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**CONTROL OF FINE PARTICULATE EMISSIONS FROM COAL-FIRED
UTILITY BOILERS**

Final Report

January 1990

Work Performed Under Contract No. AC22-87PC79748

**For
U.S. Department of Energy
Pittsburgh Energy Technology Center
Pittsburgh, Pennsylvania**

**By
Arthur D. Little, Inc.
Cambridge, Massachusetts**

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Cambridge, Massachusetts 02140**

TITLE

CONTRACT NUMBER: DE-AC22-87PC79748

TITLE: Control of Fine Particulate Emissions from Coal-Fired
Utility Boilers: Spin Filter Collection Device (Rotary
Cyclone)

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ABSTRACT

A bench-scale test program has been performed to evaluate the concept of placing a porous cylindrical surface (such as a metal screen) at the core of a container and spinning the surface with an external motor for fine particulate/gas separation. The rotating surface enhances the centrifugal effects in the annular region and provides a smooth transition between the flow in the annular and core regions and acts like an enhanced cyclone. It is therefore called a "rotary cyclone". The porous surface is self-cleaning and offers good steady-state pressure drop characteristics.

The objectives of this project are: (1) to carry out theoretical and experimental investigations using the rotary cyclone concept to capture particulates in the 0.5 to 10 micron size range; and (2) to evaluate its economic feasibility based on an engineering scale-up and comparison with conventional fabric filter and electrostatic precipitator systems.

It was demonstrated that the efficiency in separating fine particulates is governed by two major characteristics, i.e., the magnitude of the centrifugal force and the approach velocity or the gas-to-surface area ratio. Results from the bench-scale tests have shown a collection efficiency of well over 99% for a typical fly ash. Extrapolation of the test data and theoretical calculations indicate 99.9% efficiencies should be realizable.

A preliminary conceptual design for a 40 MW installation was developed based on the experimental work. The capital cost for such a 40 MW rotary cyclone installation is estimated to be smaller than for fabric filters and electrostatic precipitator of the same capacity. By extrapolation of data gathered from bench-scale tests, operating and maintenance costs, as well as levelized costs, are estimated to be smaller than fabric filters and electrostatic precipitator.

1.0 EXECUTIVE SUMMARY

The Pittsburgh Energy Technology Center (PETC) of the Department of Energy has been directing development effort of environmental control technology for new and existing utility and industrial coal-fired power plants. As a result of a solicitation for new concepts and approaches, Arthur D. Little, Inc. (ADL) proposed a program of work in Control Technology Development using a "Rotary Cyclone" (Spin Filter) concept for Fine Particulate Emissions Control.

This concept consists of placing a porous cylindrical surface (such as a metal screen) at the core of a container shaped like a cyclone and spinning the surface with an external motor. The screen hole size can be orders of magnitude larger than the particles to be separated. Separation of particulates is achieved by enhanced centrifugal forces.

A bench-scale test program has been performed to evaluate this concept. The objectives of this project are (1) to carry out theoretical and experimental investigations for fine particulate/gas separation; and (2) to evaluate its economic feasibility based on engineering scale-up and comparison with conventional particulate clean-up systems. More specifically, the following tasks have been undertaken:

- Literature survey;
- Theoretical analysis and experimental design;
- Equipment procurement, erection and checkout;
- Flowfield tests and a collection efficiency;
- Data analysis;
- Engineering scale-up; and
- Comparative cost analysis.

It was demonstrated that the efficiency in separating fine particulates is governed by two major characteristics, i.e., the magnitude of the centrifugal force and the

approach velocity of the gas-to-surface ratio. Results from the bench-scale tests have shown that:

- Theoretical prediction on minimum size of particulate to be separated correlates relatively well with the experimental result;
- Fly ash collection efficiencies of 99.58% (mass basis) were achieved in a 24-hour test. Based on theoretical considerations and extrapolation of this data, an efficiency of 99.9% should be realizable by increasing the ratio of centrifugal to drag forces, but this has yet to be demonstrated;
- Pressure drop from inlet gas to outlet cleaned gas is small;
- Performance did not degrade over the test period; and
- Dust loading on inlet gas appears to have little impact on performance.

A conceptual design for a 40 MW installation was developed based on the experimental work. The capital cost for such a 40 MW Rotary Cyclone installation is estimated to be smaller than for fabric filters and electrostatic precipitator of the same capacity. By extrapolation of data gathered from bench-scale tests, operating and maintenance costs, as well as levelized costs, are estimated to be smaller than fabric filters and electrostatic precipitator. Further test work on a larger scale are needed to confirm these preliminary technical results and economic assessments.

2.0 BACKGROUND AND INTRODUCTION

The Pittsburgh Energy Technology Center (PETC) of the Department of Energy has been directing development effort of environmental control technology for new and existing utility and industrial coal-fired power plants. As a result of a solicitation for new concepts and approaches, Arthur D. Little, Inc., proposed a program of work in Control Technology Development using a "Rotary Cyclone" (Spin Filter) concept for Fine Particulate Emissions Control.

This concept consists of placing a porous cylindrical surface (such as a metal screen) at the core of a container shaped like a cyclone and spinning the surface with an external motor. Such a device is particularly promising for fine particulate/gas separation because:

- The spin filter enhances the centrifugal effects in the annular region of a cyclone and provides a smoother transition between the flow in the annular and core region.
- The porous surface may consist of a screen with hole sizes which are larger than particles to be separated. As a result, the surface remains clean and offers low pressure drop characteristics.
- The device offers design flexibility and can be tailored to maximize performance over a wide range of applications (e.g., turndown ratio, dust loading, minimum particle size to be separated, etc.).

A bench-scale test program has been performed to evaluate this concept. The objectives of this project are: (1) to carry out theoretical and experimental investigations for fine particulate/gas separation; and (2) to evaluate its economic feasibility based on engineering scale-up and comparison with conventional particulate cleanup systems.

The performance of the device is governed by two major characteristics, i.e., the magnitude of the centrifugal force and the magnitude of the approach velocity toward the rotating surface. The former enhances the centrifugal effect on fine particulates, hence accelerating their separation in the annular region. The latter incurs a drag effect and tends to pull particulates through the device. The rotary cyclone works under a greater centrifugal force than cyclones. Thus, it separates much finer particulates than typical cyclones. On the other hand, the rotary cyclone does not filter fine particulates through a filter surface as fabric filters do. Thus, it runs at lower pressure drops. In a scaled-up rotary cyclone module, it is estimated that the approach velocity can be 30 to 100 times higher than in a fabric filters, based on an equivalent air/cloth ratio resulting in much smaller "filtration" surface areas for the rotary cyclone.

3.0 OBJECTIVES

The objectives of this project are:

- To carry out a coordinated bench-scale experimental/theoretical investigation for gas-particulate separation using the rotary cyclone concept.
- To evaluate its economic feasibility based on engineering scale-up and comparison with conventional particulate clean-up systems.

More specifically, the following tasks have been undertaken to fulfill these objectives:

- Literature survey;
- Theoretical flowfield analysis;
- Experimental design;
- Equipment specification and procurement;
- Equipment assembly, installation and checkout;
- Flowfield tests and data analysis;
- Collection efficiency tests, and data analysis; and
- Preliminary engineering scale-up, conceptual design, and comparative cost analysis with fabric filters and electrostatic precipitators.

Evaluations have been conducted on:

- Effectiveness of particulate separation at different centrifugal forces and gas flow rates;
- Pressure drop at different centrifugal forces and gas flow rates;
- Power consumption of the rotor at different centrifugal forces and gas flow rates;
- Effectiveness of special air-seal mechanism,
- Screen condition and durability; and
- Impact from inlet gas loadings.

4.0 METHODOLOGY

4.1 Literature Survey

A literature search was conducted which involved reviewing about 3 million records in NTIS, INSPEC, ISMEC, COMPENDEX AND MATHSCI databases. About 188 articles were identified and about 40 of specific interest were reviewed in greater detail. One U.S. Patent (No. 4,268,394, Laughlin, et al., 1981) was found having a rotating screen for fiber product production. After review, it was clear that the principal of operation is different than the current rotary cyclone and this prior art is not relevant to this project. The other articles largely focused on Couette flow between concentric rotating cylinders. No articles were found that described flowfields with "cross flow," that is, radially from one cylinder to the other.

4.2 Flowfield Analysis

Since no prior work was found to mathematically describe the flow in the rotary cyclone, a two-dimensional flowfield analysis was developed. The purpose of this analytical work was to estimate theoretical profiles of tangential and radial velocities and to predict the rotary cyclone's performance in particulates/gas separation. To simplify the analytical difficulties, this was done by solving two-dimensional continuity and momentum equations with assumptions of steady-state, viscous and incompressible fluid flow to obtain closed form solutions of tangential and radial velocity profiles. By balancing the centrifugal force and drag force acting on spherical shape particulates, the required angular velocity of the spinning surface is obtained in relations with other parameters, such as the size of particulate to be separated and the approach velocity of the gas stream at the spinning surface, etc. A summary of the mathematical model is included in Appendix A of this report. Sample calculations and plots of tangential velocities in the annulus are included in Appendix B of this report.

The results from this analysis have indicated that the annular region of the rotary cyclone device is a quasi-potential flow region. Tangential velocity varies inversely

with respect to changes in radius. However, the core region is a forced vortex where tangential velocity is proportional to the radius. The mathematical model also shows the predicted minimum size of particulates to be separated varies proportionally to the square root of approach velocity but inversely to the square root of centrifugal force.

For illustrative purposes, Table 4-1 shows calculations to relate the rotational speed and cross flow (approach velocities) with particle sizes and densities at which separation of solids from the gas stream is expected to occur. Calculations indicate that a rotary cyclone with a radius of 3 inches (as used in this test program) rotating at 1800 rpm will theoretically separate:

- An 0.5 micron diameter particle with an approach velocity of 0.017 ft/sec; and
- A 10 micron diameter particle with an approach velocity of 6.8 ft/sec.

As noted earlier, the rotary cyclone efficiency in particle separation does not rely on having a fine screen mesh. Because particles above the cutsize never reach the rotor, we have simply assumed that the drag force is given by an approach velocity calculated as the air flow divided by the total active rotor surface area (ACFM/ft²). We believe this is a reasonable approximation but clearly further experimental/theoretical work is needed to confirm this assumption.

4.3 Experimental Design and Rotary Cyclone Assembly

Based on the above-described mathematical analysis, a test rotary cyclone was designed with dimensional configurations as follows:

- Diameter of rotary cyclone surface - 6 inches
- Inner diameter of the housing - 12 inches
- Length (height) of filter - approximately 3 feet

Further details of the assembly drawings of the rotary cyclone device are included in Appendix C.

Table 4-1: Approach Velocities to Achieve Particle Separation

	<u>0.5 Micron Particle</u>	<u>10 Micron Particle</u>
Spin filter radius, a	0.25 ft	0.25 ft
Outside housing radius, b	0.50 ft	0.50 ft
Approach velocity*, V_a	0.017 ft/sec	6.8 ft/sec
Air density, $(\rho)_a$ @ 70°F	0.0808 lb _m /cu ft	0.0808 lb _m /cu ft
Air viscosity, $(\mu)_a$	1.17×10^{-5} lbm/sec ft	1.17×10^{-5} lb _m /sec ft
Particle density, $(\rho)_{part}$	155 lb _m /cu ft	155 lb _m /cu ft
Rotational speed (ω)	1,800 rpm	1,800 rpm

*Approach velocity is defined by the following expression:

Approach velocity (ft/sec) = Actual Volumetric Flow Rate (cu-ft/sec)/Total
Active Rotor Surface Area (ft²)

The experimental test device has the following features:

- Ability to control and operate the rotor at various rotational speed from zero to 1900 RPM.
- Ability to use plexiglass shell or steel shell;
- Ability to use various screen sizes from 1/4 inch holes in the rotor surface to a 400 mesh screen.
- Flue gas inlet angle variation of up to 25 degrees (with a new entry duct) to provide a vertical component to the gas flow; and
- Ability to vary screen length from zero to 26 inches.

System components include a number of assemblies or subsystems:

- Assembly containing the rotating surface;
- Drive system;
- Air seal mechanism;
- Plexiglass or steel shell and bottom plate assembly;
- Inlet and outlet duct work and dampers;
- Induced fan; and
- Inlet air filter assembly.

Instrumentation includes:

- Nine magnehelic manometers for dynamic pressure measurements;
- Three magnehelic manometers for static pressure measurements;
- DC motor controller for rotor rpm control;
- Seal air filter and regulator;
- Seal air flow rotameter;

- AC ammeters for induced fan and DC motor; and
- Digital tachometer and sensor.

After assembling the system, a number of preliminary runs were carried out for system checkout. These included: (1) gas leak proof effort; (2) DC motor driving power compensation fine-tuning; (3) pitot tube tip position adjustment synchronization; and (4) pitot tube tubing connection switching test to ensure consistent, reliable readings.

4.4 Test Program

The experimental program included flow visualization and collection efficiency tests. Bulk gas flow rates were 0, 7 and 50 acfm and rotational speeds of the rotor were at 500, 1,000 and 1,800 rpm. Data were obtained with and without a 200 mesh screen on the rotating surface. Ten tests were conducted with each one lasting 15 minutes to 2 hours as summarized in Appendix E (Table E-1). Long duration tests are summarized in Section 5.1.

4.5 Fly Ash Properties

Coal fly ash was used for all the collection efficiency tests. The fly ash used in the collection efficiency tests was obtained from a baghouse after the burning of pulverized subbituminous coal. Particulate size varied from less than 1 micron to about 40 microns.

The distribution of particle sizes is shown in Table 4-2. The photographs in Appendix I were taken by a scanning electron microscope showing the rather regular spheroidal shape and size of the fly ash.

Table 4-2: Fly Ash Used in Experimental Work

<u>Size</u> (micron)	<u>Cumulative</u> (wt. %)
0.56	1.19
0.91	9.57
1.82	16.75
2.79	22.13
4.03	29.31
6.17	40.68
9.75	61.63
16.25 and greater	100.00

Source: Arthur D. Little, Appendix E.

5.0 TEST RESULTS AND DISCUSSIONS

5.1 Flowfield Test and Data Analysis

The Rotary Cyclone device has run smoothly up to 1,900 rpm; such rotational speeds have been sufficient to test the concept. Data was obtained at three different speeds, namely, 500, 1,000 and 1,800 rpm. Analysis of the data indicates the following:

- End effect; measured tangential velocities were higher near the middle portion of the rotor and lower near the ends of the rotor;
- Tangential velocities measured at 1,800 rpm run were about 82-86% of the values theoretically calculated; and
- Average pressure drop across the spinning surface at 1,800 rpm was 0.29" water. Note that this is only about 50% of the velocity head ($0.5 PV_r^2$), with the tangential velocity (V_r) measured at the rotor surface. This pressure drop was seen also to vary slightly with respect to changes in bulk flow rate.

Photographs for flowfield visualization at different rpm and bulk flow rate were taken. The flowfield was established in each case by bringing the rotor to the designated rpm for a few minutes. Smoke was injected near the center portion of the rotor, and photographs were taken with a synchronized strobe light focussing at the annulus between the shell and the rotor. Other conditions during the test were as follows: (1) temperature was 70°F; (2) in the case of zero bulk flow rate, the rotor surface was covered with masking tape; (3) in the case of 7 acfm bulk flow rate, the rotor surface was covered with 200 mesh screen; and (4) the speed of strobe light was set at 1/800 of a second.

Examination of photographs taken shows that there are local turbulences in each case, but these did not appear to affect the efficiency of separation as discussed below.

5.2 Initial Collection Efficiency Tests and Data Analyses

For the collection efficiency tests, the following instruments are used: (1) Wright Dust Feeder; (2) Cascade Impactor for trace amount of particulate collection and size distribution determinations; and (3) Balance with an accuracy of 0.0001 gram or 0.1 milligram. Additional equipment included: (1) air inlet regulator and filter; (2) outlet air rotameter; (3) impactor's vacuum systems including vacuum pump, manometer and flow meters; and (4) glass jar desiccators.

We had encountered problems with the air seal mechanism earlier during the tests but later made substantial progress in solving this problem. With the new configuration of air seal mechanism (Appendix J), the performance has been excellent because (1) bypassing is eliminated; and (2) consumption of sealing air is minimal or negligible.

Data on actual seal air consumption for the testing device were observed for each test series. Results are shown in Appendix J of this report. Table J-1 shows that the air for sealing typically amounts to less than 10% of total air flow with some runs showing no net requirements for sealing air (i.e., pressure balance was achieved).

There are ten tests in the collection efficiency test series. One of them has a relatively long period test with continuous operation at 1,800 rpm for two hours. A summary of the test results are listed in Table E-1 of Appendix E of this report. Total collection efficiencies were in accord with theory, namely higher centrifugal forces and lower approach velocities tended to increase particulate collection efficiencies. From a theoretical viewpoint (Appendix A), the collection efficiency should be 100% down to the cutsize (e.g. 0.5 micron) and zero percent below the cutsize as shown in Figure 5-1. Collection efficiencies below one micron remain surprisingly high (i.e. 96%), possibly due to particulate agglomeration. Details are found in Appendix E in this report. There is no indication of degradation of system

THEORETICAL EFFICIENCY

Example Basis: cutsize determined by centrifugal and drag forces (See Appendix A)

Figure 5-1: Theoretical Efficiency

performance during these extended tests. This indicates there is no major blinding of the spinning surface.

The size distributions measured at the inlet, as well as at the outlet of the rotary cyclone, is illustrated in Appendix E, Tables 3 and 4. The aforementioned two tables show that the device is capable of separating particulates near the cutsize diameter which is consistent with the theoretical analysis.

We have noticed during the tests the existence of electrostatic charge resulting from the particulate dispersing, as well as the moisture influence to the weighing process. The Rotary Cyclone is well grounded by connection wires and four glass jar desiccators are used to ensure a dry base measurement. However, deposits of fly ash on the inner wall of the shell and bottom cone are still visible, and measuring errors incurred from humidity conditions may affect results in the 0.1 to 0.2 milligram range compared to the total collections of 2 to 3 milligrams at the outlet of the device and total fly ash fed to the rotary cyclone in a test of a few hundred milligrams.

The pressure drop did not change significantly over the test period from an average value of 0.23 ± 0.01 inches of water with an initial (starting) and end value of 0.24 inches of water and dropping to 0.22 inches of water from the sixth to the fourteenth hour of testing (Appendix E, Table E-6). Clearly longer term tests are needed to establish if there is a trendline but as stated above the system efficiency did not degrade over the test period leading one to believe that steady state may have been achieved. Appendix F shows average pressure drop across the test device (Table F-1) and motor amperages of the rotor (Table F-2). Pressure drop and motor amperage data were taken over a range of (1) bulk flow rates or approach velocities; and (2) rotational velocities, with and without screens on the spinning surfaces.

Pressure drops were found to be small; for example at 1800 RPM:

- 0.20 inches of water with an approach velocity of 0.05 ft/sec.

- 0.335 inches of water with an approach velocity of 0.35 ft/sec.

5.3 Long Duration Test and Data Analysis

The objective of the long duration test was to observe if there is degradation of system performance such as by blinding of the rotor surface over a 24-hour period of operation. The equipment used to perform the long duration test was the same system described in Section 4.

The long duration test was conducted in four consecutive periods of continuous operation the test device, namely (1) test series 301: six hours; (2) test series 302: eight hours; (3) test series 303: six hours; and (4) test series 304: four hours. The total duration of the test was 24 hours. The equipment was not cleaned or disassembled between these tests. Measurements were taken in each period for determination of the collection efficiency of each period and the total collection efficiency and fractional efficiency for the total 24-hour duration. Major test conditions and rotary cyclone parameters included:

- (1) Ambient and air temperature: 70°F;
- (2) Rotor diameter: 6 inches;
- (3) Rotor rotational speed: 1800 rpm;
- (4) Rotor surface: covered with 200 mesh screen;
- (5) Bulk flowrate: 7 acfm;
- (6) Approach velocity: 0.05 ft/sec;
- (7) Particulates: coal fly ash;
- (8) Design cutpoint of the test: 1 micron, i.e., the test device under above test conditions will separate out all particulates of size larger than 1 micron;
- (9) Test series duration: 24 hours.

During the course of the long duration test, pressure differences across the rotor surface were monitored in order to examine if there is degradation of system performance. The pressure did not change significantly over the test period from an

average value of 0.23 ± 0.01 inches of water. Details are included in Appendix E. Key data from the long duration test are included in Tables 5-1 and 5-2. The results show the total collection efficiency of the 24-hour long duration test is over 99.58% (mass basis). As in the earlier tests, fractional efficiencies are calculated from measurement of particulate size distributions at inlet and outlet duct of the test device. The data are plotted in Figure 5-2. The results show a complete separation of particulates with size greater than twice the cut point (i.e., greater than two microns). As stated earlier, one expects a decrease in particle collection efficiency below the cutsize (see Figure 5-1). However, the experimental data (Figure 5-2) show that over 96% of the particles below the cutsize were collected. We believe that agglomeration of submicrons with larger particulates might be the contribution to the very high efficiency especially below the one micron "cutsize". (Based on theoretical considerations and extrapolation of this data, an efficiency of 99.9% should be realizable by operation of the rotary cyclone with a smaller cutsize. However, this has yet to be demonstrated.)

It can be seen that the test results of the long duration test are consistent with the results of earlier collection efficiency tests (refer to Section 5.2). The results indicate that the device is capable of separating particulates near the designed cutsize over a longer term period of time without degradation in performance.

Table 5-1: Summary of Test Results for Long Duration Test

<u>No.</u>	<u>Test Series</u>	<u>Q</u> ¹ (cfm)	<u>L</u> ² (gr/cf)	<u>w</u> ³ (rpm)	<u>t</u> ⁴ (hrs)	<u>Mesh</u> ⁵	<u>Eff.</u> ⁶ (mass %)
1	301	7	0.2	1800	6	Yes	99.36
2	302	7	0.2	1800	8	Yes	99.70
3	303	7	0.2	1800	6	Yes	99.67
4	304	7	0.2	1800	4	Yes	99.56
5	300	7	0.2	1800	24	Yes	99.58*

¹Q-Bulk flow rate entering the rotary cyclone, cfm

²L-Fly ash loading rate, grains/cu ft

³w-Angular velocity of the rotor, rpm

⁴t-Time duration of continuous operation, hours

⁵Mesh-Rotor surface condition, with 200 mesh screen ("Yes")

⁶Efficiency-Collection efficiency (mass base) %

*"300" designates the calculated time average of tests 301, 302, 303, and 304 with total test duration of 24 hours and mass base efficiency of 99.58%

Table 5-2: Fractional Efficiency of Long Duration Test

Basis: Design Cutpoint = 1 micron
Rotor Speed = 1800 rpm
Rotor Diameter = 6 inches
Approach Velocity = 0.05 ft/sec
Test Duration = 24 hours
Particulates = Coal Fly Ash

<u>ECD*</u>	<u>Fractional Efficiency**</u>
> 2	100%
1.2-2	99.41%
< 1.2	96.48%

*ECD-Effective cutoff diameter in microns

**Fractional efficiencies of each particulate size shown are calculated from weight fractions of inlet and outlet size distributions. The total efficiency (mass base) of 24-hour long duration test is 99.58%.

Basis: Test designed for 1 micron cut point

Figure 5-2: Fractional Efficiency vs. Average Size of Particles
(Long Duration Test)

6.0 ENGINEERING SCALE-UP

There are three dominant parameters in scale-up of the test device, i.e., the centrifugal force, the approach velocity (CFM gas/ft² of "filter" surface), and effect of temperature on flue gas viscosity. In order to achieve a desired particulate "cutsize," an increase in approach velocity must be incorporated with an increase in centrifugal force. From theoretical considerations, increase in centrifugal force alone while keeping the approach velocity the same will increase the separation performance or reduce the cutsize of particulates to be collected.

The volumetric capacity of a single rotary cyclone unit can be expressed in the following formula:

$$q = \pi Dh V_a \quad (6-1)$$

where V_a is the approach velocity and πDh is the cross flow area of the rotor. V_a can be found in Appendix A (see "Critical Angular Velocity") and substituted into 6-1.

$$q = 5.98 \times 10^{-6} (h)(D)^2 (\omega)^2 (dp)^2 \quad (6-2)$$

Physical properties of particulates and gas stream are taken into consideration in the conversion coefficient in equation 6-2 as follows:

Gas viscosity @ 300°F = 1.6×10^{-5} lbm/sec ft

Particle density = 155 lbm/cu ft (specific gravity = 2.5)

where q = volumetric capacity of a single rotary cyclone unit, acfm
 h = height of the rotor, ft
 D = diameter of the rotor, ft
 ω = angular velocity of the rotor, rpm
 dp = particulate size to be separated, microns

"Cutsizes" is defined such that particulates with sizes larger than the cutsizes will be separated from gas stream by the rotary cyclone device.

The total volumetric capacity of the scaled-up rotary cyclone installation will be:

$$Q = (N) (q) \quad (6-3)$$

where Q = total volumetric capacity of scaled-up rotary cyclones, acfm

q = volumetric capacity of a single rotary cyclone unit, acfm

N = Number of rotary cyclone units

A coal-fired utility boiler with generating capacity of 40 MWe is chosen as the basis for the conceptual design of the scaled-up rotary cyclone as well as the basis for cost comparisons with fabric filters and electrostatic precipitators.

The conceptual scaled up rotary cyclone is based on the test work using one micron cutsize; it is anticipated that the scaled up device can obtain efficiencies similar to the device used in this test program (i.e. 99.58% as shown in Table 5-1). (It should be noted that one could design also for other cutsizes: e.g., a 2 micron cutsize, 0.5 micron cutsize, etc. Experimental data and theory suggest that operating with a smaller cutsize increases particle collection efficiencies. For each cutsize, the design methodology is the same as that described below).

Key parameters and dimensions of the scaled-up rotary cyclone are tabulated in Table 6-1. As the RPM of the device is increased, a smaller rotor area is needed for treating a given volume of gas. Based on information to date, we can only estimate a practical RPM range for a scaled-up device by drawing on industrial experience with rotating equipment (e.g., turbines, fans, etc.) where rotational speeds of 3,600 to 10,000 RPM may be found, typically limited by keeping tip velocities below sonic. As a result of such considerations and to illustrate potential tradeoffs of capital investments and operating costs, there are two cases of the scaled-up rotary cyclone installations presented in Table 6-1 for cost analysis. Case I incorporates lower rotor speed (3,600 rpm) and lower approach velocity (1.364 ft/sec). Case II utilizes higher rotor speed (6,400 rpm) and higher approach velocity (4.312 ft/sec). However, performance criteria in both cases are the same, i.e., to separate one micron and larger particulates from flue gas stream at 300°F. (Calculations take into account the higher viscosity and lower density of the flue gas at these higher temperatures.)

In the conceptual design developed, rotary cyclones are clustered into modules, each of which contains a number of rotary cyclones. Rotary cyclones in one module share main inlet and outlet ducts, but have their own rotors, motors and shells. Figures 6-1 and 6-2 show the side view and top view of a scaled-up module having a cluster of six rotary cyclone units. Overall dimensions of the scale-up module are also shown in these two figures. There are three modules in Case I application and one module in Case II application (i.e., Case II with its higher centrifugal forces needs only one module to treat the same volume of gases as in Case I with its 3 modules operating at a lower centrifugal force).

For each rotary cyclone, incoming gas enters tangentially and exits tangentially as well. Driving motors are located at the lower end of the rotor for easy access and maintenance work. Both bearings are mounted outside the device and are protected by mechanical seals from the hot and dirty environment inside the rotary cyclone. The air seal mechanism near the top of the rotor is a key element to the performance of the rotary cyclone device; it uses a minimum amount of air to seal the outgoing clean gas stream from the incoming dirt gas stream.

Table 6-1: Parameters and Dimensions of Scaled-up Rotary Cyclone Device
Basis: Separation of 1 micron and larger-sized particulates

	<u>Case I</u>	<u>Case II</u>
Boiler size, MWe	40	40
Total Flue Gas, acfm @ 300°F	125,000	125,000
Diameter of the rotor, ft	3	3
Height of the rotor, ft	10	10
Rotor speed, rpm	3,600	6,400
Approach velocity, ft/sec	1.36	4.3
Volumetric capacity of rotary cyclone unit, acfm @ 300°	6,975	22,045
Number of rotary cyclone units	18	6
Number of rotary cyclone modules	3	1

FIGURE 6-1
SCALED-UP MODULE OF ROTARY CYCLONE
(Side View)

FIGURE 6-2
SCALED-UP MODULE OF ROTARY CYCLONE
(Top View)

7.0 COST ANALYSIS

Preliminary capital costs as well as O&M costs of the scaled-up rotary cyclone modules were calculated and were estimated with fabric filter and electrostatic precipitator particulate control devices. The basis of this comparison is a coal-fired boiler with 40 MWe generating capacity giving off-gas volume of 125,000 acfm at 300°F as described in Section 6. To illustrate the effect of rotor speed on capital and operating costs on scaled-up rotary cyclone, two cases are considered in the cost analysis. Case I incorporates lower rotor speed (3,600 rpm) and lower approach velocity (1.36 ft/sec). Case II utilizes higher rotor speeds (6,400 rpm) and higher approach velocity (4.31 ft/sec). It should be recognized that the scale-up is very significant in terms of equipment size, approach velocity, etc. and thus the results of these scale-up calculations should be used with caution.

The pressure drop of the scaled-up rotary cyclone and motor amperage of the rotor are estimated by extrapolating laboratory-scale tests (Appendix F) to the scaled-up size. Data were plotted on logarithmic papers for estimating performance on the scaled-up device as shown in Appendix G of this report.

The relation between independent and dependent variables for extrapolation calculations is given as follows:

$$\frac{Y_2}{Y_1} = \left(\frac{X_2}{X_1} \right)^n$$

where X = independent variables (centrifugal force or approach velocity)

Y = dependent variables (pressure drop or motor amperage)

n = scale factor derived from experimental data

= $\log (Y_2/Y_1)$ divided by $\log (X_2/X_1)$

The scale factor is determined from the slope on a plot of Y vs. X on log-log coordinates. A summary of scale factors calculated from the plots in Appendix G is given in Table 7-1.

Table 7-1: Summary of Scale-up Factors

Y	X			
	g		g	
	<u>W 200</u>	<u>W/O 200</u>	<u>W 200</u>	<u>W/O 200</u>
<u>ΔP</u>	0.635	0.654	0.256	0.149
<u>A</u>	0.240	0.259	0.0495	0

X = independent variables (g or Va)
 Y = dependent variables (Δp or A)
 n = scale-up factor
 ΔP = pressure drop, "H₂O"
 A = rotor amperage
 g = "g" force
 Va = approach velocity, ft/sec
 W/O 200 = without 200 mesh screen
 W 200 = with 200 mesh screen

Pressure drop and motor amperage for the scaled-up rotary cyclone are:

- Pressure drop Δp
 - = 3.745" H₂O (Case I)
 - = 9.78" H₂O (Case II)
- Rotor motor amperage; A = 10.15-amp (Case I, continuous operation @ 110 volts)
 - = 14.11 amp (Case II, continuous operation @ 110 volts)

Based on the operating data of the scaled-up rotary cyclones, 20 HP (Case I) and 30 HP (Case II) motors with motor starters are chosen to provide smooth acceleration of rotors during the start-up period as well as the driving power during normal operation. Power consumption for rotor motors as well as for induced draft fans in the system are shown in Appendix H of this report (Table H-7). This information is used to estimate the total operating and maintenance costs.

In addition, the estimated capital costs are developed in Appendix H. Costs of the shell including inlet, outlet and the cone are obtained from a similar cyclone investment. Costs of the rotor including the shaft, static and dynamic balancing, as well as cost of motor, bearings, etc. were obtained from various vendors.

The estimated capital cost and O&M costs of fabric filters and electrostatic precipitators are based on EPRI-CS-4083 (June 1985)* and data in our files supplemented with vendor information. Costs are expressed in January 1989 dollars.

*EPRI Report "Economics of Fabric Filters and Electrostatic Precipitators - 1984"

Comparisons are also made for 30-year levelized costs of scaled-up rotary cyclone devices, fabric filters and electrostatic precipitators. The capital charge rate is 15.3% and the O&M charge factor is 1.633 for all three technologies (based on annual discount rates at 11% and escalation rate at 5%). In addition, the construction period is assumed to be three years and an allowance is made for this cost at 5.8% of the total capital investment.

The "differential cost" in the estimation of capital costs is defined as the capital investment cost incorporated with the I.D. fan in order to overcome additional pressure lost through the particulate control devices.

In summary, Table 7-2 highlights assumptions used in undertaking the cost comparisons of scaled-up rotary cyclone device (RC), the fabric filters (FF) and electrostatic precipitators (ESP), based on applications to typical pulverized coal-fired boilers.

The result of cost comparisons of these three particulate emission control technologies is shown in Table 7-3. This economic analysis has indicated that for utility sized (40 MWe) coal-fired boiler application:

- The capital investments of the scaled-up rotary cyclone device in Case I is 82% of that of fabric filters and 77% of that of electrostatic precipitators.
- The estimated operating and maintenance costs of the scaled-up rotary cyclone device in Case I is 75% of that of fabric filters and 84% of that of electrostatic precipitators.
- Capital investment cost in Case II is 44% of that of fabric filters and 41% of that of electrostatic precipitators. The operating and maintenance costs in Case II is 85% of that of fabric filters and of that of electrostatic precipitators.

Table 7-2: Basis for Cost Estimates

	<u>Fabric Filter</u>	<u>ESP</u>	<u>Rotary Cyclone</u>
Coal-fired boiler capacity	40 MWe	40 MWe	40 MWe
Gas volume	125,000 acfm	125,000 acfm	125,000 acfm
Gas temperature	300°F	300°F	300°F
Rotor speed	--	--	3,600 rpm (Case I) 6,400 rpm (Case II)
Air/cloth ratio (A/C)	2.7	--	82 (Case I) 259 (Case II)
Approach velocity	0.045 ft/sec	--	1.364 ft/sec (Case I) 4.312 ft/sec (Case II)
Specific collection area (SCA)	--	452	--
Relative g force	--	--	6654 (Case I) 21,030 (Case II)
Structure	Baghouse	Rigid Frame	Rotor/Shell
Bag material	Fiberglass	--	--
Pressure drop* (inches, H ₂ O)	9.8	3.0	5.0 (Case I) 11.78 (Case II)
Emission standard	0.03 lb/10 ⁶ Btu	0.03 lb/10 ⁶ Btu	0.03 lb/10 ⁶ Btu**
Coal	Appalachian Low-Medium Sulfur	Appalachian Low-Medium Sulfur	Appalachian Low-Medium Sulfur

*Include plenum pressure drop of 1.25" to 2" H₂O for FF, ESP and R.C;

**Scaled-up spin filter is designed to separate particles with one-micron sizes or larger from the gas stream.

Table 7-3: Cost Comparison-Rotary Cyclone (RC) vs. Fabric Filter (FF) and Electrostatic Precipitator (ESP))

Basis: Coal-fired Boiler 40 MWe, Emission Limit 0.03/10⁶ Btu, 1988 Dollars

	<u>FF</u>	<u>ESP</u>	<u>RC</u>	
			<u>Case I*</u>	<u>Case II**</u>
<u>Installed Capital</u>				
\$ x 10 ⁶	2.73	2.92	2.24	1.20
<u>Installed Capital/kW</u>				
\$/kW	68.3	73.1	56.0	30.0
<u>O&M Costs</u>				
\$ x 10 ³ /yr	362	324	271	309
<u>30-year Levelized Cost</u>				
Mills/kWh	4.43	4.29	3.45	3.03

*Case I: Rotor speed = 3,600 rpm
Approach velocity = 1.36 ft/sec
Equivalent A/C ratio = 82

**Case II: Rotor speed = 6,400 rpm
Approach velocity = 4.31 ft/sec
Equivalent A/C ratio = 259

- The 30-year levelized cost of the scaled-up rotary cyclone device is up to 28% (Case I) and 44% lower than that of fabric filters and electrostatic precipitators.
(case II)
- The 30-year levelized cost of the scaled-up rotary cyclone device is up to 32% lower than that of fabric filters and electrostatic precipitators.

This shows that the rotary cyclone device might be a potential candidate and economic choice in controlling fine particulate emissions from coal-fired utility boilers. Case II shall result in substantial capital investment savings up to about 50%, while offering O&M costs comparable to an ESP and fabric filters. However, Case I offers lower O&M cost at the expense of capital investments. As a result, there is the potential of designing the rotary cyclone to fit a specific user's needs (e.g., trading off lower operating costs against higher capital investments).

8.0 CONCLUSIONS

The following summarizes some key findings and conclusions drawn from this research effort:

- Test data taken indicate:
 - Theory correlates relatively well with experiment on cutsize;*
 - Vortex phenomena does not appear to be a major problem in efficiency of particle separation;
 - Dust loading on inlet gas in the order of 0.22 to 1.97 grain/cu-ft appears to have little impact on performance in accordance with theory; and
 - Fly ash collection efficiencies of 99.58% (mass basis) have been achieved in the laboratory tests and 99.9% should be realizable by operating the rotary cyclone at a smaller cutsize.*
- The particulate collection efficiency for the rotary cyclone is expected to be competitive with fabric filters and electrostatic precipitators.
- For utility applications with coal-fired boilers, estimated capital investment costs together with operating and maintenance costs of the scaled-up rotary cyclone is predicted to be lower than fabric filters and electrostatic precipitators and, hence, to offer economic advantages.

*Cutsize is such defined as a critical size such that particulates with sizes larger than the cutsize will be separated from gas stream by rotary cycle device; experimental data show that over 96% of the particulates below the cutsize are also collected.

In summary, Table 8-1 shows technical and economic comparisons of the rotary cyclone device with other particle collection technologies including ESP's, fabric filters, venturi scrubbers, and multiple cyclones. In technical performance, the rotary cyclone device is projected to be competitive with Fabric Filter (FF) and Electrostatic Precipitator (ESP) in terms of the minimum size of particulates to be separated and the efficiency of separation, while offering lower power consumption than a venturi scrubber and better particle collection efficiencies than multiple cyclones. Although moving parts are incorporated in the rotary cyclone device, the pressure drop is expected to be lower than that of fabric filters. The approach velocity (which is equivalent to the air/cloth ratio) of the scaled-up rotary cyclone device is calculated to be 30 to 100 times greater than fabric filters. Therefore, the rotary cyclone incorporates much less surface area at which the gas/solids separation occurs. The economic analysis has also indicated that the estimated 30-year levelized cost of the scaled-up rotary cyclone device (40 MWe) is significantly lower than that of fabric filters and electrostatic precipitators. Moreover, the rotary cyclone offers the potential for separating out smaller (sub-micron sized) particles than the ESP, offers no greater pressure drop for collecting sub-micron sized particles, and potentially is able to operate at high gas temperatures and corrosive atmospheres beyond the capability of fabric filters as summarized in Table 8-2. As a result, the rotary cyclone offers a number of potentially interesting features, but work on a scaled-up apparatus is needed in order to confirm the results of these small-scale tests and economic projections.

Table 8-1: Technical Comparison - Rotary Cyclone vs. Other Particle Collection Devices

	Min. Size of Part. (Micron)	Efficiency % <u>Mass Base</u>	Pressure <u>Drop</u>	<u>Cost</u>
Electrostatic precipitators	>1	95-99	Low	<ul style="list-style-type: none"> • More <u>expensive</u> initially • Nominal O&M costs
Fabric filters	<1	>99	High	<ul style="list-style-type: none"> • Less expensive initially than ESP • More expensive to operate due to <u>replacement of bags</u>
Venturi scrubbers	>0.5	<99	High	<ul style="list-style-type: none"> • <u>High power costs</u>
Multiple cyclones	>5	50-90 95 maximum under ideal conditions	High	<ul style="list-style-type: none"> • Relatively low capital cost
Rotary cyclone	<~1	>99	Low	<ul style="list-style-type: none"> • Offers potentially lower capital costs than ESP or FF

Table 8-2: Technical Comparison - Rotary Cyclone vs. Other Particle Collection Devices

	<u>Advantages</u>	<u>Disadvantages</u>
Electrostatic precipitators	<ul style="list-style-type: none"> • Can operate at 300°F or higher 	<ul style="list-style-type: none"> • Large unit size and <u>expensive</u> • Sensitive to dust flue gas characteristics • Require safeguards due to high voltage
Fabric filters	<ul style="list-style-type: none"> • Collect submicron particles • Provide continuing reaction surface if coupled with dry SO₂ scrubber 	<ul style="list-style-type: none"> • Can't operate at high temp. (500°F) • <u>Excessive pressure drop</u> • Susceptible to moist dust and chemical attack
Venturi scrubbers	<ul style="list-style-type: none"> • Require less maintenance • Insensitive to type of ash, flue gas condition 	<ul style="list-style-type: none"> • Cause <u>secondary pollution</u> • Corrosion problems • Losing favor in application
Multiple cyclones	<ul style="list-style-type: none"> • Near maintenance free • Simplicity of design 	<ul style="list-style-type: none"> • <u>Susceptible</u> to flue gas flow rate, temp. and dust loading • Difficulty in meeting air emission standards
Rotary cyclone	<ul style="list-style-type: none"> • Can operate efficiently over a large turndown rate • Potential operation at high temperatures • Low pressure 	<ul style="list-style-type: none"> • Incorporates moving parts

REFERENCES

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2. Scheck, R.W., et. al., Economics of Fabric Filters and Electrostatic Precipitators, EPRI, June 1985.
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APPENDIX A

MATHEMATICAL MODEL

A.1 Overview

This appendix provides additional details on the theoretical analysis of the laminar flowfield in the annulus of the rotary cyclone based on a relatively simple mathematical model. Table A-1 (Mathematical Model) summarizes the equations in this analysis. Equations are developed in cylindrical coordinates where the velocity is given by scalar quantities, V in the radial direction, U in the tangential direction, and W in the axial direction. Details on the flowfield momentum equations in cylindrical coordinates can be found in standard texts on fluid flow (e.g., H. Schlichting, "Boundary Layer Theory"; Bird, et. al., "Transport Phenomena"; F. White, Fluid Mechanics, etc.). Table A-2 (Symbols) provide definitions of symbols used in the mathematical model.

Calculations are made to determine:

- The angular velocity of the fluid in the annulus, and
- The angular velocity at which a particle of diameter $2a$ is thrown off the rotating surface due to centrifugal forces.

Key assumptions are shown in Table A-3.

Near the rotating filter surface, centrifugal forces are an order of magnitude greater than the gravity forces (i.e., in the order of 25 or more times gravitational force near the rotating filter). Therefore, the flow near the rotor surface can be estimated by neglecting the axial component of the forces.

The flow profiles are obtained by solving the Navier-Stokes equations. For velocities less than about 335 ft/sec, the air can be treated as though the density

TABLE A-1
MATHEMATICAL MODEL

• Continuity Equation

$$\nabla \cdot \vec{V} = 0$$

eq A-1

• Momentum Equation (Navier-Stokes)

$$\rho \frac{D\vec{V}}{Dt} = \vec{F} - \nabla P + \mu \nabla^2 \vec{V}$$

eq A-2

• Assumptions: ANGULAR SYMMETRY $\frac{dU}{d\phi} = 0$

eq A-3

NEGLECT VELOCITY $\frac{dW}{dz} = 0$

eq A-4

• Continuity Equation in Cylindrical Coordinates

$$\frac{\partial V}{\partial r} + \frac{V}{r} = 0$$

eq A-5

• N-S Equation in Cylindrical Coordinates

$$\phi - \text{Dir}, \rho \left(\frac{VU}{r} + V \frac{\partial U}{\partial r} \right) = \mu \left(\frac{\partial^2 U}{\partial r^2} + \frac{1}{r} \cdot \frac{\partial U}{\partial r} - \frac{U}{r^2} \right)$$

eq A-6

$$r - \text{Dir}, \rho \left(V \frac{dV}{dr} - \frac{U^2}{r} \right) = F_r - \frac{\partial P}{\partial r} + \mu \left(\frac{\partial^2 V}{\partial r^2} + \frac{1}{r} \frac{\partial V}{\partial r} - \frac{V}{r^2} \right)$$

eq A-7

• V PROFILE

$$V = V_s \left(\frac{a}{r} \right)$$

eq A-8

• DIFFERENTIAL EQUATION FOR U

$$\frac{\partial^2 (rU)}{\partial r^2} - \frac{L}{r} \frac{\partial (rU)}{\partial r} = 0$$

eq A-9

WHERE $L = 1 + (R_c / 2)$

eq A-10

$$R_c = \frac{2\rho(a)V_s}{\mu}$$

eq A-11

TABLE A-1 (Continued)

MATHEMATICAL MODEL

• U PROFILE

$$U = \frac{1}{\left[\left(\frac{r_a}{r_b}\right)^{L+1} - 1\right]} \left(\left[\left(\frac{r_a}{r_b}\right) U_a - U_b \right] \left(\frac{r}{r_b}\right)^L - \left[U_a - \left(\frac{r_a}{r_b}\right)^L U_b \right] \left(\frac{r_a}{r}\right) \right) \quad \text{eq A-12}$$

• DRAG FORCE

$$D = 6\pi\mu a_p V \quad \text{eq A-13}$$

• CENTRIFUGAL FORCE

$$F_c = \frac{4}{3} \pi \rho_p a_p^3 r \omega^2 \quad \text{eq A-14}$$

• CRITICAL ANGULAR VELOCITY

$$\omega_c = \frac{90}{\pi d_p} \left(\frac{2\mu V_a}{a\rho_p} \right)^{1/2} \quad \text{eq A-15}$$

TABLE A-2

SYMBOLS

a	Radius of rotating surface, ft
a_p	Radius of particle, ft
b	Inner wall radius of the shell, ft
D	Drag force, lb _f
d_p	Diameter of particle, ft
F	Body force, lb _f
F_c	Centrifugal force acting on particles, lb _f
P	Pressure, lb _f /ft ²
r	Radius in cylindrical coordinates, ft
R_c	Modified Reynolds number for a rotating cylinder
t	Time
U	Angular velocity component, ft/sec
V	Radial velocity component (approaching velocity), ft/sec
μ	Absolute viscosity, lb _m /ft-sec
ϕ	Angle in cylindrical coordinates
ρ	Density, lb _m /ft ³
ω_c	Critical rotational speed, rpm

Table A-3: Key Assumptions

- Flow is viscous.
- Flow is at steady state.
- Flow is incompressible (for velocities less than about 335 ft/sec, the air can be treated as incompressible fluid: Schlichting).
- Fluid is Newtonian and isotropic, and viscosity is constant.
- Flow is two-dimensional, i.e., in cylindrical coordinates, the vertical component of velocity is assumed negligible.
- Flow is symmetrical about the center axis of the cylinder (entrance effects are neglected).
- Solids are of small size, and thus their velocity is assumed to be the same as that of the fluid.
- Solid particles are of spherical shape.

were constant (Schlichting). Since the rotational velocities and approach velocities for this rotating filter are much below 330 ft/sec, use of a constant density in the fluid flow equations yields a very good approximation.

A.2 Continuity and Navier-Stokes Equations

The first two equations in Table A-1 show in vectorial form the continuity and Navier-Stokes equations. Upon assuming angular symmetry (eqs A-3 and A-5) and neglecting the vertical component of the gas velocity (eq A-4), the Navier-Stokes (N-S) Equations in cylindrical coordinates are formulated in eqs A-6 and A-7 of Table A-1. The approach velocity in the radial direction is immediately obtained from the continuity equation (see "V profile", eq A-8, in Table A-1). By substitution of the velocity, V , into the Navier-Stokes equation A-6, equation A-9 is obtained. The solution to the tangential velocity profile, U , is provided in eq A-12 upon assuming the following boundary conditions:

- At the filter surface, the fluid is moving with the angular velocity of the filter: ($U = U_0$): and
- At the outside edge of the annulus or boundary layer, the angular velocity is $U = U_\infty$.

It is seen that the angular velocity is described by R_θ which represents a modified Reynolds number for a rotating cylinder.

Eq A-12 describes the angular velocity of the fluid as a function of radius, r . Examination shows that when there is no flow through the filter ($V_r = 0$, $L = 1$), this equation breaks down into the velocity profile given in several references for the angular velocity of fluid in the annulus of concentric rotating cylinders (e.g., Bird, et.al., H. Schlichting). A sample calculation is shown in Appendix B.

A.3 Drag and Centrifugal Force Balances

The drag force on a particle is given by $D = C_D (0.5 \rho V_a^2)$ where C_D is the drag coefficient. Since the particle Reynolds number is generally quite small, the drag force is found by Stokes Law (see Table A-1, "Drag Force", eq A-13). The centrifugal force, F_c , acting on the particle due to the rotation of the fluid is given by eq A-14 in Table A-1. The fluid drag force results from the approaching flow velocity towards the center of the device while the centrifugal force is produced by angular flow velocity tending to "throw" particles away towards the outside shell wall. The main function of the rotating surface is to create a centrifugal force field for particles in order to overcome the drag force so that particle-gas separation can be achieved. If a particle is on the rotating surface, the rotational speed can be increased to the point where the centrifugal forces will just equal the drag forces. A further increase in the rotational speed will throw the particle off the surface. When the centrifugal forces just equal the drag force, a "critical" angular velocity of the rotating surface is achieved as shown by eq A-15.

An analysis of these equations shows:

- For most reasonable approach velocities (e.g., over 0.02 ft/sec), the angular velocity, U , is dictated largely by the rotor. The approach velocity, V_a , has little effect on the U profile.
- Particle separation is achieved close to the rotor surface and not in the annulus. This is because the ratio of centrifugal force to particle drag forces is maximized on the rotor surface. Thus, even if the annulus exhibited turbulent flow (vortices), particle separation should still be achievable if there is a laminar boundary layer on the spinning rotor.
- The boundary layer is expected to be stabilized with higher approach velocities much as "suction" on a wing foil stabilizes a foil's boundary layer. This should aid in obtaining higher throughputs through a scaled-up device having higher rotational velocities.

APPENDIX B

VELOCITY PROFILE

B.1 Overview

This appendix contains sample calculations and plots of the tangential velocities in the annulus of the spin filter device. Table B-1 (Sample Calculations of Theoretical Value of Tangential Velocities) tabulates theoretical value of the tangential velocities calculated from the formula in Appendix A, Table A-1 (Mathematical Model specifically the equation for the "U profile").

B.2 Results

Figure B-1 (Plot of Calculated Values of Tangential Velocities in Annulus for very Small Approach Velocities and Figure B-2 (Plot of Calculated Values of Tangential Velocities in Annulus for Large Approach Velocities) provide tangential velocity profiles in the annulus against radius as well as various approach velocities. Key parameters used in these sample calculations are: (1) radius of spinning surface = 0.25 ft; (2) radius of inner wall of the shell = 0.5 ft; (3) angular velocity of the spinner = 3,918 rpm; and (4) approach velocities of 0, 0.02, 0.005, 0.02, 0.05 and 0.2 ft/sec.

Examination of Figure B-2 shows that for most reasonable approach velocities ($V_a > 0.02$ ft/sec), the velocity profile in most of the annular region is independent of V_a . This indicates that the rotor speed has a major and dominating force in dictating the velocity profile throughout the annular region.

B.3 Sample Calculation

To illustrate how the values in Table B-1 are derived, the tangential air velocity is calculated in the annulus at $r = 0.40$ ft. (radius) and a rotational velocity of the rotor of 3918 rpm for the following conditions (see Table B-1):

- $Q = 2.8274$ CFM (inlet gas flow rate)
- $V_a = 0.02$ ft./sec. (approach velocity)
- $A = 0.25$ ft. radius (rotor)
- $B = 0.50$ ft. radius (shell)

TABLE B-1

SAMPLE CALCULATIONS OF THEORETICAL VALUE OF TANGENTIAL VELOCITIES

DOE SPIN FILTER ***SP2***						
ADL CONF						
$\rho(a)$ lb/ft ³	0.0908					
$\rho(b)$ lb/ft ³						
μ (lbm/s-ft)	0.0000					
<hr/>						
A(ft)	0.2500					
B(ft)	0.5000					
Va(ft/s)	0.0000	0.0000	0.0050	0.0100	0.0200	0.0400
$Rc(2 \cdot A \cdot Va \cdot \rho(a) / \mu)$	0.0000	6.9060	17.2650	34.5300	69.0600	138.1200
$L(1 + Rc/2)$	1.0000	4.4530	9.6325	35.5299	87.3248	346.2991
<hr/>						
Wa(rpm)	3919					
Wal(rad/s)	410.2917					
Vohl(A), ft/min, cal	6154.375					
l(drum)(ft)	3.0000					
n,(2*a), ft, cal	0.5000					
b,(A), ft, cal	0.2500					
sin(ft ²), cal	0.1250					
<hr/>						
Q(cfm), 0.5*Va*2pi*A*1.60	0.0000	0.2827	0.7069	1.4137	2.8274	5.6548
Vin(ft/min), Q/sin	0.0000	2.7519	5.6548	11.3096	22.6191	45.2382
Wb(rpm), Vin/B/2pi	0.0000	0.7200	1.8000	3.6000	7.2000	14.4000
Wb(rad/s), cal	0.0000	0.0754	0.1885	0.3770	0.7540	1.5080
<hr/>						
(r) ft	Tangential Air Velocity Vohl (ft/min)					
0.2500	6154.375	6154.375	6154.375	6154.375	6154.375	6154.375
0.2500	5984.725	5984.725	5984.725	5984.725	5984.725	5984.725
0.2500	5815.075	5815.075	5815.075	5815.075	5815.075	5815.075
0.2500	5645.425	5645.425	5645.425	5645.425	5645.425	5645.425
0.2500	5475.775	5475.775	5475.775	5475.775	5475.775	5475.775
0.2500	5306.125	5306.125	5306.125	5306.125	5306.125	5306.125
0.2500	5136.475	5136.475	5136.475	5136.475	5136.475	5136.475
0.2500	4966.825	4966.825	4966.825	4966.825	4966.825	4966.825
0.2500	4797.175	4797.175	4797.175	4797.175	4797.175	4797.175
0.2500	4627.525	4627.525	4627.525	4627.525	4627.525	4627.525
0.2500	4457.875	4457.875	4457.875	4457.875	4457.875	4457.875
0.2500	4288.225	4288.225	4288.225	4288.225	4288.225	4288.225
0.2500	4118.575	4118.575	4118.575	4118.575	4118.575	4118.575
0.2500	3948.925	3948.925	3948.925	3948.925	3948.925	3948.925
0.2500	3779.275	3779.275	3779.275	3779.275	3779.275	3779.275
0.2500	3609.625	3609.625	3609.625	3609.625	3609.625	3609.625
0.2500	3439.975	3439.975	3439.975	3439.975	3439.975	3439.975
0.2500	3270.325	3270.325	3270.325	3270.325	3270.325	3270.325
0.2500	3100.675	3100.675	3100.675	3100.675	3100.675	3100.675
0.2500	2931.025	2931.025	2931.025	2931.025	2931.025	2931.025
0.2500	2761.375	2761.375	2761.375	2761.375	2761.375	2761.375
0.2500	2591.725	2591.725	2591.725	2591.725	2591.725	2591.725
0.2500	2422.075	2422.075	2422.075	2422.075	2422.075	2422.075
0.2500	2252.425	2252.425	2252.425	2252.425	2252.425	2252.425
0.2500	2082.775	2082.775	2082.775	2082.775	2082.775	2082.775
0.2500	1913.125	1913.125	1913.125	1913.125	1913.125	1913.125
0.2500	1743.475	1743.475	1743.475	1743.475	1743.475	1743.475
0.2500	1573.825	1573.825	1573.825	1573.825	1573.825	1573.825
0.2500	1404.175	1404.175	1404.175	1404.175	1404.175	1404.175
0.2500	1234.525	1234.525	1234.525	1234.525	1234.525	1234.525
0.2500	1064.875	1064.875	1064.875	1064.875	1064.875	1064.875
0.2500	895.225	895.225	895.225	895.225	895.225	895.225
0.2500	725.575	725.575	725.575	725.575	725.575	725.575
0.2500	555.925	555.925	555.925	555.925	555.925	555.925
0.2500	386.275	386.275	386.275	386.275	386.275	386.275
0.2500	216.625	216.625	216.625	216.625	216.625	216.625
0.2500	46.975	46.975	46.975	46.975	46.975	46.975

Figure B-1: Plot of Calculated Values of Tangential Velocities in Annulus for Small Approach Velocities (V_a)

Figure B-2: Plot of Calculated Values of Tangential Velocities in Annulus for Large Approach Velocities (V_a)

$$\rho = 0.0808 \text{ lb./ft}^3 \text{ (air density)}$$

$$\mu = 1.17 \times 10^{-5} \text{ lbs./sec-ft. (note that Table B-1 shows a zero value because only four significant figures are shown after the decimal point on the printout)}$$

$$s = 0.125 \text{ sq. ft. (inlet cross-sectional area of duct for gas flow)}$$

Based on the above, calculated values are:

$$R_c = 69.059 \text{ (dimensionless)}$$

$$L = 35.53 (= 1 + R_c/2)$$

$$U_s = 6154 \text{ ft./min. } (= \pi A \cdot 3918 \text{ rpm})$$

$$U_b = 22.62 \text{ ft./min. (inlet gas velocity at shell wall } = 2.8274 \text{ CFM}/0.125 \text{ sq ft.)}$$

Substitution of these values into equation 12 of Table A-1 yields a tangential velocity of 3845 ft./min. in accord with Table B-1 (see row labeled 0.40 ft.(r) and column $V_s = 0.02$).

APPENDIX C

EXPERIMENTAL DESIGN OF ROTARY CYCLONE DEVICE

This appendix contains design details of the rotary cyclone device. Figure C-1 is an assembly drawing followed by drawings of components:

- Figure C-1: Experimental Design of Rotary Cyclone Assembly
- Figure C-2: Top Plate of Rotary Cyclone
- Figure C-3: Bottom Plate of Rotary Cyclone
- Figure C-4: Inlet Section of Rotary Cyclone
- Figure C-5: Outlet Section of Rotary Cyclone
- Figure C-6: Rotor of Rotary Cyclone
- Figure C-7: Shaft of Rotary Cyclone
- Figure C-8: Shell of Rotary Cyclone
- Figure C-9: Bottom Cone of Rotary Cyclone

4. 10. 11

ADL

REF. 60683

JUNE, 1928

13

Figure C-2: Top Plate of Rotary Cyclone

ADL
REF 60683
MAY, 1988

REV. A 3mm

Figure C-3: Bottom Plate of Rotary Cyclone

1. UNIT OF DIMENSIONS . INCH
2. DO NOT SCALE
3. CLEAN BUBBLES AFTER CUTTING, SIX OPERATIONS
BUT, SIX ARMS
4. MATERIAL . CARBON STEEL

Figure C-4: Inlet Section of Rotary Cyclone

A-A

B-B

NOTES.

1. UNIT OF DIMENSIONS - INCH
2. TO NET SCALE

ADL
REF. 60683
JUNE, 1988
Bm

Figure C-5: Outlet Section of Rotary Cyclone

C-7

NOTES:

1. DIMENSIONS - INCH
2. MATS - PLEXIGLASS, 3/8" THK (TRANSPARENT)
3. DO NOT SCALE

ADL
REF. 60683
MAY, 1988

Figure C-7: Shaft of Rotary Cyclone

ADL
REF. 60683
JUNE, 1988

NOTES:
1 UNIT OF DIMENSIONS INCH
2 DO NOT SCALE

Figure C-8: Shell of Rotary Cyclone

APPENDIX D

SYSTEM LAYOUTS

This appendix summarizes the spin filter system layouts for three series of tests, i.e. (1) 100 test series (flowfield tests); and (2) 200 and 300 test series (collection efficiency and long duration tests). Figure D-1 (System Layout for 100 Test Series) provides an overview of the system for flowfield tests and Figure D-2 (System Layout for 200, and 300 Test Series) provides an overview of the system for collection efficiency tests. In both figures, locations of measurements taken are indicated with symbols. Symbols are explained in a legend block in each figure.

FIGURE D-2

SYSTEM LAYOUT FOR 200, AND 300 TEST SERIES

- A - Amperes
- F - Flow Rates
- FD - Dust Feeder
- FN - Induced Fan
- FT - Inlet Air Filter
- G - Dampers
- IMP - Anderson Impactor
- M - Motor
- P - Static Pressures
- PM - Pump
- REG - Regulator
- S - Size Distribution Analyzer
- T - Temperature
- VAC - Vacuum System
- VAL - Valve
- V - Velocities
- W - Mass Measurement
- ω - Rotational Speed

APPENDIX E

COLLECTION EFFICIENCY TEST

The main body of this report has summarized the collection efficiency tests and data analyses. This appendix contains test results from these collection efficiency tests. It includes the following tables and figures:

Table E-1: Summary of Test Results

Table E-2: Fractional Efficiency of Test Series #207

Table E-3: Fly Ash Size Distribution at Inlet of Rotary Cyclone

Table E-4: Fly Ash Size Distribution at Cleaned Gas Outlet of Rotary Cyclone

Table E-5: Pressure Difference Across the Spinning Surface and Pressure Difference Between Air Seal Chamber and Rotary Cyclone Annular Region (Series 200 Tests)

Table E-6: Pressure Drops in Long Duration Test (300 Series)

Figure E-1: Microscopic View of 200 Mesh Screen After Efficiency Tests

Figure E-2: Closeup View of Fine Particulates (about one micron size) on 200 Mesh Wire

Figure E-3: Appearance of Inner Wall and Rotor Surface After Efficiency Tests

Examination of Table E-1 shows that:

- Volumetric Q (CFM) was either 7 or 20 CFM.
- The dust loading (L) varied from 0.158 to 1.975 grains/SCF.
- Rotor RPM was typically 1800 with one test at 500 RPM.
- Typical test runs were conducted over 0.25 hrs to 2 hrs.
- Eight runs were made with a 200 screen mesh and two without a mesh (bare rotor surface with 1/4" holes and with open area of about 60%).
- Mass efficiencies ranged from 91% to greater than 99%.

Table E-1: Summary of Test Results

<u>No.</u>	<u>Test Series</u>	<u>Q</u> (cfm)	<u>L</u> (gr/cf)	<u>ω</u> (rpm)	<u>t</u> (hr)	<u>Mesh</u> (y/n)	<u>Eff.</u> (%)
1	201	7	0.632	1800	0.5	Yes	97
2	202	7	0.158	1800	0.5	Yes	96
3	203	7	1.975	1800	0.25	Yes	98
4	201-1	7	0.632	1800	0.5	Yes	97
5	204	20	0.22	1800	0.5	Yes	96
6	205	7	0.632	1000	0.5	Yes	91
7	206	7	0.632	500	0.5	Yes	82
8	207	7	0.632	1800	2.0	Yes	>99
9	208	7	0.632	1800	0.5	No	96
10	209	20	0.22	1800	0.25	No	92

Where:

Q - Bulk flow rate entering the rotary cyclone, cfm

L - Fly ash particulate loading rate, grains/cu ft

ω - Angular velocity of the rotor, rpm

t - Time duration of the test/hr

Mesh - Rotor surface condition with 200 mesh screen ("yes") or without it ("no")

Efficiency - Collection efficiency (mass base), %

Table E-2: Fractional Efficiency of Test Series #207

Basis: Design Cutpoint 1 Micron
Rotor speed 1800 rpm
Approach Velocity 0.05 ft/sec

<u>ECD*</u>	<u>Fractional Efficiency**</u>
13.97	100%
8.93	99.88%
5.95	100%
3.77	98.6%
2.30	99.53%
1.49	98.96%
<0.87	95.86%

*ECD - Effective Cutoff Diameter in Microns

**Fractional efficiencies of each particulate size are calculated from weight fractions of inlet and outlet size distributions. The total efficiency (mass base) of Test Series #207 is 99.43%.

Table E-3: Fly Ash Distribution at Inlet of Rotary Cyclone

Stage	Plate	Tare (g)	Final (g)	Net (mg)	%	Cum %	ECD (μ)	
							S.G.=1	S.G.=2.5 f=0.65
	0	31.0462	31.0526	6.4	38.37	100	>25	>16.25
0	1	14.9568	14.9603	3.5	20.95	61.63*	15	9.75*
1	2	14.5923	14.5942	1.9	11.37	40.68	9.5	6.17
2	3	15.4296	15.4308	1.2	7.18	29.31	6.2	4.03
3	4	15.4208	15.4217	0.9	5.38	22.13	4.3	2.79
4	5	15.3853	15.3865	1.2	7.18	16.75	2.8	1.82
5	6	15.4183	15.4197	1.4	8.38	9.57	1.4	0.91
6	7	15.0464	15.0466	0.2	1.19	1.19	0.87	0.56
	Backfilter	14.6427	14.6427	0	0	0	<0.87	<0.56
Total				16.7	100			

where ECD - Effective Cutoff Diameter in Microns
 S.G. - Specific Gravity
 f - Factor of S.G. Correction

* e.g., 61.63 percent of input sample weight is smaller than 9.75 microns

Table E-4: Fly Ash Size Distribution at Cleaned Gas Outlet of Rotary Cyclone

Stage	Take (g)	Final (g)	Net (mg)	g	Cum g	ECD (μ)	
						S.G.=1	S.G.=2.5 f=0.65
0	15.0748	15.0748	0	0		>30	>19.5
1	15.0411	15.0411	0	0		18	11.7
2	15.4693	15.4694	0.1	4.35	100	12.5	8.12
3	14.9837	14.9837	0	0		8.8	5.75
4	15.4279	15.4238	0.4	17.39	95.65	5.4	3.51
5	14.0406	14.0407	0.1	4.35	78.26	2.8	1.82
6	15.0634	15.0637	0.3	13.04	73.91*	1.8	1.17
Backfilter	14.9929	14.9943	1.4	60.87	60.87*	<1.3	<0.84*
Total			2.3	100			

where ECD - Effective Cutoff Diameter in Microns
 S.G. - Specific Gravity
 f - Factor for S.G. Correction

* e.g., 60.87 percent of total particulate collected are less than 0.84 microns

Table E-5: Pressure Difference Across the Rotor Surface and Pressure Difference Between Air Seal Chamber and Rotary Cyclone Annular Region

No.	Test Series	Time	P ₁	P ₂	P ₃	ΔP_{1-3}	ΔP_{2-1}
1	201	B	0.11	0.105	0.34	0.23	0.005
		E	0.11	0.105	0.335	0.225	0.005
2	202	B	0.11	0.105	0.33	0.22	0.005
		E	0.11	0.105	0.33	0.22	0.005
3	203	B	0.07	0.065	0.30	0.23	0.005
		E	0.08	0.07	0.30	0.22	0.01
4	201-1	B	0.12	0.115	0.345	0.225	0.005
		E	0.12	0.115	0.34	0.22	0.005
5	204	B	0.38	0.345	0.70	0.32	0.035
		E	0.38	0.345	0.70	0.32	0.035
6	205	B	0.195	0.17	0.280	0.085	0.025
		E	0.190	0.17	0.28	0.09	0.02
7	206	B	0.22	0.18	0.265	0.045	0.04
		E	0.195	0.175	0.295	0.10	0.02
8	207	B	0.165	0.155	0.405	0.24	0.01
		E	0.165	0.155	0.415	0.25	0.01
9	208	B	0.13	0.11	0.44	0.31	0.02
		E	0.13	0.11	0.44	0.31	0.02
10	209	B	0.31	0.30	0.68	0.37	0.01
		E	0.31	0.30	0.68	0.37	0.01

where:

P₁ - Static Pressure (negative) at Inlet Duct, inch water

P₂ - Static Pressure (negative) at Air Seal Chamber, inch water

P₃ - Static Pressure (negative) at Outlet Duct, inch water

ΔP_{1-3} = -(P₁-P₃), Pressure Difference Across the Rotor Surface, inch water

ΔP_{2-1} = -(P₁-P₂), Pressure Difference Between Seal Air Chamber and Rotary Cyclone Annular Region, inch water

B - Measured at Beginning of Test

E - Measured at End of Test

Table E-6: Pressure Difference Across the Rotor Surface (Long Duration Test)

<u>No.</u>	<u>Test Series</u>	<u>Time</u>	<u>P₁</u>	<u>P₂</u>	<u>P₃</u>	<u>$\Delta P_{1,3}$</u>
1	301 (6 hrs)	B	0.13	0.15	0.37	0.24
		E	0.14	0.155	0.36	0.22
2	302 (8 hrs)	B	0.14	0.15	0.36	0.22
		E	0.14	0.15	0.36	0.22
3	303 (6 hrs)	B	0.13	0.14	0.36	0.23
		E	0.125	0.145	0.36	0.235
4	304 (4 hrs)	B	0.12	0.14	0.36	0.24
		E	0.12	0.14	0.36	0.24

Where:

P₁ - static pressure (negative) at inlet duct, inch water

P₂ - static pressure (negative) at air seal chamber, inch water

P₃ - static pressure (negative) at outlet duct, inch water

$\Delta P_{1,3} = -(P_1 - P_3)$, pressure difference across the rotor surface, inch water

B - measured at beginning of test period

E - measured at end of test period

Figure E-1: Microscopic View of 200 Mesh Screen After Efficiency Tests

Figure E-2: Closeup View of Fine Particulates (About One Micron Size on 200 Mesh Wire)

Figure E-3: Appearance of Inner Wall and Rotor Surface After Efficiency Tests

APPENDIX F

SUMMARY OF OPERATIONAL DATA FROM LABORATORY TESTS

This appendix provides a summary of operational data from experimental tests, specifically the average pressure drops across the rotary cyclone and rotor motor amperages. Both are used in Appendix G of this report for scaling parameters to a commercial sized unit. There are two tables in this appendix:

Table F-1: Average Pressure Drop Across the Rotary Cyclone (Laboratory-scale Test Data)

Table F-2: Motor Amperage (Laboratory-scale Test Data)

Table F-1: Average Pressure Drop Across the Rotary Cyclone (Laboratory-Scale Test Data)

Q	V _a	<u>500 rpm (g=21)</u>		<u>1,000 rpm (g=85)</u>		<u>1,800 rpm (g=276)</u>	
		<u>W/O 200</u>	<u>W 200</u>	<u>W/O 200</u>	<u>W 200</u>	<u>W/O 200</u>	<u>W 200</u>
0	0	0.005	0	0.0717	0.0525	0.2555	0.185
7	0.05	0.0387	0.25	0.0915	0.06265	0.2725	0.20
50	0.35	0.07	0.0575	0.155	0.1225	0.3725	0.335

Pressure Drop = inch water
 Q = bulk inlet flow rate (acfm)
 V_a = approach velocity (ft/sec)
 W/O 200 = without 200 mesh screen
 W 200 = with 200 mesh screen
 g = "g force"; ratio of centrifugal force to gravitational force

Table F-2: Motor Amperage (Laboratory-scale Test Data)

Q	Va	<u>500 rpm (g=21)</u>		<u>1000 rpm (g=85)</u>		<u>1800 rpm (g=276)</u>	
		<u>W/O 200</u>	<u>W 200</u>	<u>W/O 200</u>	<u>W 200</u>	<u>W/O 200</u>	<u>W 200</u>
0	0	2.0	-	2.8	-	3.6	-
7	0.05	2.0	2.2	2.8	3.15	3.6	4.0*
50	0.357	2.0	-	2.7	-	3.6	
20	0.142	-	-	-	-	-	4.2*

Q - bulk flow rate (acfm)
 Va - approach velocity (ft/sec)
 W/O 200 - without 200 mesh screen.
 W 200 - with 200 mesh screen
 g - "g" force

*average value

APPENDIX G

DETERMINATION OF SCALE-UP FACTORS

This appendix provides details on factors used in scaling operational data measured from experiments up to 40 MWe utility size application. Operational data, such as pressure drops and motor amperages (both are summarized in Appendix F), are plotted on logarithmic papers at various approach velocities and "g" force measured as the ratio of centrifugal force to the gravitational force. The slopes are used to extrapolate to a commercial sized device. Figures found in this appendix include:

Figure G-1: Determination of Scale-up Factors: Pressure Drop vs. g
Force (Tests with 200 Mesh Screen)

Figure G-2: Determination of Scale-up Factors: Pressure Drop vs. g
Force (Tests without 200 Mesh Screen)

Figure G-3: Determination of Scale-up Factors: Pressure Drop vs.
Approach Velocity (Tests with 200 Mesh Screen)

Figure G-4: Determination of Scale-up Factors: Pressure Drop vs.
Approach Velocity (Tests without 200 Mesh Screen)

Figure G-5: Determination of Scale-up Factors: Motor Amperage (Rotor) vs.
Centrifugal Force (Tests with 200 Mesh Screen)

Figure G-6: Determination of Scale-up Factors: Motor Amperage (Rotor) vs.
Centrifugal Force (Tests without 200 Mesh Screen)

Figure G-7: Determination of Scale-up Factors: Motor Amperage (Rotor) vs.
Approach Velocity (Tests with 200 Mesh Screen)

Figure G-1: Determination of Scale-up Factors: Pressure Drop vs. g Force (Tests with 200 Mesh Screen)

Figure G-2: Determination of Scale-up Factors: Pressure Drop vs. g Force (Tests without 200 Mesh Screen)

Figure G-3: Determination of Scale-up Factors: Pressure Drop vs. Approach Velocity (Tests with 200 Mesh Screen)

Note: Approach velocities calculated on the basis of open area (60%)

Figure G-4: Determination of Scale-up Factors: Pressure Drop vs. Approach Velocity (Tests without 200 Mesh Screen)

Figure G-5: Determination of Scale-up Factors:
Force (Tests with 200 Mesh Screen)

Motor Amperage vs. g

Figure G-6: Determination of Scale-up Factors:
Force (Tests without 200 Mesh Screen)

Motor Amperage vs. g

Figure G-7: Determination of Scale-up Factors: Motor Amperage vs. Approach Velocity (Tests with 200 Mesh Screen) Figure I-1: Photograph of Biggest Particulate of Fly Ash Under a Scanning Electron Microscope

APPENDIX H

CAPITAL AND O&M COSTS ESTIMATION

The main body of this report has summarized the comparative economics of the Rotary Cyclone (RC) with fabric filters (FF) and electrostatic precipitators (ESP). This appendix details the capital as well as the operating and maintenance cost estimations. The estimations are based on a 40 MWe coal-fired boiler with flue gas volume of 125,000 acfm at 300°F.

There are two cases of the scaled-up rotary cyclone installations in the cost analysis: Case I incorporates lower rotor speed (3,600 rpm) and lower approach velocity (1.364 ft/sec); Case II utilizes higher rotor speed (3,600 rpm) and higher approach velocity (4.312 ft/sec). Performance criteria of both cases are the same, i.e., to separate one micron or larger than one micron particulates from the flue gas stream. This appendix contains the following tables:

Table H-1: Estimated Capital Cost for Scaled-up Rotary Cyclone Device (Case I)

Table H-2: Estimated Capital cost for Scaled-up Rotary Cyclone Device
(Case II)

Table H-3: Capital Cost for Fabric Filters

Table H-4: Capital Cost for Electrostatic Precipitators

Table H-5: Estimated O&M Cost and 30-year Levelized Cost of Scaled-up
Rotary Cyclone Device (Case I)

Table H-6: Estimated O&M Cost and 30-year Levelized Cost of Scaled-up
Rotary Cyclone Device (Case II)

Table H-7: O&M Cost and 30-year Levelized Cost of Fabric Filters

Table H-8: O&M Cost and 30-year Levelized Cost of Electrostatic Precipitators

Table H-9: Power Requirement for Scaled-up Rotary Cyclone Device (SF),
Fabric Filter (FF) and Electrostatic Precipitator (ESP)

Table H-1: Estimated Capital Cost for Scale-up Rotary Cyclone Device (Case I)

Basis: Coal-fired boiler 40 MWe, flue gas volume 125,000 acfm
 Rotor speed, 3,600 rpm
 Approach velocity, 1.364 ft/sec
 Number of rotary cyclones, 18
 Minimum size of particulates to be separated = 1 micron
 Emission limit 0.03 lb/10⁶ Btu

<u>Description</u>	<u>Size</u>	<u>Estimated Cost \$ (1988)</u>
Collector		
(1) Rotary cyclone unit	@ 6944 acfm	
- shell (including inlet, outlet, cone)	Dia = 6 ft	9,703
- rotor (including shaft)	Dia = 3 ft	12,000
- in-site balance	static and dynamic	2,000
- roller bearings		2,000
- driving motor	20 HP	700
- motor starter		900
- driving parts		1,200
	Total Unit	27,703
(2) Rotary cyclone module	6 units/module	166,218
- Frame		3,500
- Insulation		1,800
- Dust bin	14 ft x 14 ft	4,200
	Total Module	175,718
	Total Module Delivered	193,289
(3) Rotary cyclone Collector	3 modules/collector	579,867
- Earthwork, foundation		115,973
- Instrumentation electrical		57,986
	Total Rotary Cyclone Collector	753,826
	Total Collector Erected	1,507,652
Duct work		46,000
Ash handling system		301,000
Differential cost**	I.D. fan 125,000 acfm, 5 inches H ₂ O Motor 180 HP	2,000
	Total Process Capital	1,860,252

Table H-1: Estimated Capital Cost for Scale-up Rotary Cyclone Device (Case I)
(continued)

Basis: Coal-fired boiler 40 MWe, flue gas volume 125,000 acfm
Rotor speed, 3,600 rpm
Approach velocity, 1.364 ft/sec
Number of rotary cyclones, 18
Minimum size of particulates to be separated = 1 micron
Emission limit 0.03 lb/10⁶ Btu

<u>Description</u>	<u>Size</u>	<u>Estimated Cost \$ (1988)</u>
General facility (1% (TPC)		18,602
Engineering fees (10% TPC)		186,025
Project contingency (10% TPC)		186,025
	Total Plant Cost	2,065,065
	Total Plant Investment*	2,184,838
Pre-production costs (2.5% TPI)		54,621
	Total Capital Requirement	2,239,459

*Including fund allowance for construction

**This cost includes the differential fan and motor equipment cost due to the higher pressure loss as a result of adding the particulate collectors to the ductwork train

Table H-2: Estimated Capital Cost for Scale-up Rotary Cyclone Device (Case II)

Basis: Coal-fired boiler 40 MWe, flue gas volume 125,000 acfm
 Rotor speed, 6,400 rpm
 Approach velocity, 4.312 ft/sec
 Number of rotary cyclones, 6
 Minimum size of particulates to be separated = 1 micron
 Emission limit 0.03 lb/10⁶ Btu

<u>Description</u>	<u>Size</u>	<u>Estimated Cost \$ (1988)</u>
Collector		
(1) Rotary cyclone unit	@ 20,833 acfm	
- shell (including inlet, outlet, cone)	Dia = 6 ft	12,000
- rotor (including shaft)	Dia = 3 ft	21,240
- in-site balance	Static and dynamic	3,540
- roller bearings		2,700
- driving motor	30 HP	1,000
- motor starter		1,100
- driving parts		1,600
	Total Unit	41,580
(2) Rotary cyclone module	6 units/module	249,480
- Frame		5,250
- Insulation		1,800
- Dust bin	14 ft x 14 ft	4,200
	Total Module	260,730
	Total Module Delivered	286,803
(3) Earthwork, foundation		38,658
Instrumentation electrical		19,329
	Total Rotary Cyclone Collector	344,790
	Total Collector Erected	689,580
Duct work		25,000
Ash handling system		100,333
Differential cost**	I.D. fan 125,000 acfm, 11.78" H ₂ O Motor 285 HP	96,000
		4,000
	Total Process Capital	914,933
General facility (1% TPC)		9,149

Table H-2: Estimated Capital Cost for Scale-up Rotary Cyclone Device (Case II)
(continued)

Basis: Coal-fired boiler 40 MWe, flue gas volume 125,000 acfm
 Rotor speed, 6,400 rpm
 Approach velocity, 4.312 ft/sec
 Number of rotary cyclones, 6
 Minimum size of particulates to be separated = 1 micron
 Emission limit 0.03 lb/10⁶ Btu

<u>Description</u>	<u>Size</u>	<u>Estimated Cost \$ (1988)</u>
Engineering fees (10% TPC)		91,493
Project contingency (10% TPC)		91,493
	Total Plant Cost	1,107,068
	Total Plant Investment*	1,171,278
Pre-production costs (2.5% TPI)		29,282
	Total Capital Requirement	1,200,560

*Including fund allowance for construction

**This cost includes the differential fan and motor equipment cost due to the higher pressure loss as a result of adding the particulate collectors to the ductwork train

Table H-3: Estimated Capital Cost for Fabric Filters

Basis: Coal-fired Boiler 40 MWe, Flue Gas Volume 125,000 acfm
2.0 A/C (air/cloth ratio), Emission Limit 0.03 lb/10⁶ Btu

<u>Description</u>	<u>Size</u>	<u>\$ (1988)</u>
Collector*		1,766,000
Ductwork		46,000
Ash handling system		307,000
Differential cost***	I.D. fan 125,000 acfm, 10" H ₂ O	90,000
	Total Process Capital	2,209,000
General facility (1% TPC)		22,090
Engineering fees (3% TPC)****		66,270
Project contingency (10% TPC)		220,900
	Total Plant Cost	2,518,260
	Total Plant Investment**	2,664,319
Preproduction costs (2.5% TPI)		66,608
	Total Capital Requirement	2,730,927

*Including (1) delivery and erection of equipment; (2) earthwork, foundation, instrumentation and electrical costs; (3) engineering fees for the collector

**Including fund allowance for construction

***This cost includes the differential fan and motor equipment cost due to the higher pressure loss as a result of adding the particulate collectors to the ductwork train

****Excludes engineering fees for the collector

Table H-4: Estimated Capital Cost for Electrostatic Precipitators

Basis: Coal-fired Boiler 40 MWe, Flue Gas Volume 125,000 acfm
2.0 A/C (air/cloth ratio), Emission Limit 0.03 lb/10⁶ Btu

<u>Description</u>	<u>Size</u>	<u>\$ (1988)</u>
Collector*		2,010,000
Ductwork		58,000
Ash handling system		331,000
Differential cost***	I.D. fan 125,000 acfm, 3" H ₂ O	30,000
	Total Process Capital	2,429,000
General facility (1% TPC)		24,290
Engineering fees (3% TPC)****		68,000
Project contingency (10% TPC)		242,900
	Total Plant Cost	2,696,190
	Total Plant Investment**	2,852,569
Preproduction costs (2.5% TPI)		71,314
	Total Capital Requirement	2,923,883

*Including (1) delivery and erection of equipment; (2) earthwork, foundation, instrumentation and electrical costs; (3) engineering fees for the collector

**Including fund allowance for construction

***This cost includes the differential fan and motor equipment cost due to the higher pressure loss as a result of adding the particulate collectors to the ductwork train

****Excludes engineering fees for the collector

Table H-5: Estimated O&M and 30-Year Levelized Cost of Scaled-up Rotary Cyclone Device (Case I)

Basis: Coal-fired Boiler 40 MWe

	<u>Unit/yr</u>	<u>\$/Unit</u>	<u>\$ (1988)/yr</u>
<u>Fixed Operating Cost</u>			
Operating labor (man hrs)	6115	19.3	118,023
Maintenance labor (man hrs)	482	22.0	10,604
Maintenance materials			8,000
Administration and support labor			19,000
Total Fixed Operating Cost			155,627
<u>Variable Operating Cost</u>			
Power	1,072,224	\$0.06/kWh	64,333
Ash disposal			52,000
Total Variable Operating Cost			116,333
<u>Levelized Cost (30-year)</u>			
Capital charge @ 15.3%			342,637
O&M charge			444,111
Levelized Cost*			3.45 mills/kWh

*Capacity factor 0.65

Table H-6: Estimated O&M and 30-Year Levelized Cost of Scaled-up Rotary Cyclone Device (Case II)

Basis: Coal-fired Boiler 40 MWe

	<u>Unit/yr</u>	<u>\$/Unit</u>	<u>\$ (1988)/yr</u>
<u>Fixed Operating Cost</u>			
Operating labor (man hrs)	6115	19.3	118,023
Maintenance labor (man hrs)	482	22.0	10,604
Maintenance materials			8,000
Administration and support labor			19,000
Total Fixed Operating Cost			155,627
<u>Variable Operating Cost</u>			
Power	1,072,944	\$0.06/kWh	102,177
Ash disposal			52,000
Total Variable Operating Cost			154,177
<u>Levelized Cost (30-year)</u>			
Capital charge @ 15.3%			183,685
O&M charge			505,909
Levelized Cost*			3.03 mills/kWh

*Capacity factor 0.65

Table H-7: Estimated O&M and 30-Year Levelized Cost of Fabric Filters

Basis: Coal-fired Boiler 40 MWe

	<u>Unit/yr</u>	<u>\$/Unit</u>	<u>\$ (1988)/yr</u>
<u>Fixed Operating Cost</u>			
Operating labor (man hrs)	6115	19.3	118,023
Maintenance labor (man hrs)	605	22.0	13,310
Maintenance materials			19,900
Administration and support labor			19,000
Filter bags			36,500
Total Fixed Operating Cost			206,733
<u>Variable Operating Cost</u>			
Power	1,716,960	\$0.06/kWh	103,018
Ash disposal			52,000
Total Variable Operating Cost			155,018
<u>Levelized Cost (30-year)</u>			
Capital charge @ 15.3%			417,832
O&M charge			590,739
Levelized Cost*			4.43 mills/kWh

*Capacity factor 0.65

Table H-8: Estimated O&M and 30-Year Levelized Cost of Electrostatic Precipitators

Basis: Coal-fired Boiler 40 MWe

	<u>Unit/yr</u>	<u>\$/Unit</u>	<u>\$ (1988)/yr</u>
<u>Fixed Operating Cost</u>			
Operating labor (man hrs)	6115	19.3	118,023
Maintenance labor (man hrs)	632	22.0	13,904
Maintenance materials			20,500
Administration and support labor			19,000
Total Fixed Operating Cost			171,427
<u>Variable Operating Cost</u>			
Power	1,688,928	\$0.06/kWh	101,335
Ash disposal			52,000
Total Variable Operating Cost			153,335
<u>Levelized Cost (30-year)</u>			
Capital charge @ 15.3%			447,354
O&M charge			53,336
Levelized Cost*			4.29 mills/kWh

*Capacity factor 0.65

Table H-9: Estimated Power Requirement for Scale-up Rotary Cyclone Device (RC), Fabric Filter (FF), and Electrostatic Precipitator (ESP)

Basis: Coal-fired Boiler 40 MWe, Offgas Volume 125,000 acfm @ 300°F

<u>Equipment</u>	<u>Load Factor</u>	<u>FF</u> (kW)	<u>ESP</u> (kW)	<u>RC Case I</u> (kW)	<u>RC Case II</u> (kW)
I.D. Fan	1.0	199	73	103	209.5
Reverse gas system	1.0	22	--	---	---
T-R set	1.0	--	110	---	---
Hopper heater	0.1	4	4	3	1
Insulator heater	1.0	--	34	---	---
Fly ash conveying	0.5	10	10	10	10
Misc.	1.0	10	10	10	10
Driving motors	1.0	--	--	27*	13.5**
Total power (kW)		245	241	153	243
Total electric energy (kWh)***		1,716,960	1,688,928	1,072,224	1,702,944

*Connected motor load of each rotor = 20 HP, operating motor load = 1.5 kW, number of motors = 18

**Connected motor load of each rotor = 30 HP, operating motor load = 2.25 kW, number of motors = 6

***Power factor = 0.8

Estimated operating costs are based on an earlier EPRI document for ESP's and Fabric Filters (EPRI-CS-4083, June 1985¹) supplemented by data in our files and vendor contacts:

- Operating labor is taken to be the same as for a baghouse or fabric filter requiring operator fulltime.
- Maintenance labor requirements for fabric filters amount to about 10% for fabric filters (9.9%) and ESP's (10.3%).

Without better information, we have assumed the same value for the rotary cyclone--added complexity for the rotary cyclone is compensated by smaller size of facility.

- Maintenance materials are estimated to be 0.7% of capital investments consistent estimates made for fabric filters and ESP's in the above referenced EPRI report. (For the Case II Rotary Cyclone involving a higher rpm device but fewer of them, we have assumed the same dollar cost for maintenance materials as for Case I Rotary Cyclone.)
- Administrative and Support and Ash Disposal are assumed to be the same for all cases in terms of dollar expenditures per year.
- Power requirements are estimated separately for each case, either from the EPRI report or experimental data on the rotary cyclone scaled-up to a 40 MW unit (see Appendix I of this report).

¹Economics of Fabric Filters and Electrostatic Precipitators, 1984, R. W. Scheck, et. al., EPRI, June 1985.

APPENDIX I

FLY ASH PARTICULATES

The Fly Ash size distribution at the inlet to the Rotary Cyclone is shown in Appendix E. Photographs from a scanning electron microscope are shown of:

- A large fly ash particulate (Figure I-1)
- Average sized particulates of about 8 to 10 microns (Figure I-2)

Particular note should be made of the spherical nature of these fly ash particles.

Figure I-1: Photograph of Large Particulate of Fly Ash Under Scanning Electron Microscope

Figure I-2: Photograph of Average Particulates (less than about 8 to 10 microns)
Under a Scanning System Microscope

Figure J-1: Air Seal Mechanism

Table J-1: Seal Air Consumption

<u>No.</u>	<u>Test Series</u>	<u>Spinner rpm</u>	<u>Seal Air Consumption*</u> (SCFH)
1	201	1800	
2	202	1800	<25
3	203	1800	<25
4	201-1	1800	60
5	204	1800	<25
6	205	1000	<25
7	206	500	0
8	207	1800	0
9	208	1800	>0
10	209	1800	>0

* Seal Air Consumption - The minimum amount of seal air which warrants a higher absolute pressure in the seal air chamber than the pressure in the annular region

END

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