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CONFINED VORTEX SCRUBBER

QUARTERLY TECHNICAL PROGRESS REPORT

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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

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TABLE OF CONTENTS

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. This is to be accomplished using a novel particulate removal device, the Confined Vortex Scrubber (CVS). The CVS consists of a cylindrical vortex chamber with tangential flue gas inlets. The clean gas exit is via tangent slots in a central 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.

This is a report of technical progress during the second quarter of this program. During this quarter a comprehensive series of two phase flow experiments have been conducted on a variety of CVS configurations. Results for

the initial CVS design, which has two tangential air inlet locations, indicated that the pressure drop of the device had been well controlled by suitable design modifications. Refinements in system design progressively reduced the device pressure drop to approximately one third that of a conventional reverse flow cyclone separator operating at the same inlet velocity. The device pressure drop was also lower with a stable liquid layer confined within the chamber than without such a layer.

Initial water addition experiments indicated that a sheet of water could indeed be established and contained within the chamber and that the proposed water removal mechanism via the chamber end-wall secondary flows was effective. However, subsequent experiments indicated three areas of concern: (1) low levels of liquid containment; (2) a high through-flow of liquid, leading to liquid handling problems in the water out-take chamber and liquid loss; and (3) atomization of the liquid layer near the air inlets at high air inlet velocities, again leading to liquid loss.

The first problem was considered the most significant of the three. The liquid layer was thin and the inlet air jets penetrated the liquid layer completely, leading to relatively poor air/liquid interaction. In other words, the inlet jets were not submerged, as desired. The lack of submerged inlet jets and of a vigorous air/liquid interaction suggested that the desired level of particulate removal may not be obtained.

Accordingly, a re-design of the CVS was undertaken. The modified design has 24 tangential slot inlets as opposed to the two in the initial CVS design. Preliminary tests of the new design (the 'squirrel cage' design) indicate that a very different flow field exists in the chamber. The inlet air jets are now clearly submerged beneath a much thicker liquid layer than had been observed for the initial design. There is an extremely vigorous interaction between the air and the liquid: the liquid layer appears thick and frothy in nature. The liquid mass contained increased dramatically to a maximum of approximately 20 percent of chamber volume. Once again, the pressure drop was a minimum when a stable liquid layer was established. Other significant differences observed with the squirrel cage CVS 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. It should be noted that the squirrel cage tested to date is undersized for the design mass flow rate: the new chamber was sized such that an existing CVS model could be used as a plenum chamber to feed the squirrel cage CVS.

In summary, preliminary results obtained for a 4.25" ID CVS of squirrel cage design indicate 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. However, these results are of a preliminary nature and must be confirmed for a CVS chamber of size appropriate to the design mass flow.

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). The CVS 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 tangent slots in a central 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.

2.1.2 Progress Prior to This Reporting Period

During the reporting period previous to this one a CVS design geometry and a number of parametric variations were defined and the necessary hardware was designed and fabricated. The initial CVS configuration is shown in Figure 2-2. A modular design approach was adopted in order to allow rapid and simple modification of the CVS chamber aspect ratio and of air and water inlet and

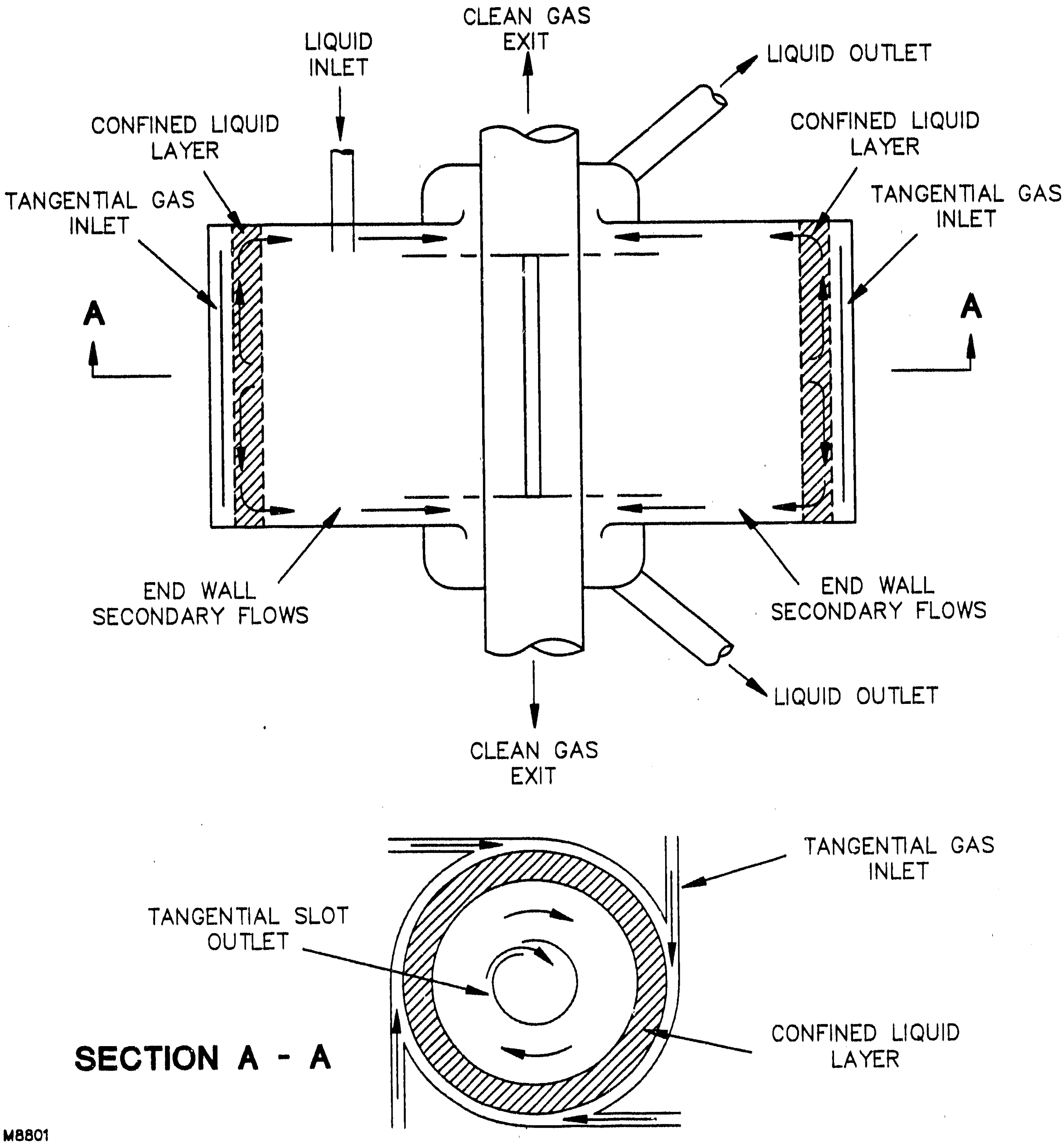

Figure 2-1 Schematic Diagram of Confined Vortex Scrubber

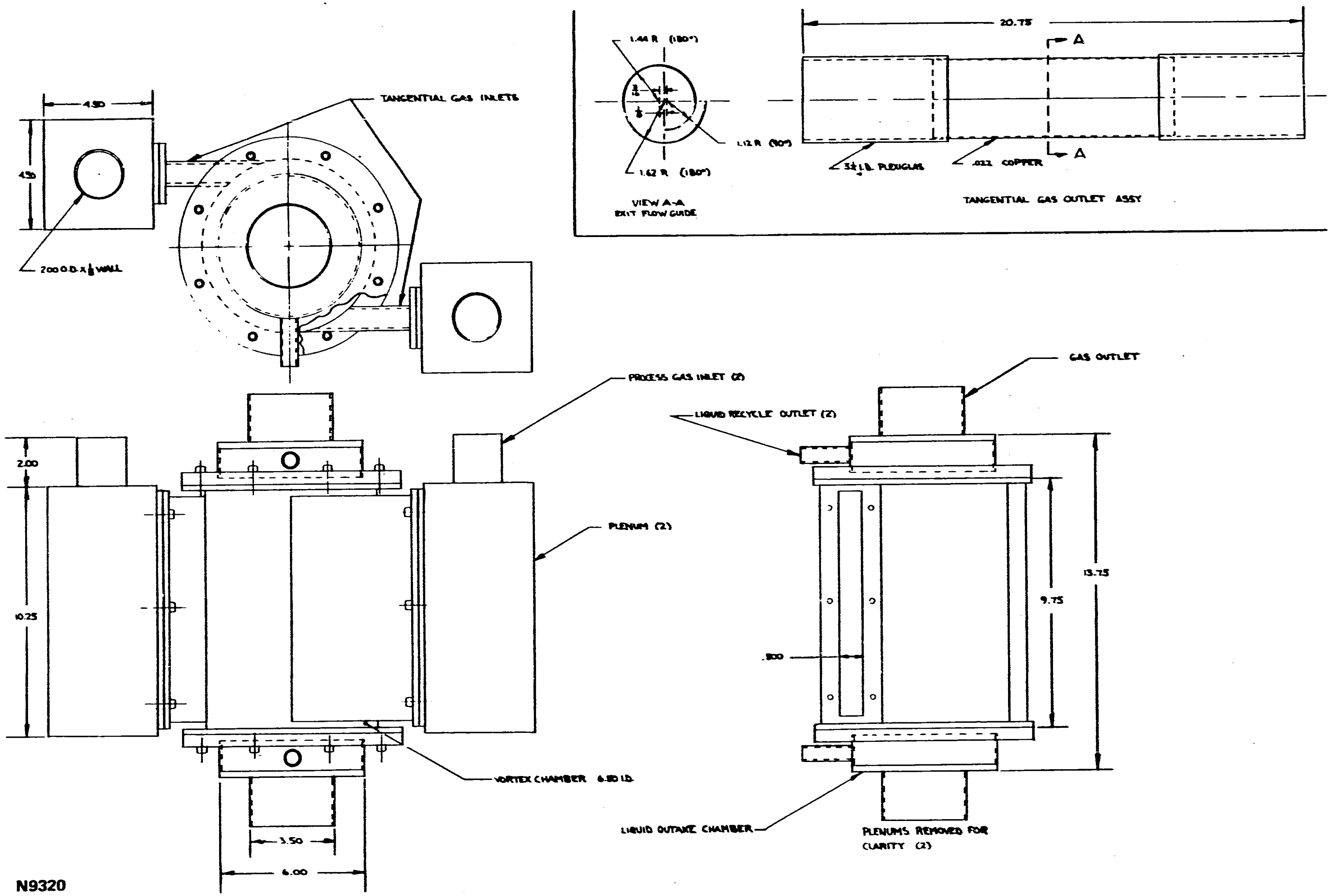

Figure 2-2 Initial CVS Configuration

outlet geometries. The experimental hardware was assembled and installed at ARL's Haverhill, Massachusetts test facility. A schematic diagram of the experimental arrangement is shown in Figure 2-3.

Initial aerodynamic testing of the CVS experimental hardware indicated that the CVS slot exit tube design produced significantly lower pressure drops that a conventional vortex finder type exit tube. The exit tube size was also demonstrated to have a dramatic effect on device pressure drop. Changing the exit tube diameter from one half to one quarter of the main chamber diameter producing a tripling of the device pressure drop. Reducing the slot height of the air inlet was also found to reduce the non-dimensional pressure drop of the device. Further refinements in system design progressively reduced the device pressure drop to less than half that of a conventional reverse flow cyclone separator operating at the same inlet velocity. For reference, the configurations tested are listed in Table 2-1.

Preliminary water addition experiments indicated that a sheet of water could indeed be established and contained within the chamber and that the proposed water removal mechanism via the chamber end-wall secondary flows was effective. However, some of the input water was being lost via the clean gas exit. The mechanism responsible for this loss appeared to be related to management of the water flow in the water out-take chamber.

2.2 INITIAL CVS CONFIGURATION

2.2.1 Initial Water Addition Experiments

Initial water addition experiments were made for the $L/D = 1.5$ chamber with the flow guide slot exit tube ($D_e/D = 0.50$). The water was introduced initially via a single 0.125" OD stainless steel pipe located on axial

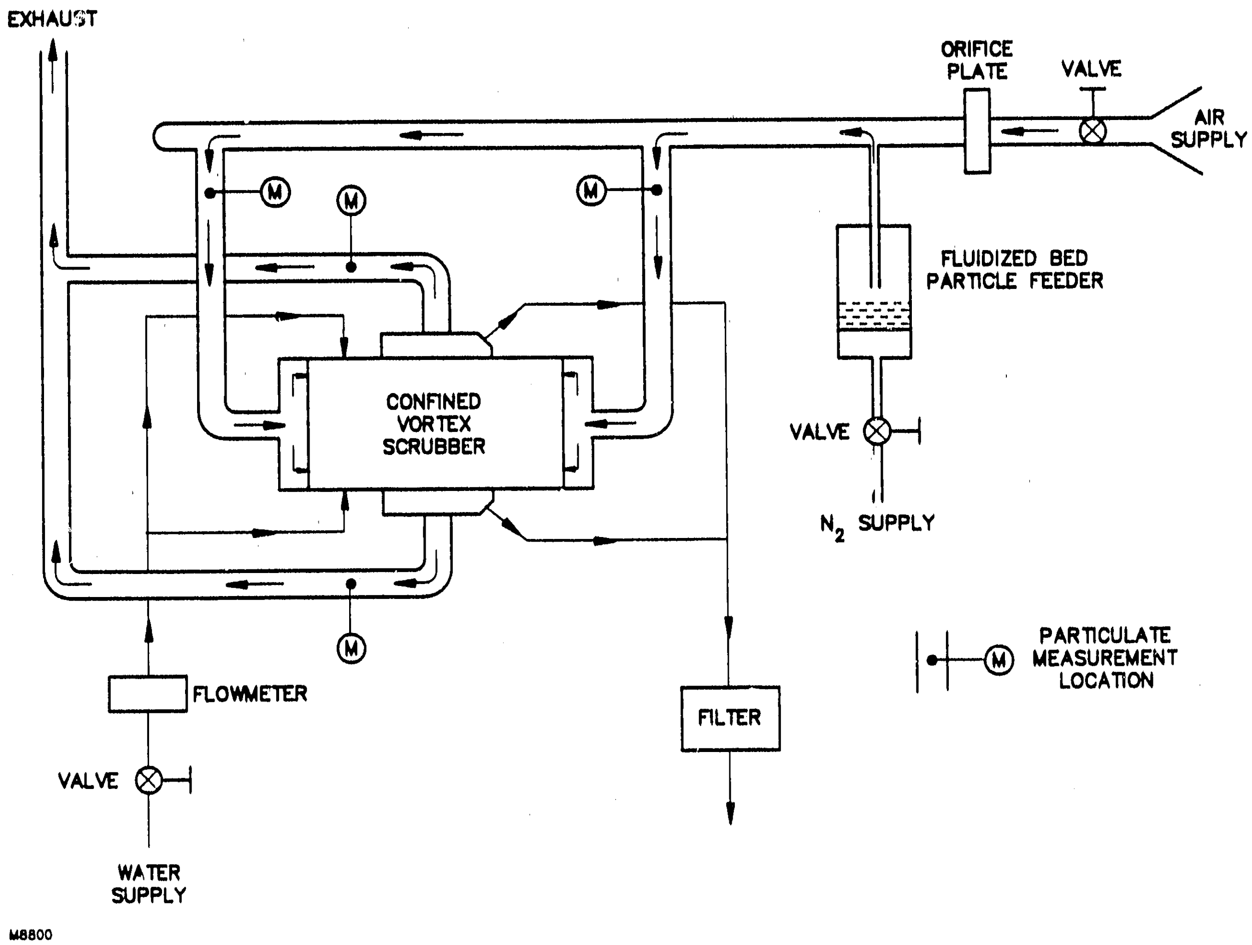

Figure 2-3 Schematic Diagram of CVS Experimental Arrangement

TABLE 2-1

CVS CONFIGURATIONS FOR AERODYNAMIC TESTS

Configuration	L/D	D_e/D	S/D	Air Exit	Water Exit
A	1.50	0.25	0.077	S	W1
B	1.50	0.25	0.077	V	W1
C	1.50	0.50	0.077	S	W1
D	1.50	0.50	0.045	S	W1
E	1.50	0.50	0.045	S	W2
F	1.50	0.50	0.035	S	W2

Legend

L = Chamber Length
D_e = Exit Tube Diameter
D = Chamber Diameter
S = Inlet Slot Height

Air Exit:
S = Slot Exit
V = Vortex Finder Exit

Water Exit:
W1 = One 0.372" ID Exit Tube
W2 = One 0.372" Exit Tube + Three 0.627" Exit Tubes

centerline of CVS chamber close to the chamber wall and subsequently through two such tubes, one being introduced from either end of the CVS chamber. Initial observations were that a liquid layer could indeed be contained within the chamber, but that a considerable fraction of the input water flow exited via the central clean gas exit tube. Initial estimates were that this fraction was as much as 50 percent of the input water. Careful visualization of the CVS central exit tube indicated that the water appeared to be entering the clean gas exit at either end of the slot. Use of pulses of water as a flow visualization agent revealed that the loss mechanism was actually water flowing back into main chamber from water out-take chamber, see Figure 2-4.

In order to address this problem, additional water outlet tubes were added to the water out-take chambers. The initial water exit design had one 0.372"

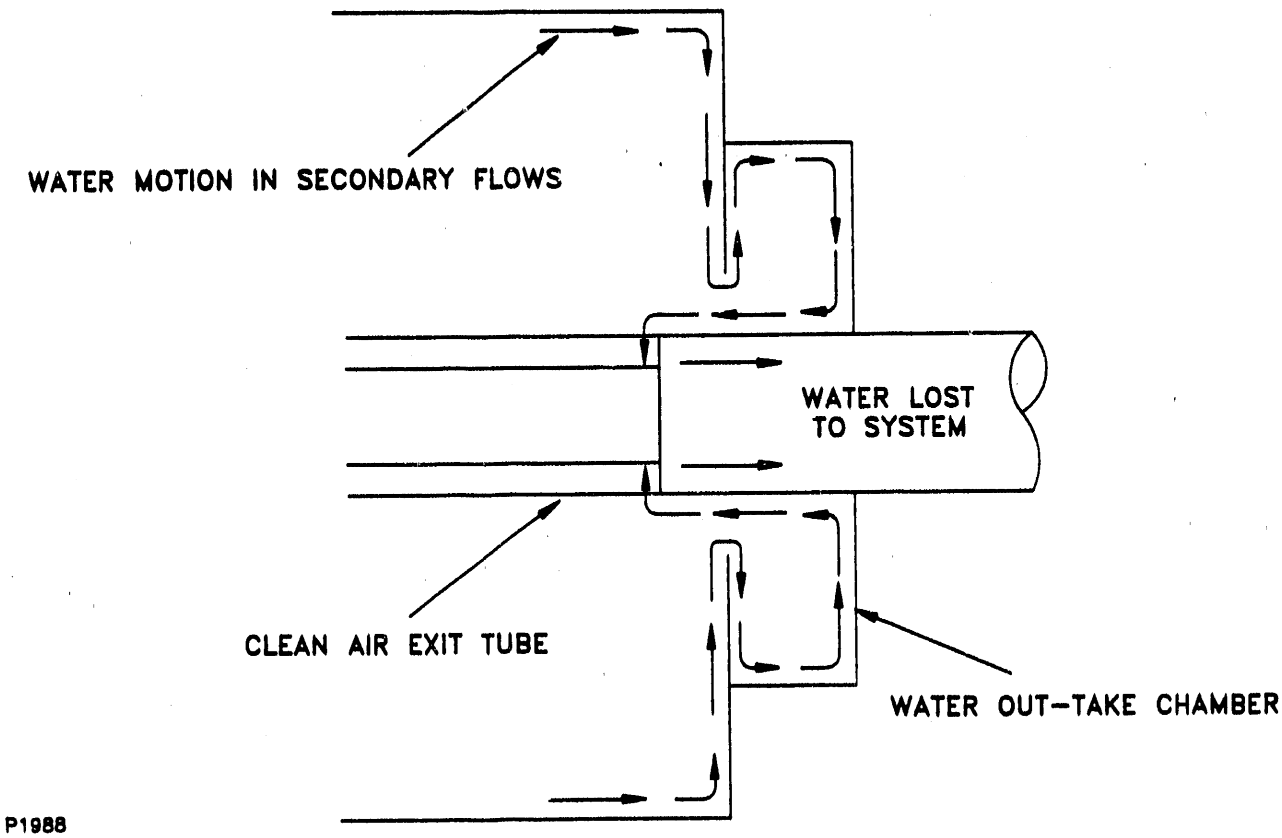

Figure 2-4 Water Loss Mechanism via Clean Gas Exit

ID exit tube per chamber (W1 exit). The revised water exit design (W2 exit) had three 0.627" ID exit tubes in addition to the single smaller tube. The effect of this change on the water loss can be seen in Figure 2-5. In this figure, the water loss, expressed as a percentage of the total water input, is plotted as a function of the input water flow rate for the two different water exit arrangements. A dramatic improvement in the water loss was achieved by adopting the W2 exit arrangement. At one condition, the loss was eliminated entirely. The reason for the improvement was that the water entering the out-take chamber is now removed from that chamber quickly before it has a chance to reach the outer surface of the center tube and hence re-enter the main chamber.

The mechanism for water removal from the main chamber via the endwall boundary layer secondary flows proved very effective. In fact, the removal mechanism was so effective that a greater input flow rate of water than expected was required in order to establish a stable liquid layer within the chamber. At input water flow rates lower than this minimum, two incomplete layers were established at either end of the chamber. The minimum flow rate required to establish a stable liquid layer is plotted as a function of the tangential air inlet velocity in Figure 2-6.

In general for a given air mass flow rate, the device pressure drop was lower with a stable liquid layer in the chamber than without such a layer. In Figure 2-7 the non-dimensional pressure drop and the water loss rate are both plotted against the input water flow rate. It is interesting to note that the minimum pressure drop is measured for the case where there is no water loss at all.

Liquid containment is plotted as a function of water input flow rate in Figure 2-8. The liquid containment is expressed as a percentage of the chamber

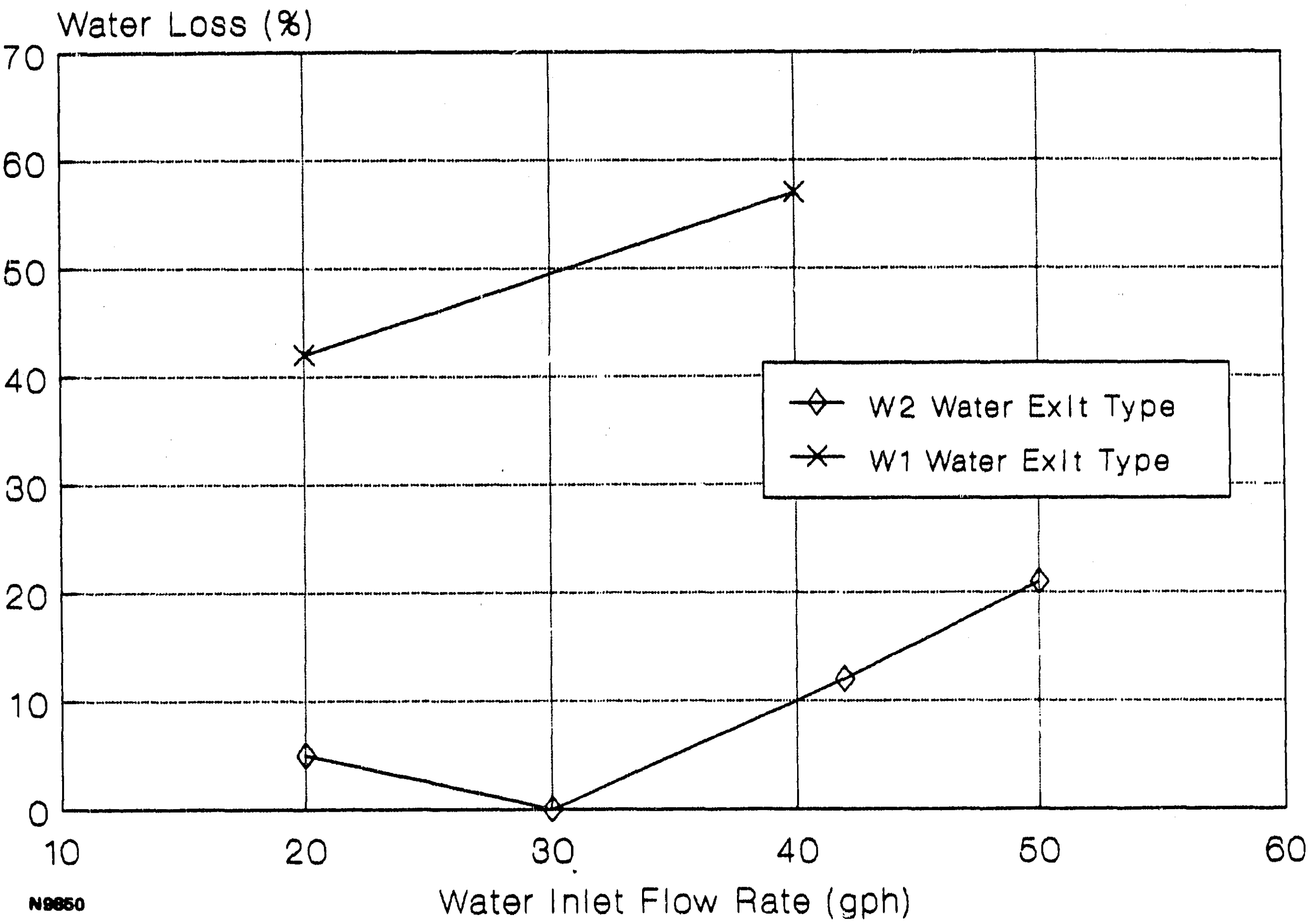

Figure 2-5 Effect of Water Outlet Area on Water Loss via Clean Gas Exit for Initial CVS Design

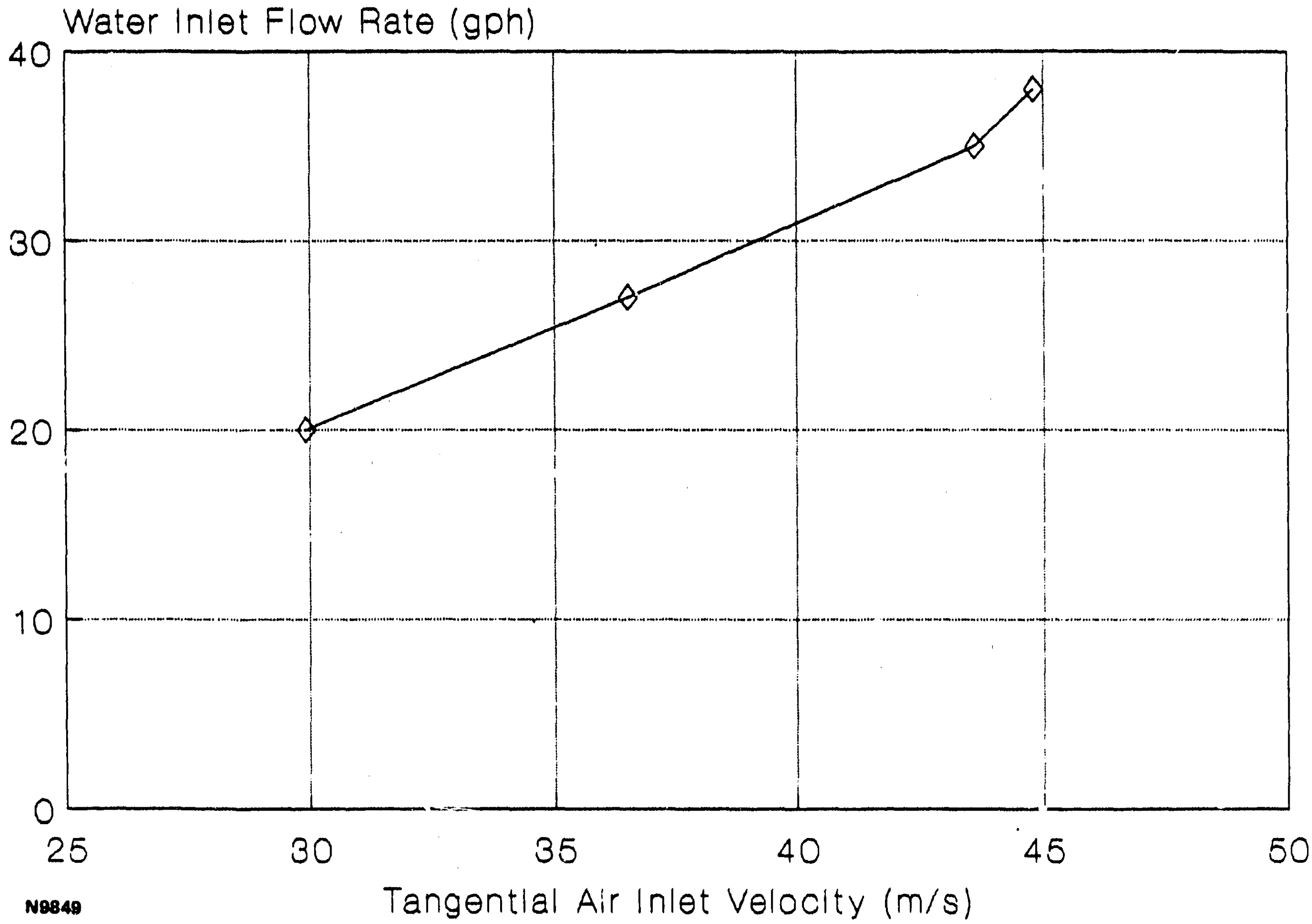

Figure 2-6 Minimum Input Water Flow Rate Required to Establish Stable Liquid Layer as a Function of Air Inlet Velocity for Initial CVS Design

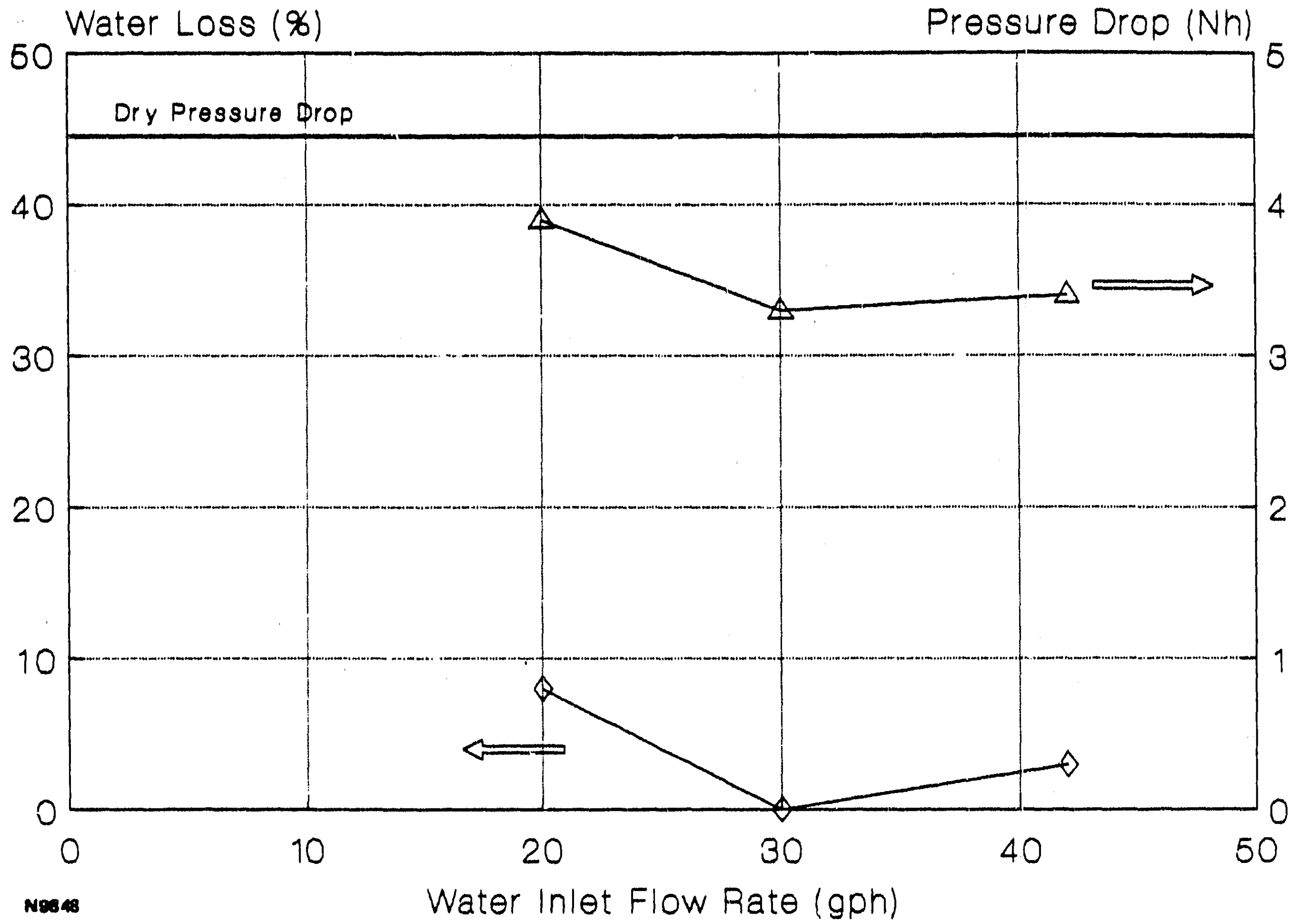

Figure 2-7 Non-Dimensional Pressure Drop and Liquid Loss Rate as a Function of Water Input Flow Rate for Initial CVS Design, Configuration F

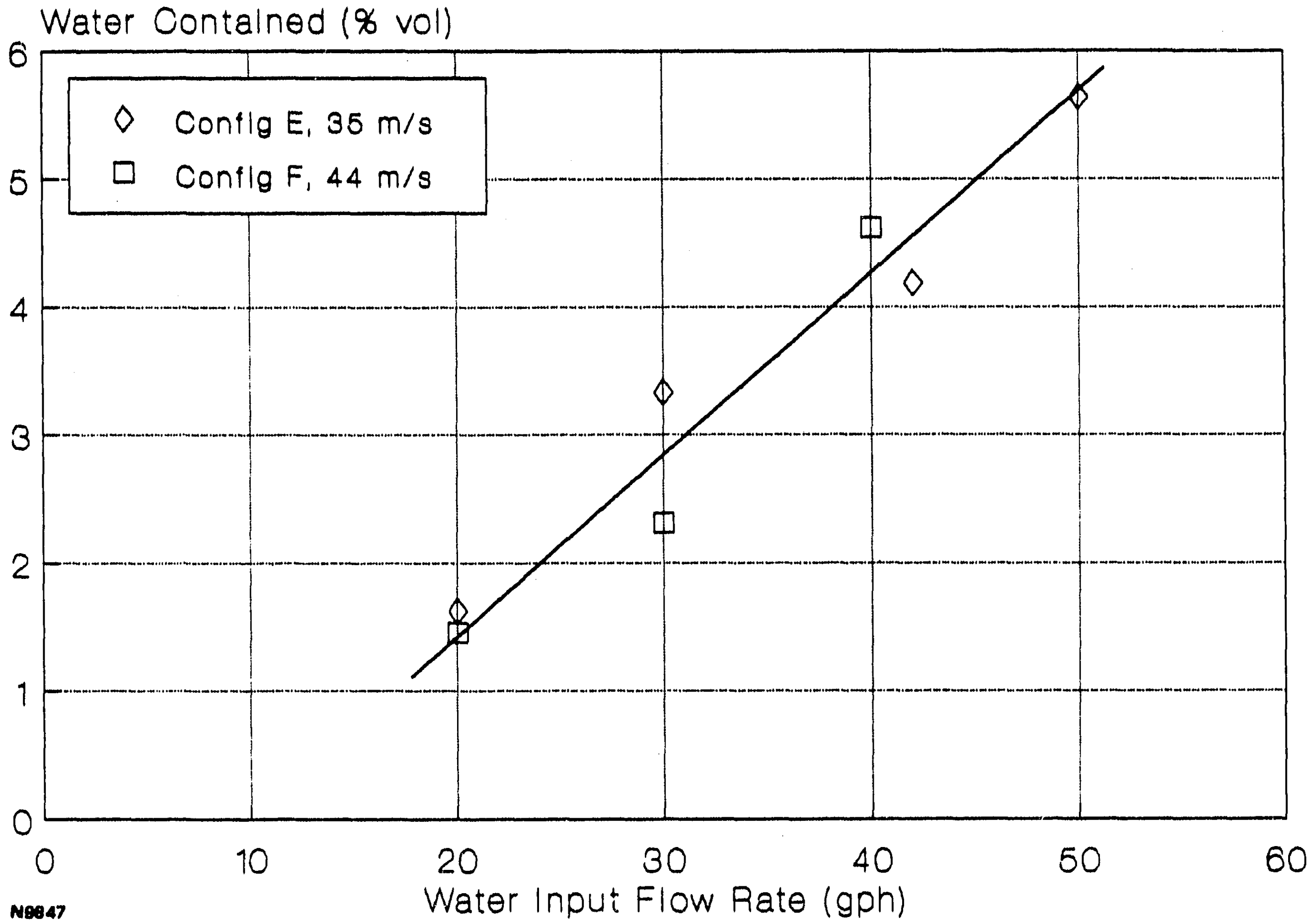

Figure 2-8 Mass of Liquid Contained, Expressed as a Percentage of Chamber Volume, as a Function of Water Input Flow Rate for Initial CVS Design

volume. At water flow rates at which the liquid loss is small, the containment is only 3 - 4 percent. This is considerably lower than the containment measured in related experiments at MIT (Lewellen and Stickler, 1972), where containments of order 10 - 12 percent were achieved. One major difference between the CVS and the previous work at MIT is that in the CVS there is a net through-flow of liquid. In the MIT experiments the aim was to maximize the containment and prevent all liquid outflow. The requirement for a controllable through-flow adds significant complexity to the problem.

Thus two important issues to be resolved were (1) the low water containment and (2) the water loss via the clean gas exit. Both these issues are related to the high water through-flow. The containment is low because of the efficiency of the endwall liquid removal approach and the water loss problem is also related to the high rate of water flow through the out-take chambers, leading to some water re-entering the main chamber on the outside of the central exit tube and being lost to the system. A series of experiments were undertaken to investigate the control of the water outflow in order to increase the liquid containment and to control the water loss mechanism. These experiments and their results are described below.

2.2.2 Endwall Modifications to Control Liquid Outflow

The approach taken to control the endwall water outlet flow was to energize the endwall boundary layer in order to reverse the direction of the secondary flows (i.e. to drive the endwall boundary layer flow radially outward). This approach was utilized in the liquid containment experiments at MIT (Stickler et al., 1974): gas with high angular momentum was injected into the boundary layer on the exhaust port end wall in order to minimize the loss of water due to end wall secondary flow effects. In order to accomplish this, the CVS chamber endwalls were modified to include four tangential jets, as illustrated schematically in Figure 2-9. The jet diameter was 0.125", and the jets were located midway between the chamber walls and the inner edge of the water exit annulus. In the initial design the jets were supplied with air from the main inlet plenums, see Figure 2-10. Testing of this configuration showed no beneficial effect of the endwall jets. The momentum flux through the endwall jets was apparently insufficient to energize the endwall boundary layer.

The endwall jets were therefore disconnected from the main air inlet plenums and connected to a regulated shop air supply. Tests were conducted for steadily increasing endwall mass flows, until the endwall jets were choked. No improvement in water outflow characteristics, water loss, mass of water required to establish a stable liquid layer or mass of water contained was observed. In fact, at high endwall jet mass flows, the water loss at the endwalls increased significantly, due to liquid spraying where the high velocity jet impacted the liquid layer on the chamber walls. Tests were also conducted for both water outflow geometries (W1 and W2) in order to modify the net axial air flow through the water exit annulus. No effect was detected.

The poor performance of the endwall jets at modifying the secondary flows was unexpected, given the fact that the same technique had been used successfully in the MIT experiments. A significant difference between the two experiments, however, is the fact that there is a net through-flow of liquid in the CVS. A brief experiment was conducted in which the water outlet annulus at either end of the CVS chamber was closed off, by inserting a Plexiglas ring. In this manner the current experiment was made to simulate conditions in the MIT experiment. Under these conditions the endwall jets were seen to have a beneficial effect. The mass of liquid contained was increased over that for the

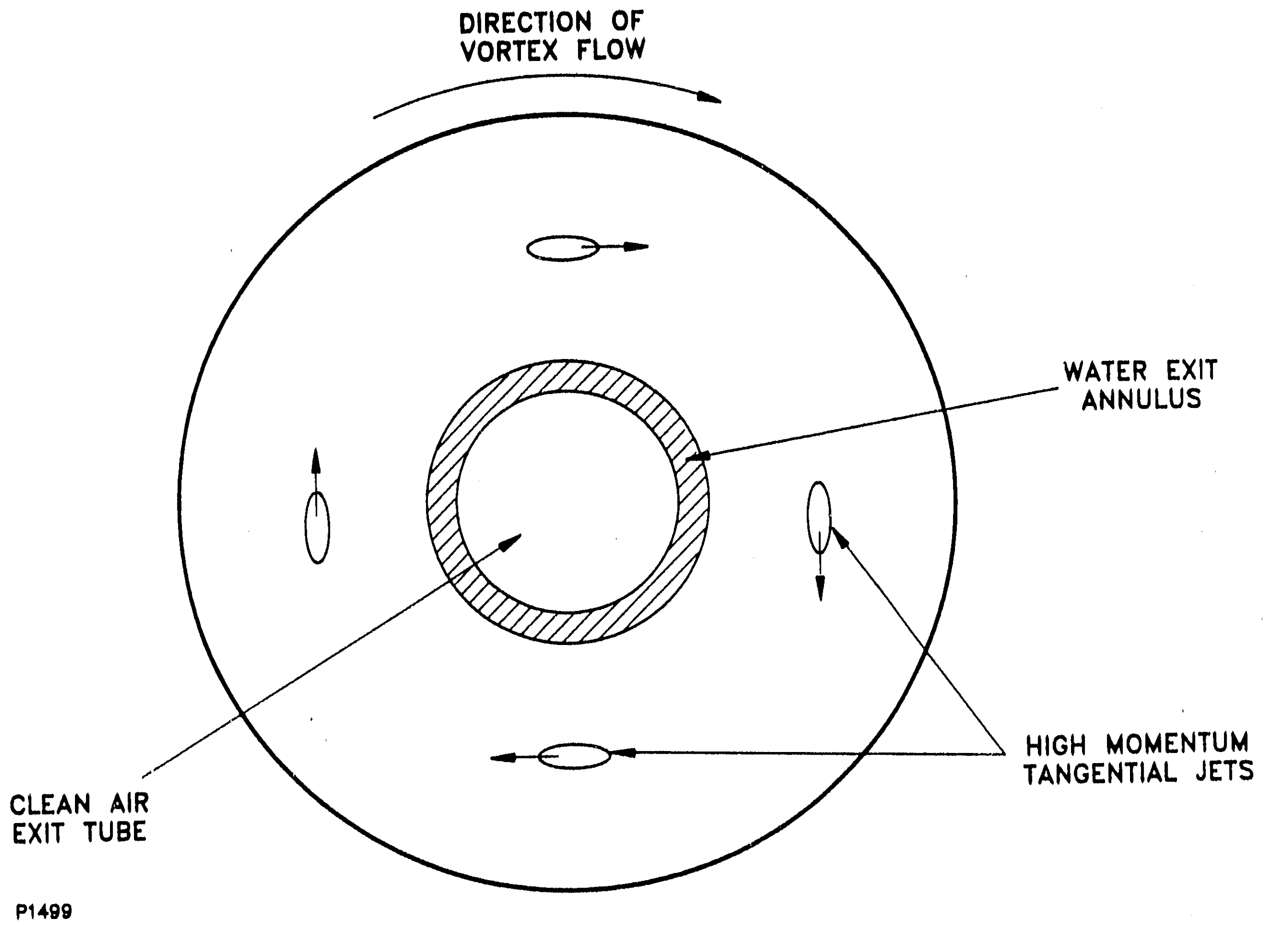

Figure 2-9 Schematic Diagram Showing Location of Jets on CVS Chamber Endwalls

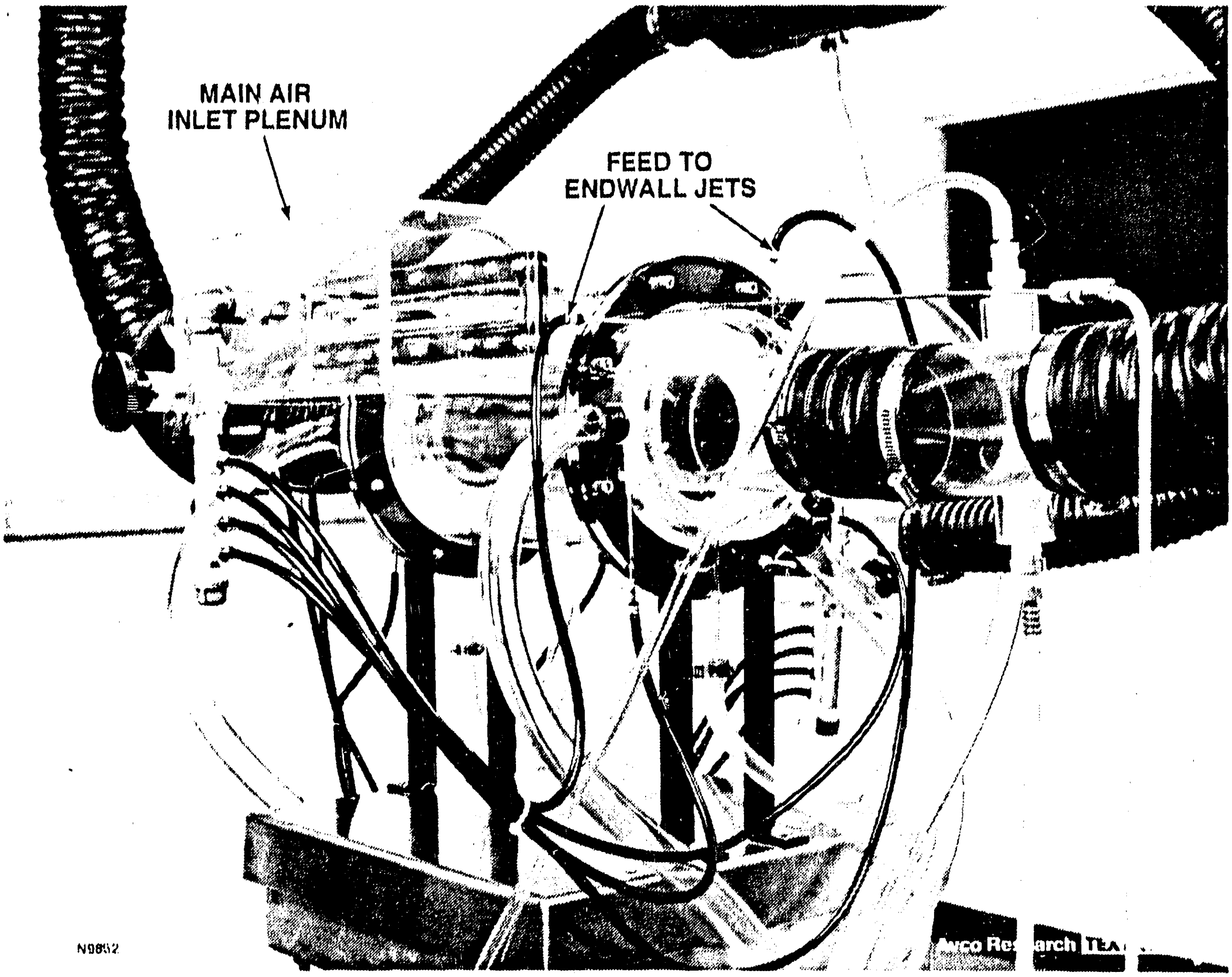

Figure 2-10 Photograph of Initial CVS Design, Showing Endwall Jet Air Supplies

normal CVS configuration. Therefore the failure of the endwall jets to improve the water containment in the CVS appears to be related to the fact that there is a liquid and an air outflow at the endwall.

2.2.3 Alternate Geometries

Tests were also conducted for the case of multiple jet air inlets. For the L/D = 1.5 model, the inlet arrangement consisted of two sets of eight inlet jets of diameter 0.358". Based on gas turbine film cooling practice (Loftus and Jones, 1983) the jet centers were spaced at one and a half hole diameters in order to give optimum jet interaction and film coverage on the chamber wall. An aerodynamic test of this inlet arrangement (no liquid injection) showed that inlet velocities up to 53 m/s were obtained and the dimensionless pressure drop was 3.7 inlet dynamic heads. This is the lowest dry pressure drop of any of the configurations tested to date. Dry pressure drops for the six previously tested configurations listed in Table 2-1 are given in Table 2-2.

TABLE 2-2

CVS NON-DIMENSIONAL PRESSURE DROP - NO WATER ADDITION

Configuration	Number of Dynamic Heads Loss
A	40.7
B	62.0
C	13.2
D	6.6
E	5.4
F	4.4

Water addition experiments with the multiple jet inlet showed generally the same flowfield characteristics, levels of water containment, pressure drop and water loss rates as for the slot inlets. However, there appeared to be a much stronger and more vigorous air/liquid interaction. Air bubbles in the liquid were clearly visible for the jet inlet case, whereas they were not for the slot inlet case.

TABLE 2-3

CONFIGURATION FOR CVS OF ASPECT RATIO = 1.0

Chamber Internal Diameter	6.5"
Aspect Ratio (L/D)	1.00
Air Inlet Type	Slots
Inlet Slot Height	0.312"
Air Outlet Type	Flow Guide Slot Exit
Air Outlet Diameter (D_e/D)	0.50
Water Outlet Type	Single Tube, 0.372" ID

Tests have also been made with a CVS chamber of unity aspect ratio. The dimensions of this model are given in Table 2-3. An aerodynamic test of this inlet arrangement (no liquid injection) showed that inlet velocities up to 43 m/s were obtained and the dimensionless pressure drop was 6.1 inlet dynamic heads. Water addition experiments with the L/D = 1.0 model showed generally the same flowfield characteristics, levels of water containment, pressure drop and water loss rates as for the higher aspect ratio model.

2.2.4 <u>Conclusions</u>

At this point, some conclusions may be drawn about the performance of the initial CVS configuration. The pressure drop of the device has been well controlled by suitable design modifications: refinements in system design progressively reduced the device pressure drop to approximately one third that of a conventional reverse flow cyclone separator operating at the same inlet velocity. The device pressure drop was also lower with a stable liquid layer confined within the chamber than without such a layer.

Preliminary water addition experiments indicated that a sheet of water could indeed be established and contained within the chamber and that the proposed water removal mechanism via the chamber end-wall secondary flows was effective. However, subsequent experiments indicated three areas of concern:

1. The amount of liquid contained within the CVS was small - the layer of liquid in the CVS was thinner than desired and did not lead to the level of air/liquid interaction expected.

2. There was a relatively high through-flow of liquid, leading to flow handling problems in the water out-take chamber and liquid loss.

3. At higher air inlet velocities there is some atomization of the liquid layer at the air inlets, leading to liquid loss.

The first problem is illustrated in Figure 2-11. The observed liquid layer behavior (a) is compared with the desired behavior (b). The intention is to have a liquid layer which is not in contact with the wall and is 'supported' on a layer of air, the air bubbling through the liquid in order to exit the chamber. The actual layer is thin and does appear to be on the chamber wall. The inlet air jets penetrate the liquid layer completely (hence the atomization problem), leading to relatively poor air/liquid interaction. The inlet jets are not submerged, as desired. The problems described above apply to all configurations tested to date, though problems (1) and (2) can essentially be eliminated at certain conditions. However, the lack of submerged inlets jets

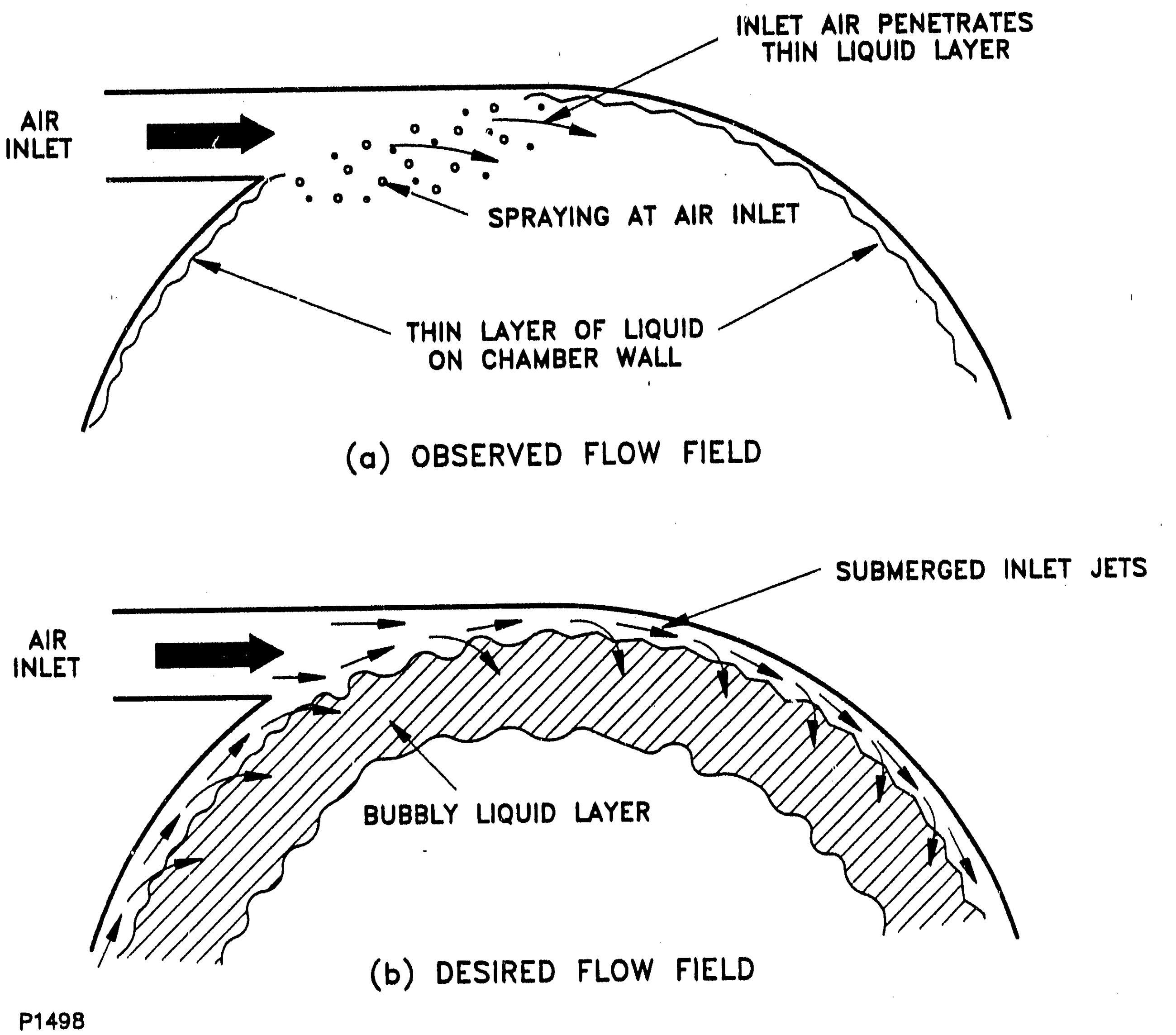

Figure 2-11 Schematic Diagram Showing (a) Observed Flowfield Within Initial CVS Design and (b) Desired Flowfield

and a vigorous air/liquid interaction suggests that the desired level of particulate removal may not be obtained.

2.3 CVS CHAMBER RE-DESIGN

2.3.1 Design Details

The CVS chamber was re-designed in order to establish a flowfield with submerged inlet air jets, to increase the level of liquid containment and to enhance the air/liquid interaction. The re-designed chamber is illustrated schematically in Figure 2-12. The number of tangential air inlets was increased from 2 to 24. A plenum is required in order to feed all 24 inlets. In order to facilitate progress, the revised CVS chamber was designed such that the existing 6.5" internal diameter, L/D=1.0 CVS model could be used as a plenum chamber to feed a 4.25" internal diameter, 24 inlet CVS, see Figure 2-12. This minimized the amount of machining and fabricating required before the new design could be tested. The key dimensions of the revised CVS design are given in Table 2-4. A photograph of the new test arrangement is given in Figure 2-13.

TABLE 2-4

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

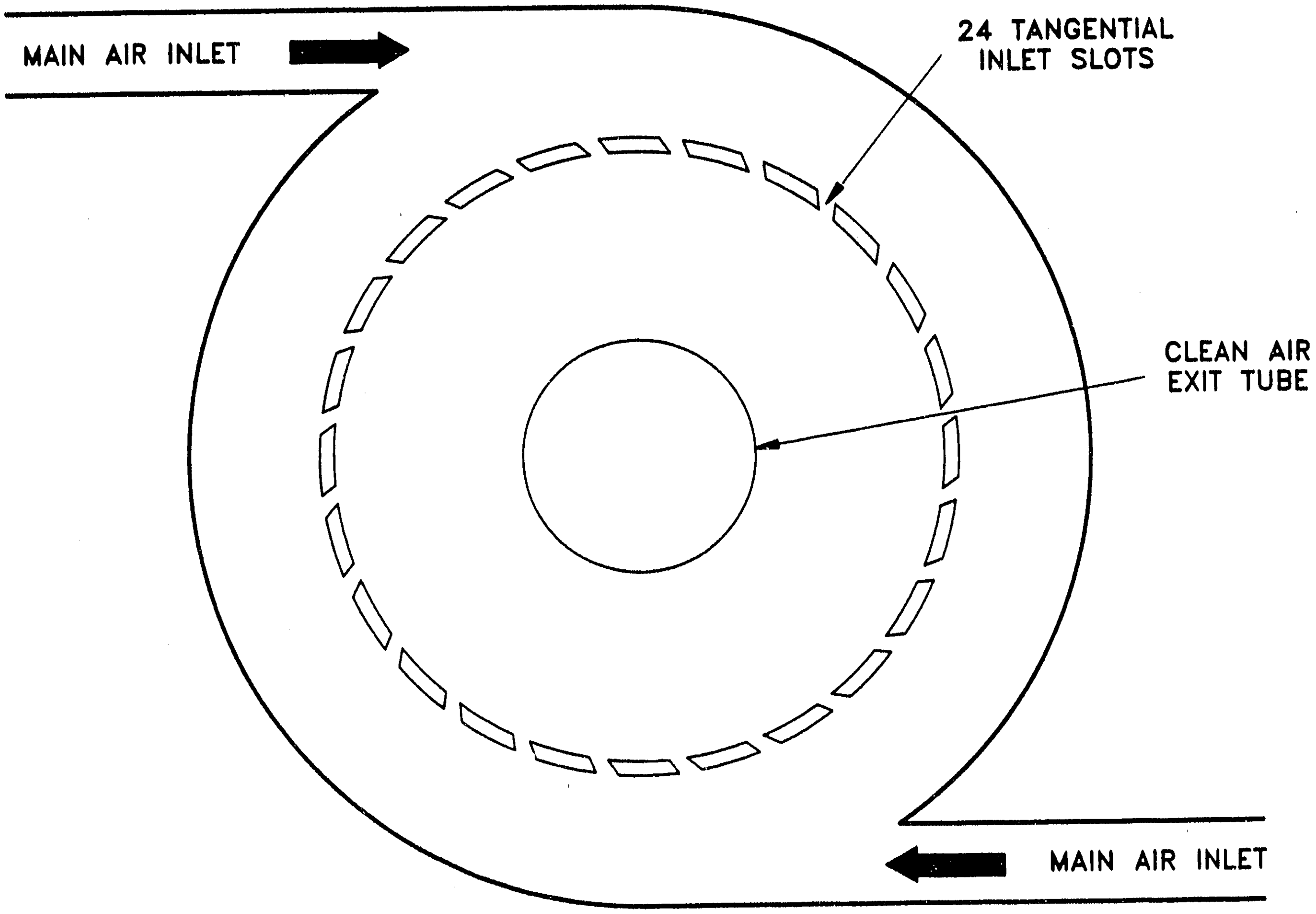

Figure 2-12 Schematic Diagram Showing Re-Designed CVS Chamber of 'Squirrel Cage' Design

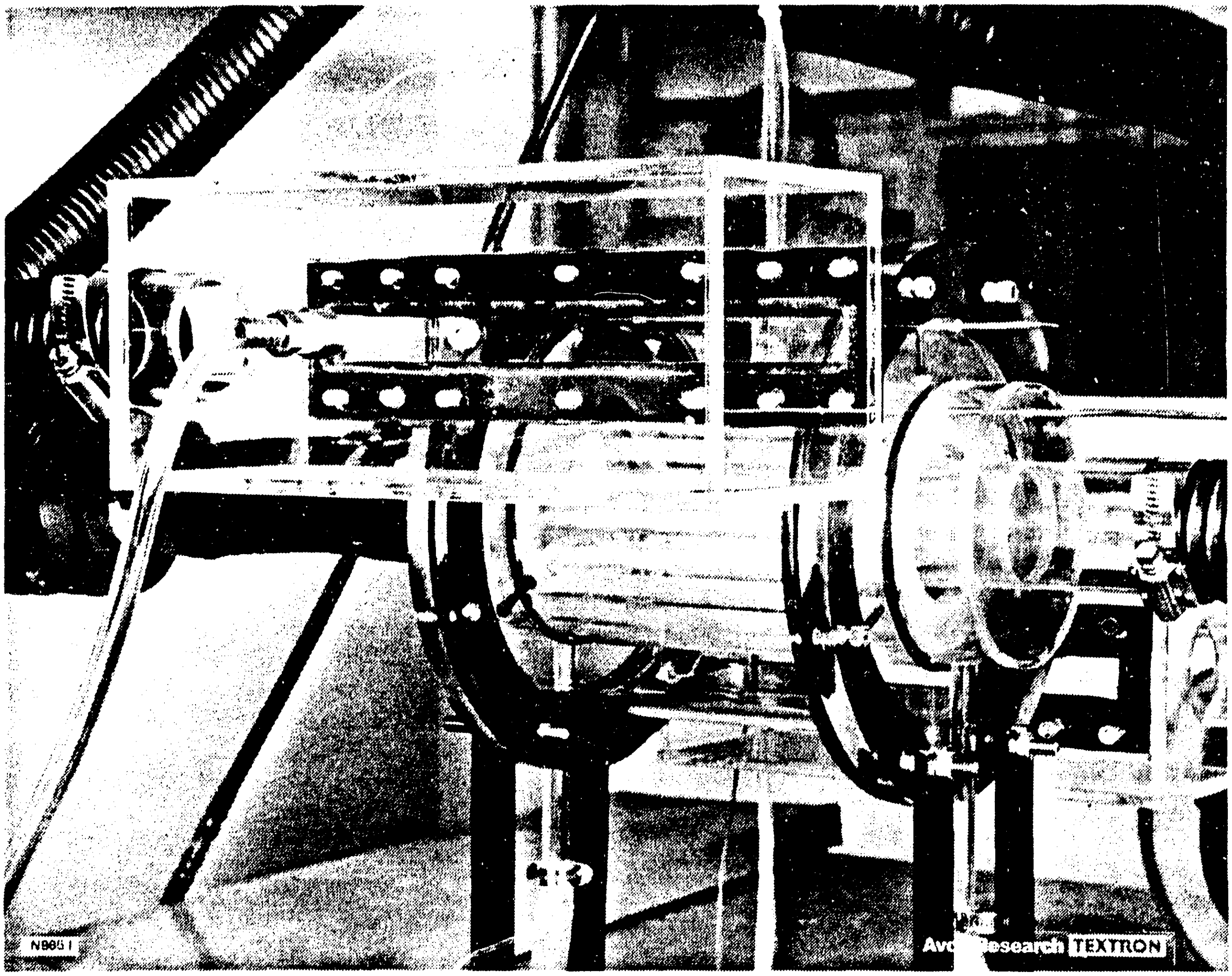

Figure 2-13 Photograph of 4.25" ID Squirrel Cage CVS Installation

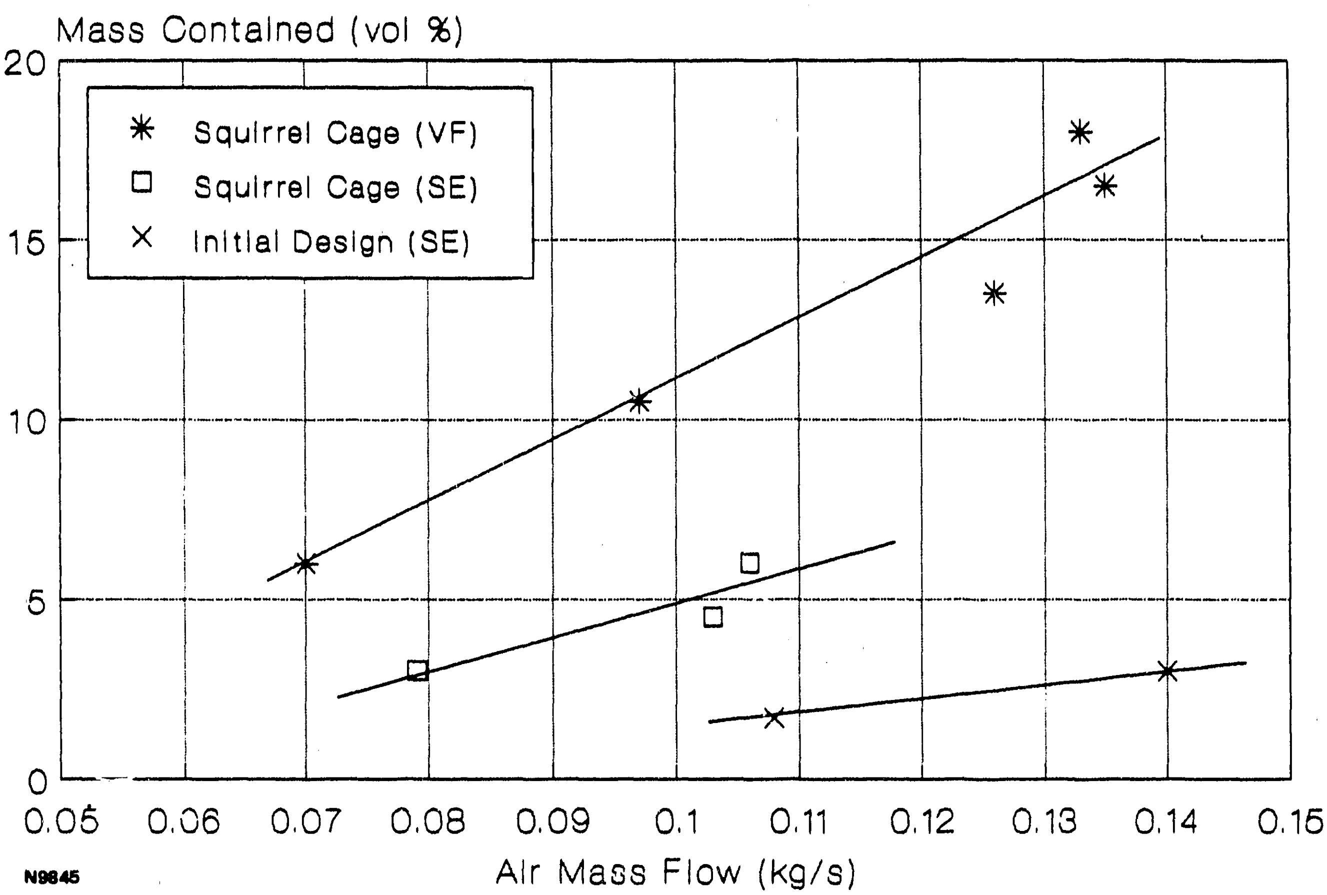

Figure 2-14 Mass of Liquid Contained, Expressed as a Percentage of Chamber Volume, as a Function of Air Mass Flow Rate for Squirrel Cage Design with Vortex Finder (VF) and Slot Exits (SE) and for Initial CVS Design

2.3.2 Test Results

First tests with the 24 inlet configuration (hereinafter referred to as the 'squirrel cage' configuration) showed a dramatically different two phase flowfield than had been observed with the initial, two-inlet CVS configuration. The inlet air jets were now clearly submerged beneath a much thicker liquid layer than had been observed hitherto. There was a much more vigorous interaction between the air and the liquid: the liquid layer appeared thick and frothy in nature. The mass contained increased dramatically to a maximum of approximately 20 percent of chamber volume. Once again, the pressure drop was a minimum when a stable liquid layer was established. Other significant differences observed with the squirrel cage CVS 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 atomi and entrainment of liquid in this region. Results obtained to date for the squirrel cage CVS are described in more detail below.

Figure 2-14 shows the liquid containment results for the squirrel cage CVS. Liquid containment, expressed as an equivalent percentage of chamber volume, is plotted against total air mass flow rate. Data for the two air outlet types (vortex finder (VF) and flow guide slot exit (SE)) are plotted. The vortex finder shows clearly superior performance, with a maximum containment of 18 percent of chamber volume. For comparison purposes, data from the original two-inlet CVS tests is included. At the same air and water mass flow rates, the measured containment is one sixth that of the squirrel cage design. The monotonic upward trend of containment with air mass flow observed for the squirrel cage design is as expected.

Significant qualitative flowfield differences were observed between the vortex finder and the slot exit arrangements. As mentioned above, for the vortex finder exit the liquid layer was thick (up to 0.5") and appeared frothy. The layer was of uniform thickness along the length of the CVS chamber. For the slot exit it proved extremely difficult, if not impossible, to obtain a uniform liquid layer along the length of the CVS chamber. The liquid layer was always biassed to one end or another of the chamber. In addition, the layer was not as thick as for the vortex finder case, and did not appear as frothy.

It should be noted that the 4.25" ID squirrel cage is undersized for the design mass flow rate (approx 0.1 kg/s). As discussed above, the chamber was sized such that the existing 6.5" internal diameter, L/D=1.0 CVS model could be used as a plenum chamber to feed the 24 inlet squirrel cage CVS. Thus this design has a high pressure drop at the design mass flow. Pressure drop data for the 4.25" ID squirrel cage configuration is presented in Figures 2-15 and 2-16, for the vortex finder and slot outlets, respectively.

Considering the vortex finder data first (Figure 2-15), a dramatic reduction in pressure drop is clearly seen once a stable liquid layer is established (the 'wet' pressure drop is less than half the 'dry' pressure drop). In non-dimensional terms, the dry pressure drop is approximately 22 inlet dynamic heads and the wet pressure drop is only 9 inlet dynamic heads. Possible mechanisms for this large reduction in pressure drop include: (1) reduction of angular momentum at vortex finder outlet; (2) reduction of wall skin friction losses; and (3) turbulence suppression by liquid droplets. The first of these mechanisms is most likely responsible for most of the reduction, with effects (2) and (3) producing second order effects. The bulk of the pressure drop produced in devices with vortex finder type outlets is associated with the high angular momentum exit flow. It is possible that the presence of the liquid

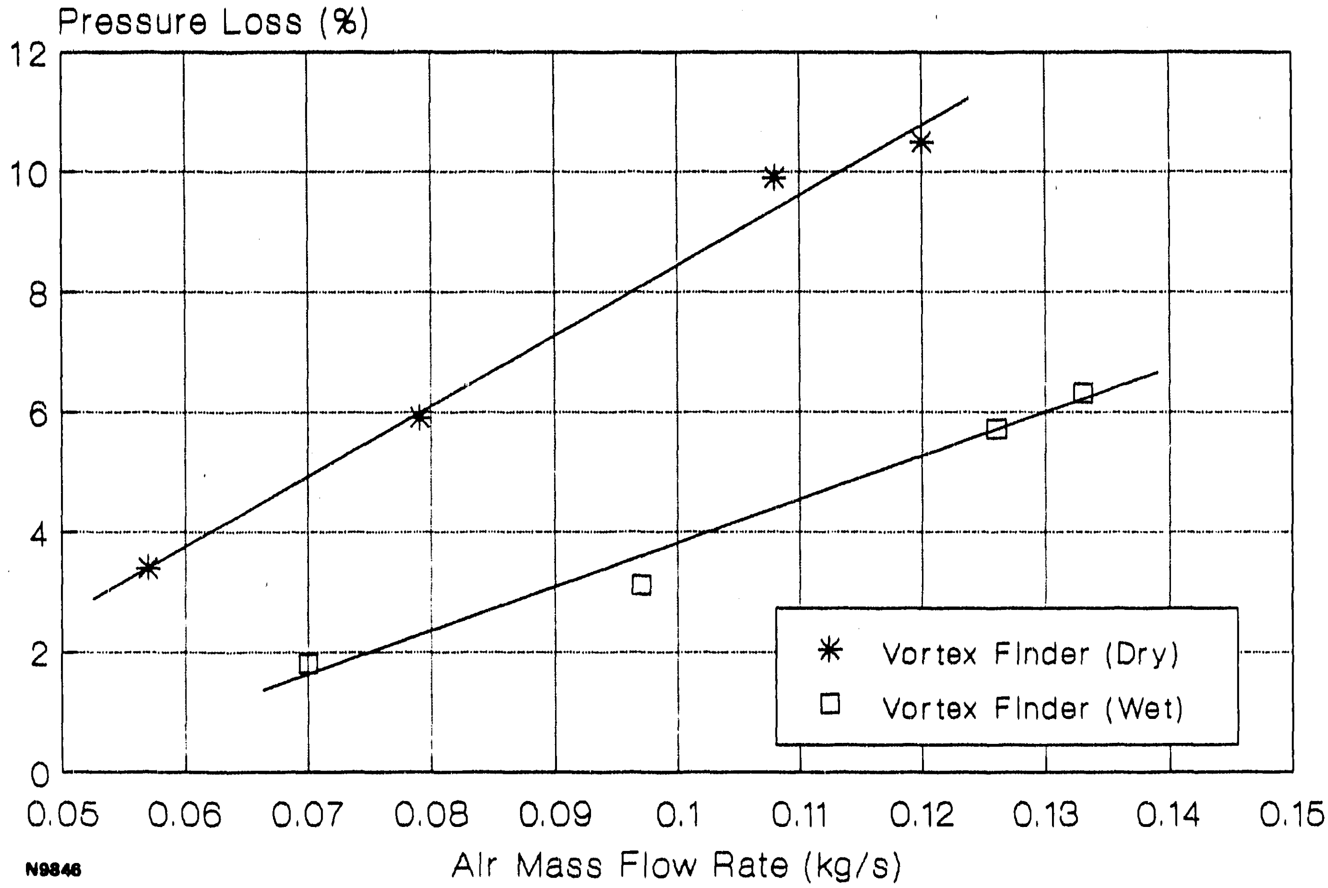

Figure 2-15 Pressure Loss, Expressed as Percentage of CVS Inlet Total Pressure, as a Function of Air Mass Flow Rate for Squirrel Cage CVS with Vortex Finder Exit, With (Wet) and Without (Dry) Liquid Layer Present

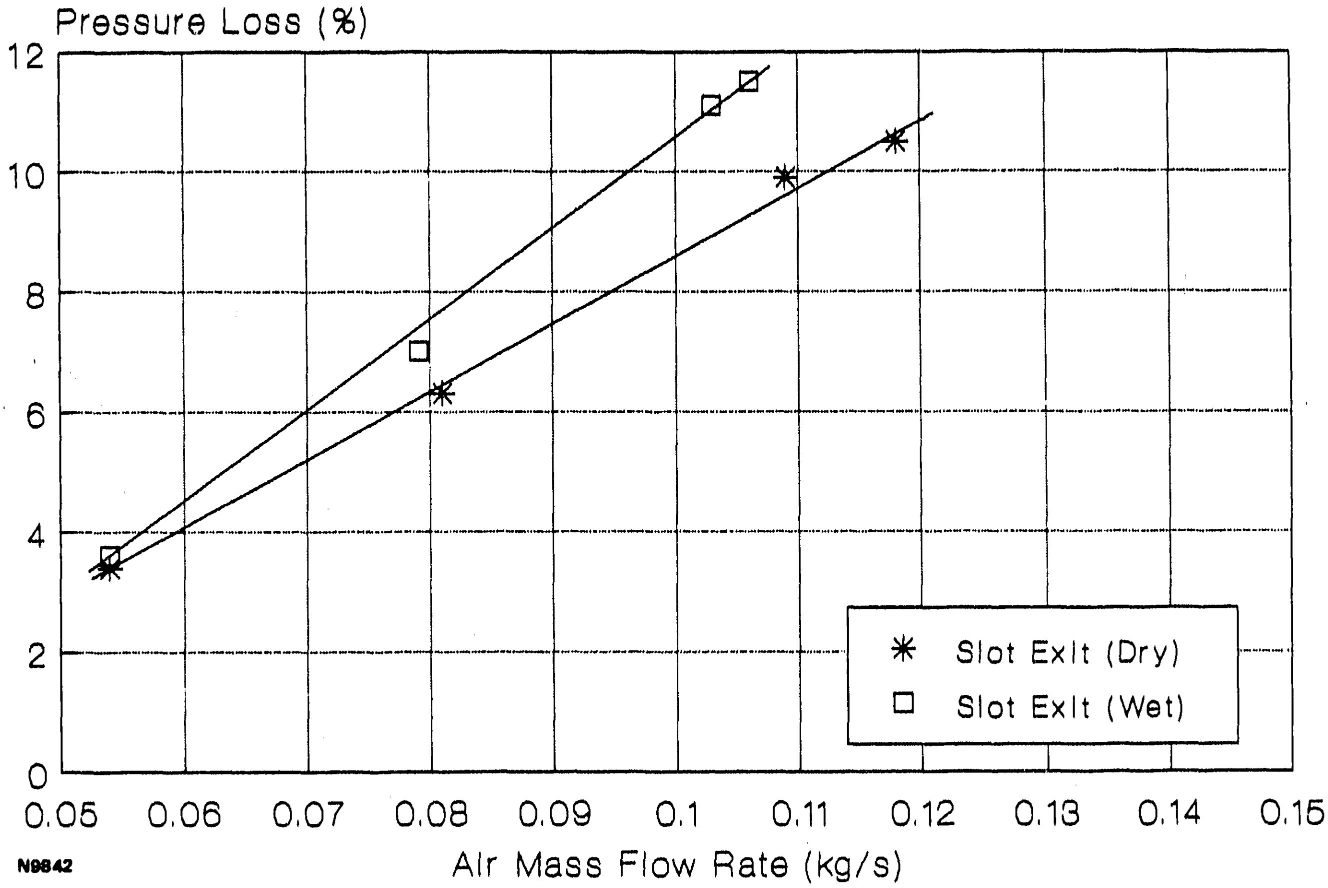

Figure 2-16 Pressure Loss, Expressed as Percentage of CVS Inlet Total Pressure, as a Function of Air Mass Flow Rate for Squirrel Cage CVS with Flow Guide Slot Exit, With (Wet) and Without (Dry) Liquid Layer Present

layer leads to reduced tangential velocities at the surface of the liquid layer, and consequently in the exit pipe itself, thereby reducing the radial pressure gradient and the pressure drop considerably.

Very different effects were observed for the slot exit, see Figure 2-16. In particular, the 'wet' pressure drop was higher than the 'dry' pressure drop, by approximately 20 percent. In non-dimensional terms, the dry pressure drop is approximately 22 inlet dynamic heads and the wet pressure drop is over 28 inlet dynamic heads. It should be remembered that with the slot exit, as discussed above, it was almost impossible to obtain a uniform liquid layer along the length of the CVS chamber: the liquid layer was biassed to one end of the chamber and was not as thick as for the vortex finder case, and did not appear as frothy. Using the arguments given above in reference to the vortex finder results, the presence of a liquid layer in only a portion of the CVS can be projected to lead to a variety of effects which could be responsible for the higher pressure drop. Assuming that the axial distribution of inlet mass flow is uniform (a significant assumption), the portion of the chamber which has no liquid layer will have a relatively high flux of angular momentum and a large radial pressure gradient. The portion of the chamber which has a liquid layer present will have a lower flux of angular momentum and a reduced radial pressure gradient. This, in turn, will lead to an axial pressure gradient near the center of the chamber, which will drive mass flow from the 'wet' portion of the CVS to the 'dry'. Thus the axial distribution of outlet mass flow will be decidedly non-uniform, potentially leading to the bulk of the inlet mass flow exiting via only a portion of the outlet slot, thereby leading to an increased pressure drop.

Given the paucity of flowfield data, these arguments are speculative.

Detailed measurement of the radial, tangential and axial velocity distributions in the chamber with and without liquid injection would provide much insight into these effects. However, not only would detailed velocity mapping of the two phase flow field be difficult and time-consuming (non-intrusive methods would be required), but it is also outside the scope of the present work. It should be remembered that the goal of the program is the proof of a novel clean-up concept.

Figure 2-17 shows the inlet water mass flow rate required for the establishment of a stable liquid layer within the CVS as a function of the air mass flow rate. For the slot exit, a stable liquid layer was only obtained for relatively low mass flow rates. Again, the vortex finder exit is clearly superior: these liquid flow rates are approximately half those required for establishment of a stable layer in the original two-inlet CVS.

Finally, Figure 2-18 shows the percentage of input water that exits via the clean gas exit, again plotted as a function of air mass flow rate. For the vortex finder, approximately one third of the water exits via this route at and above design mass flow. For the slot exit, approximately three-quarters of the water exits via the clean gas exit. In both cases, however, the liquid that leaves via the central clean gas exit tube is immediately inertially separated onto the walls of the two outlet tubes, making it very amenable to subsequent re-capture.

In summary, preliminary results obtained for a 4.25" ID CVS of squirrel cage design indicate 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,

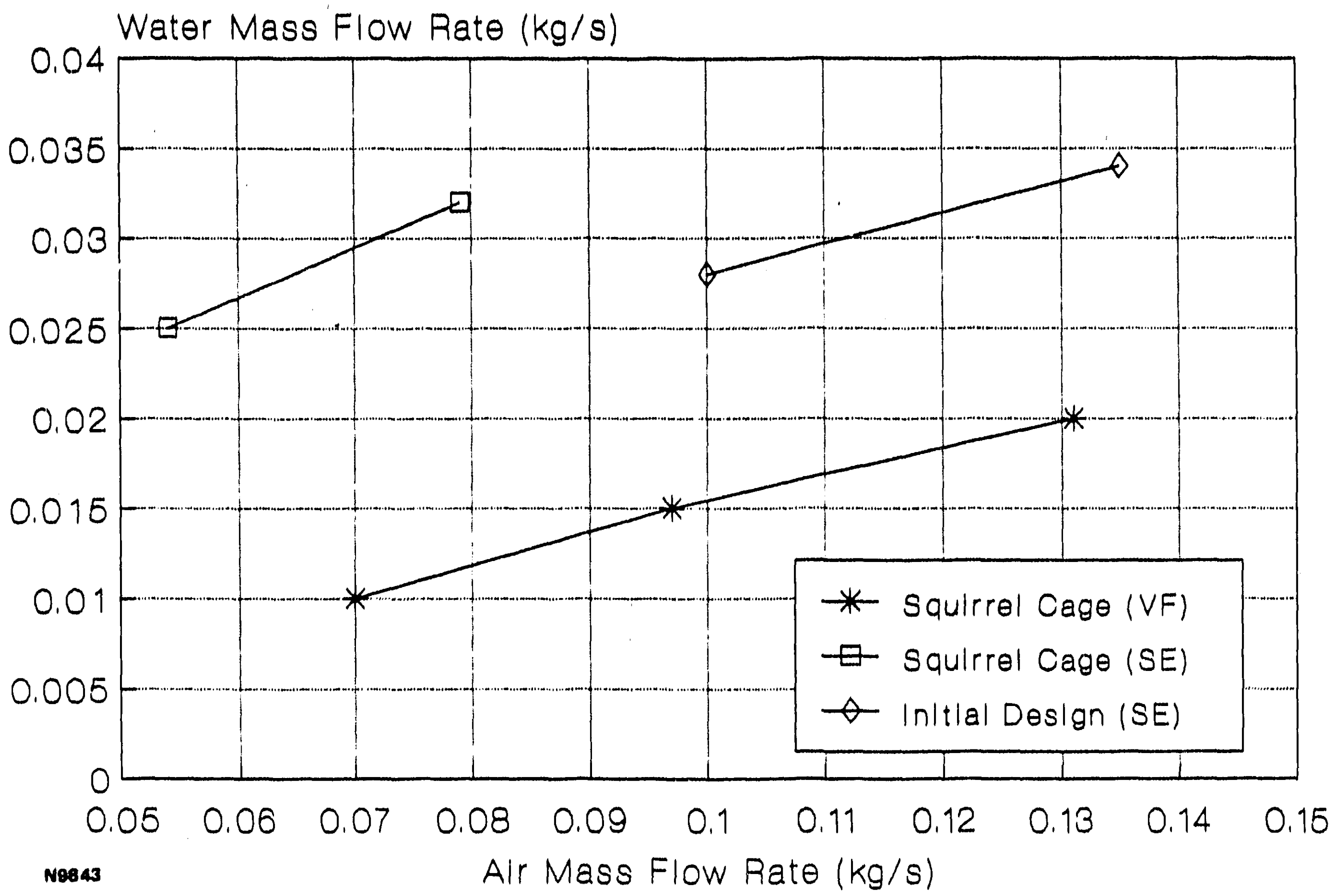

Figure 2-17 Minimum Input Water Flow Rate Required to Establish Stable Liquid Layer as a Function of Air Mass Flow for Squirrel Cage Design with Vortex Finder (VF) and Slot Exits (SE) and for Initial CVS Design

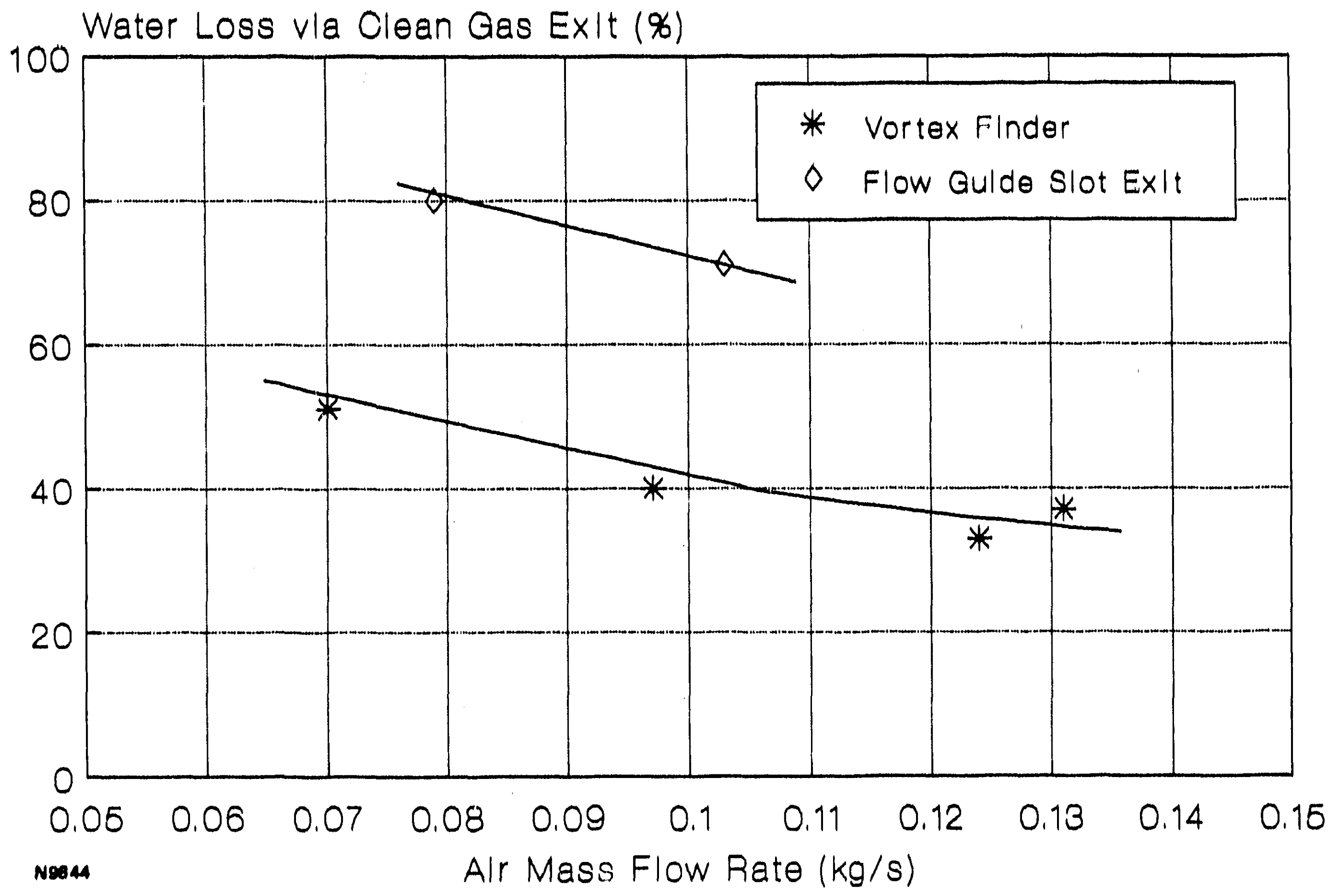

Figure 2-18 Water Loss via Clean Gas Exit for Squirrel Cage CVS with Vortex Finder and Slot Exits as a Function of Air Mass Flow Rate

level of air/liquid interaction and rate of liquid loss via clean gas exit. However, these results are of a preliminary nature and must be confirmed for a CVS chamber of size appropriate to the design mass flow.

3.0 CONCLUSIONS AND PLANS FOR FUTURE WORK

Two phase flow experiments on the initial CVS design indicated three areas of concern: (1) a low levels of liquid containment; (2) a high through-flow of liquid, leading to flow handling problems in the water out-take chamber and liquid loss; and (3) atomi of the liquid layer near the air inlets at high air inlet velocities, leading to liquid loss.

The first problem was considered the most significant of the three. The liquid layer was thin and the inlet air jets penetrated the liquid layer completely, leading to relatively poor air/liquid interaction. In other words, the inlet jets were not submerged, as desired. The lack of submerged inlets jets and a vigorous air/liquid interaction suggested that the desired level of particulate removal may not be obtained.

Accordingly, the CVS was re-designed. The re-designed squirrel cage CVS has demonstrated clear superiority over the initial CVS design. Preliminary results obtained for a 4.25" ID CVS of squirrel cage design indicate 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. However, these results are of a preliminary nature and must be confirmed for a CVS chamber of size appropriate to the design mass flow.

The importance of the level of liquid loss via the clean gas exit remains to be determined. It has been observed that all the liquid that enters either the slot exit of the vortex finder exit is very effectively inertially separated onto the exit duct walls. This is to be expected, given the centrifugal forces present in the outlet ducts. This means that it will be relatively simple to collect this water (and the separated particles it may contain), either by skimming of the exit duct flow or in a secondary device.

In the next reporting period, attention will turn to the clean-up experiments (Task 5). However, the issues raised by the preliminary squirrel cage results discussed above will also be pursued. Based on the results obtained to date, a squirrel cage CVS will be designed and fabricated at a size appropriate to the nominal design mass flow. During design and fabrication of the new CVS, clean-up experiments will commence using the 4.25" ID squirrel cage CVS.

4.0 REFERENCES

Avco Research Laboratory, 1982, " A Novel Hot Gas Cleanup Device," Internal Research and Development Reports, Avco Research Laboratory, Everett, Massachusetts.

Lewellen, W. S., and Stickler, D. B., 1972, "Two Phase Vortex Investigation Related to the Colloidal Core Nuclear Reactor," ARL TR 72-0037, Aerospace Research Laboratory, Wright Patterson Air Force Base, Ohio.

Loftus, P. J. and Jones, T. V., 1983, "The Effect of Temperature Ratios on the Film Cooling Process," ASME Journal of Engineering for Power, vol. 105, pp. 615-620.

Stickler, D. B., Lakshmikantha, H., and Lewellen, W. S., 1974, "Heat Transfer and Containment Processes in Two Phase Cavity Nuclear Reactor," ARL TR 74-0007, Aerospace Research Laboratory, Wright Patterson Air Force Base, Ohio.

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