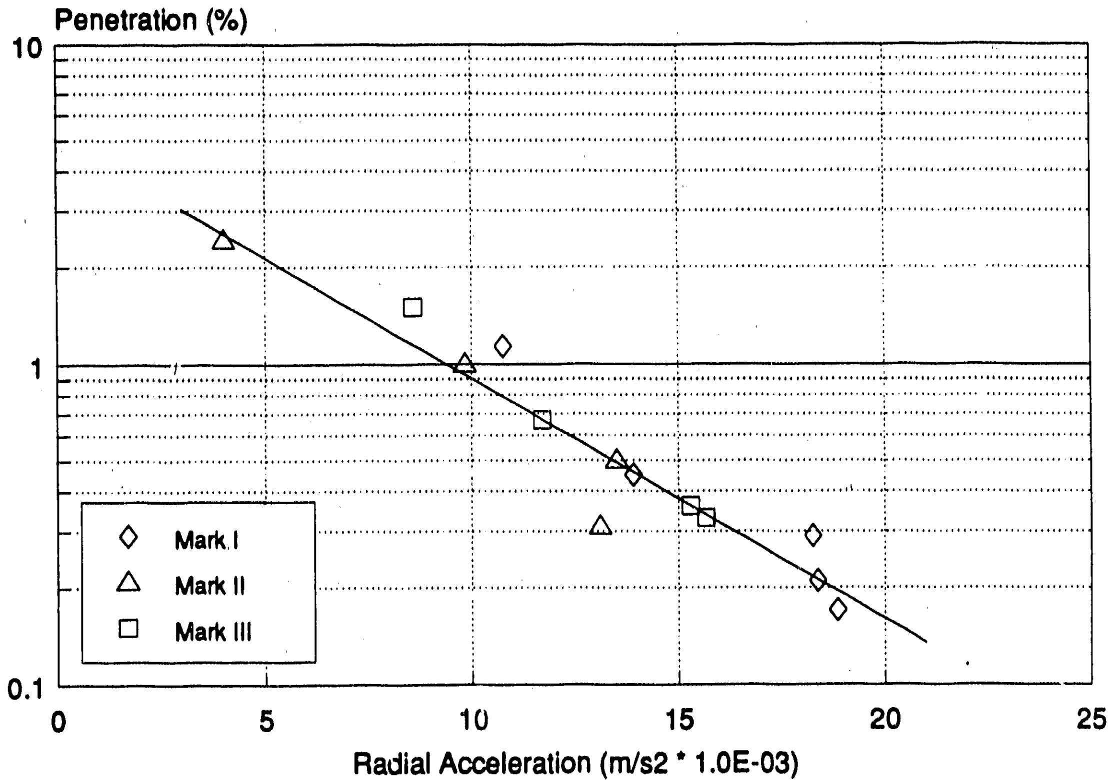

Figure 2-21 Correlation of Cleanup Data for Three CVS Designs

fly ash are 5.10 and 5777, respectively. If the data for the coarser fly ash tests (200 and 325 mesh) in the Mark I CVS is examined in the same manner, a slightly different correlation is obtained, see Figure 2-22. The values of A and B for the larger fly ash are 5.16 and 5081, respectively. The results with the larger dust show slightly but consistently higher collection efficiency than for the ultra-fine ash.

The deposition problem that had been observed with the Mark II CVS was again noticed with the Mark III design. A longer duration test was run to examine this problem. After 30 minutes of ultra-fine fly ash feed the CVS pressure drop began to increase due to inlet slot plugging. After 40 minutes the CVS pressure drop had doubled and considerable deposition was observed in the annular plenum chamber. The deposits appeared to start building up in the plenum corners and appeared to be growing counter to the main flow in the plenum, probably in secondary flow regimes. The overall collection efficiency for this test was still 99.52 percent, despite the inlet slot plugging that occurred.

2.4.3 Effect of Liquid Layer Type

Two distinct types of liquid layer have been observed in the squirrel cage CVS chamber. These may be characterized in qualitative terms as follows:

Thick Layer: The liquid layer is 1-1.5 cm in thickness and appears very frothy. Foamy water flows out of the main CVS chamber into the liquid out-take chamber. The CVS clean air exit flow has almost zero swirl and any liquid in the main air outlet tube flows along the bottom of the tube.

Thin Layer: The liquid layer is much thinner, approximately 0.1-0.3 cm and does not appear frothy. The water flowing out of the main CVS chamber into the liquid out-take chamber is not foamy. The CVS clean air exit flow has significant swirl and any liquid in the main air outlet tube flows in spirals on the tube walls.

All experiments to date have been for a thick layer, which has been seen as the desired configuration. It is (qualitatively) obvious that the degree of air/water interaction in the thick layer is greater than in the thin layer (this is evidenced not only by the degree of bubbling/foaming, but also by the fact that the inlet tangential momentum of the air has been effectively reduced to zero). On occasion

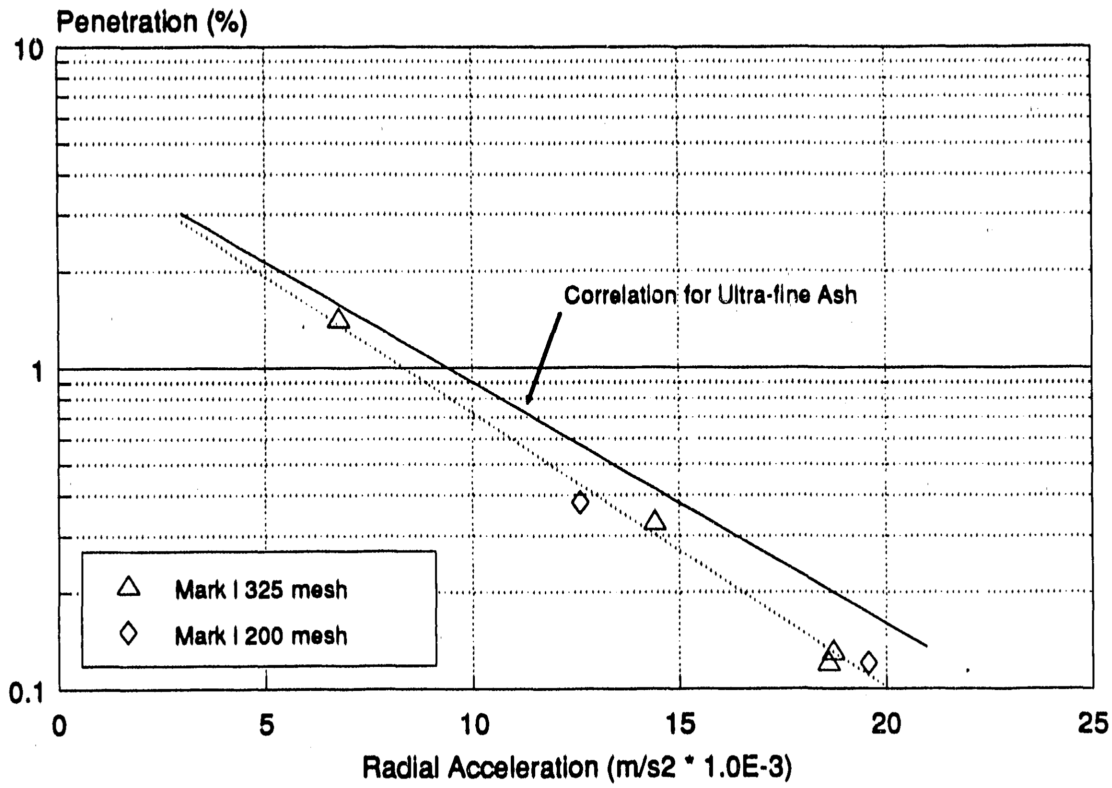

Figure 2-22 Comparison of Correlations for Ultra-Fine Fly Ash and for Larger Fly Ash

a thick layer will break down and will form a thin layer: this can happen if the air flow is quickly and significantly reduced and then increased to the original value, or if the inlet water flow is not uniformly distributed across the CVS chamber. In such a situation it is necessary to increase the water flow to a high value (say three to four times the design flow) for a short time until the thick layer is re-established, at which point the water flow can be reduced to its normal value.

A series of experiments were conducted to determine the relative cleanup performances of the two layer types. The results are shown in Figure 2-23. Though there is a clear performance improvement with a thick liquid layer, the thin liquid layer still gave better than 97 percent collection of the ultra-fine fly ash. Pressure drops for the two layer types are comparable.

One cleanup test was also made using the ultra-fine fly ash with no liquid layer present in the CVS. The measured collection efficiency was 75.2 percent. This is comparable to the result obtained for the fine alumina powder with no liquid layer, see Section 2.2.1 above.

2.4.4 Sub-Micron Alumina Cleanup Tests

The fact that better than 99 percent cleanup was obtained for ash in which 10 percent of the mass was present in particles of less than 1 micron in diameter implies that the CVS has extremely efficient collection performance for sub-micron particles. This was tested explicitly by feeding 0.3 micron alumina particles into the Mark III CVS.

As discussed above, the filter material used to filter the CVS outlet flow in these experiments is rated at 99.8 percent collection down to 1 micron particles. Accordingly, the filter collection performance for the 0.3 micron alumina particles was checked by feeding a known quantity of the alumina dust directly into the CVS outlet piping and hence into the filter. Between 80 and 90 percent collection was measured in repeat tests. The lower of these values was then used to correct the CVS cleanup data for two tests made with the 0.3 micron alumina. The corrected data showed 98.20 and 97.88 percent capture of 0.3 micron alumina particles in the CVS for the two tests. This confirms the implied result from the ultra-fine fly ash cleanup tests and again proves the CVS concept for cleanup of very fine particulate material.

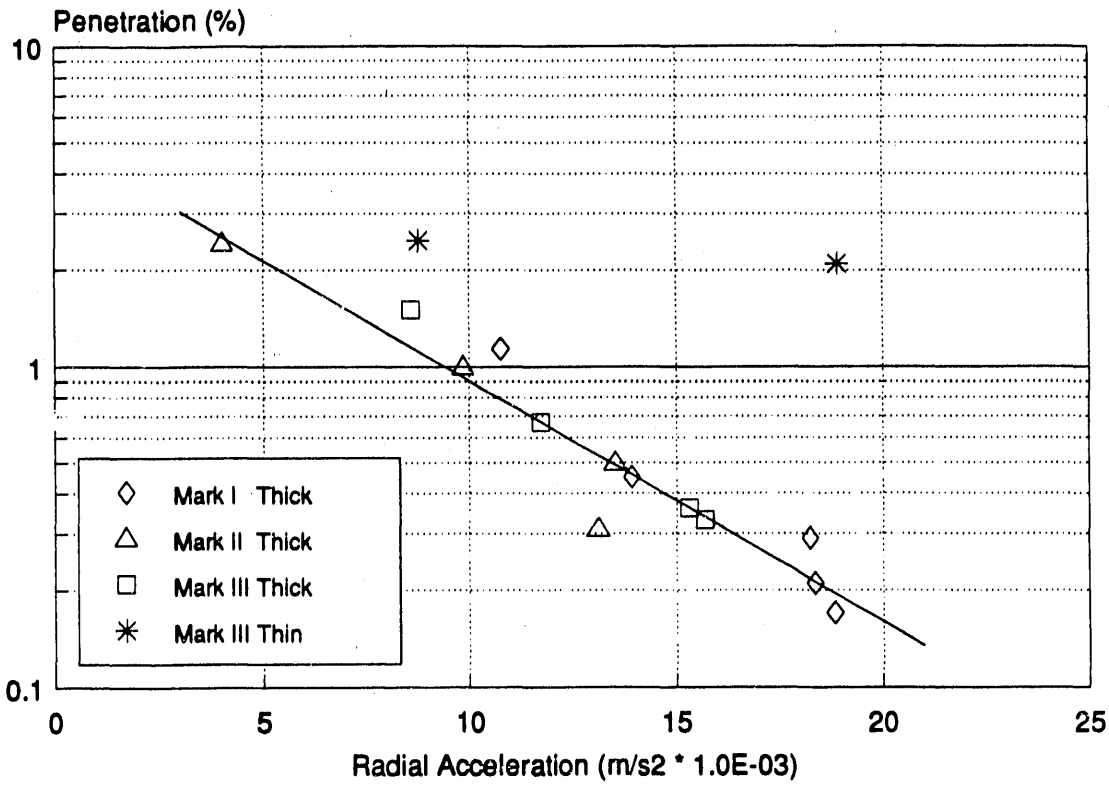

Figure 2-23 Comparison of Cleanup Performance of Thick and Thin Liquid Layers in Mark III CVS

3.0 CONCLUSIONS AND PLANS FOR FUTURE WORK

A comprehensive series of cleanup experiments have been made for three CVS configurations. All three show extremely efficient capture of ultra-fine fly ash (d_{10}, d_{50}, d_{90} = 1, 3, 8 microns as fed). Typical collection efficiencies are greater than 99 percent and have been measured at up to 99.8 percent. The Mark I CVS was successfully re-designed to produce the same very efficient fine particulate collection performance at a lower pressure drop. The current CVS configuration produces 99.4 percent cleanup of ultra-fine fly ash at the design air mass flow (1 MM BTU/hr combustor exhaust flow) at a pressure drop of 12 "WC with a liquid/air flow ratio of 0.3 l/m^3. Tests have also been made with fine silica and alumina dust, as well as larger grinds of fly ash (200 and 325 mesh). Two tests were also made with 0.3 micron alumina particles: 98 percent collection was measured. Thus unlike other scrubbers, the CVS has excellent collection performance for sub-micron particles. In addition, the collection performance of the CVS was found to be insensitive to dust loading and to liquid/air flow ratio.

Results to date indicate that the size distributions of the ash entering the CVS, the ash collected in the water and the ash collected in the downstream filter are very similar. This suggests that the CVS does not have a classic inertial separator type grade efficiency curve, with high efficiency for larger particles and significantly lower efficiency for smaller particles. Rather, it suggests that the CVS has a uniformly high collection efficiency for particles of all sizes (in the range exhibited by the fly ash used) and the mechanism by which a very small fraction of the inlet ash is passed through the CVS is connected with either failure to contact all the inlet air with the water or with re-release of a small fraction of the separated ash from the water. At present there is insufficient evidence to determine the precise mechanisms involved.

The collection efficiency data for three CVS chambers of different sizes has been successfully correlated by a simple exponential relationship between the collection efficiency and the radial acceleration in the CVS chamber.

Outstanding issues include the problem of ash deposition in the annular plenum feeding the squirrel cage slots. Future tests will address this issue, as well as the effects of liquid properties on collection performance. In addition, a liquid filtration system will be added to enable a complete dust mass closure to be made for each test.

In summary, a comprehensive series of simulated flue gas cleanup experiments made with a confined vortex scrubber have proved this novel cleanup concept for fine particulates. Greater than 99 percent capture of extremely fine fly ash at low pressure drops and liquid flow rates has been demonstrated. 98 percent collection has been demonstrated for 0.3 micron particles. Projected particulate emissions from a small scale coal combustor equipped with a confined vortex scrubber would be well below the proposed emissions limit of 0.02 lbs/MM BTU.

REFERENCES

Martin, A. E., 1981, *Emission Control Technology for Industrial Boilers*, Noyes Data Corporation, Park Ridge, New Jersey.

Roeck, D. R., and Dennis, R., 1979, *Technology Assessment Report on Industrial Boiler Applications: Particulate Collection*, US EPA 600/7-79-178h, December 1979.

END

DATE
FILMED
3/26/92

I