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Laboratory Testing of the Boundary Layer Momentum Transfer Rotational Filter System, NETL-InnovaTech, Inc. CRADA 98-F026 Final Report

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Abstract

A patented dynamic mechanical filter developed by InnovaTech was previously shown to remove fine particulate matter from industrial process gas streams *at ambient temperatures and pressures*. An all-metal, high-temperature version of this novel media-less filter was fabricated under this Cooperative Research and Development Agreement (CRADA) with DOE / NETL-Morgantown for hot gas testing of the device. The technology is entirely different in both concept and design from conventional vortex separators, cyclones, or porous media filters. This new filtration concept is capable of separating heavy loading of fine particles without blinding, fouling or bridging, and would require minimal operational costs over its anticipated multi-year service life. The all-metal filter design eliminates thermal stress cracking and premature failure prevalent in conventional porous ceramic filters. In contrast, conventional porous media filters (i.e., ceramic cross-flow or candles) easily foul, require periodic cleaning (typically backpulsing), frequent replacement and subsequent disposal.

Flyash removal efficiencies for the dynamic prototype filter were evaluated for turbomachinery protection in a simulated coal-fired electric power generation environment, such as those found in pressurized fluidized-bed combustors (PFBC). In this CRADA, several key filter components required re-engineering design and fabrication to enable the prototype to survive and operate efficiently in the harsh high-temperature/pressure environment before the technology could be proven technically feasible. The low–flow (50 to 200 SCFM) prototype filter was tested sequentially at temperatures up to 750^{o}F and pressures up to 100 psia, with flyash particle loadings varying from 3 to 5 lbs/hr. The initial filtration efficiency goal in the CRADA was to minimally filter 95% (by mass) of 5-μm particles and 99% (by mass) of 10-μm particles to match typical turbine inlet specifications which requires total particulate loading of no more than 0.002-0.02 g/Nm^3 (2-20 ppmw) to protect the turbine, while the pressure drop across the filtration system is kept to a minimum. An overall filtration efficiency of 98% to 99% (by mass) over the entire particle distribution size range was successfully achieved at elevated temperatures and pressures with this medialess prototype. Further development and subsequent commercialization of this technology will include other high-temperature industrial applications, such as conventional direct coal-fired furnaces, waste incinerators and coal gasifiers (e.g., integrated gasification combined cycle or IGCC).

1 Executive Summary

The following summarizes the theory behind the BLMT filter system and the collaborative work conducted by NETL and InnovaTech.

1.1 Opportunity

NETL and InnovaTech, Inc. (ITI) worked together to assess the technical feasibility of utilizing a mechanical filter system that ITI has developed to remove particulate matter from gas streams in a high temperature/high pressure (HTHP) environment. This novel device, defined as a Boundary Layer Momentum Transfer (BLMT) filter, has no media to clog-up, and has proven to operate with constant levels of efficiency and pressure drop in ambient temperature and pressure applications. The BLMT filter was successfully tested in a simulated Pressurized Fluidized Bed Combustor (PFBC) at NETL's High Temperature Gas-Stream Cleanup Test Facility (HTGSCTF).

This application of BLMT technology has received support from several sources, and ITI has developed successful prototypes for specific (ambient environment) applications under contracts with DOD and DOE. Primary support for the development of a high temperature/high pressure BLMT prototype has come from DOE's Energy-Related Inventions Program (ERIP). The proposal, "Novel Method and Apparatus for Ejecting Particulate from the Primary High Temperature Inlet Flow Path of a Coal-Fired Turbine Generator", was subjected to a comprehensive technical and economic review by a scientific panel at the National Institute of Science and Technology (NIST) prior to funding in FY98. The contract covered the construction of a HTHP BLMT filter, but did not include subsequent testing. In a joint venture with ITI, Haynes International supplied Hastelloy materials for this project. A successful demonstration project under this CRADA with NETL will create greater interest from A& E firms in the utility industry to further the goals of the Clean Coal Technology (CCT) program.

A BLMT filter is an alternative to (or enhancement of) ceramic barrier filters in HTHP applications. In addition to the obvious limitations of barrier filters (eventual clogging, changes in pressure drop, back-pulsing, etc.), the viability of ceramic 'candle' filters is exacerbated by HTHP conditions (particle bridging, thermal shock, brittle failure, etc.). While the mechanical BLMT filtration process has shown it can eliminate or minimize many of these deficiencies in applications at ambient conditions, performance of such a system has not been demonstrated in a HTHP environment until this CRADA. Many of the issues of concern for this project related to the engineering challenges of operating rotating equipment at HTHP: performance of materials of construction, protection of motors, bearings and seals, and various housing effects on particles entrained in the incoming hot gas stream. The CRADA allowed ITI to collaborate with NETL engineers and scientists to resolve these issues, and to utilize the existing test facilities in Morgantown, WV, to conduct the initial feasibility tests of the HTHP prototype BLMT filter.

1.2 Background

At present, conventional hot gas filtration for IGCC and PFBC systems severely limits the electrical power generation efficiency. A typical conventional hot gas cleanup unit (HGCU), located upstream of the primary gas turbine generator, might consist of:

- One or more high temperature cyclones designed to eliminate large particulate matter exceeding 20 μm, followed by
- Multiple porous ceramic media filters, usually in candle form and a parallel arrangement, to remove fine particulate matter below 20 μm
- Backpulsing equipment for periodic removal of the dust cake on the surface of the ceramic filters to lengthen their service life.

Due to the extreme capital cost of the downstream turbine generators, high filtration efficiencies common to conventional ceramic barrier filters are required. However, these barrier filters typically generate a high pressure drop and require periodic backpulse cleaning due to filter fouling, resulting in a "sawtooth" operational pressure profile, leading to their frequent replacement and disposal.

InnovaTech, Inc. (formerly Micro Composite Materials Corporation) has developed a new dynamic filtration technology that is far superior to conventional static porous media filters. The mechanical filtration device, which is based on **Boundary Layer Momentum Transfer (BLMT)**, actively "excludes" particles from entering the device, thus it is inherently self-cleaning and does not require filter element replacement for the entire service life of the filter. Because the proposed "exclusion" filter does not have to be periodically replaced, it can be manufactured from higher temperature, more thermally durable refractory metals (e.g., Hastelloys, Inconels, etc.) that do not suffer the traditional degradation problems associated with porous ceramics. Upstream cyclones, a necessity in conventional barrier filters, can be eliminated through this device implementation since all particles larger than the designated cut-off size would be removed from the hot gas stream by this exclusion filter; the physics of the device makes it naturally resistant to particle blinding. Furthermore, since utilization of high temperature refractory metals in this device would preclude the need for temperature dilution of the hot furnace gases for filter protection, the overall system energy conversion efficiency could be substantially increased. The extensive engineering and cost required for traditional backpulsing would be circumvented with the implementation of this technology. Daily non-cyclic (no backpulse) operation of the filters would simplify and further reduce operational costs. Also, since the fabrication of the device does not require porous material, the surface area of the metal in contact with the hot gases is orders of magnitude less, resulting in extremely low corrosion rates.

Additionally, previous application-specific studies for this exclusion filter show that the pressure drop across the filter would be low (typically < 3 %); the pressure drop across the device would remain constant and not increase with time as it does with conventional porous barrier filters when they begin to foul. Power plant operators using conventional barrier filters must constantly monitor the deteriorating performance of the hot gas filter system to determine when it must be backpulsed or the ceramics replaced. Implementation of this type of filter would result in constant predictable performance, resulting in a much more stable system process operation.

In summary, this novel high-efficiency particle exclusion filter will:

- Have a constant and predictably low pressure drop across the filter,
- Have a constant, predictably high level of particle removal above 2 µm,
- Allow operational parameter adjustments to the filter to achieve different levels of separation efficiency and/or pressure drop,
- Eliminate the need for both upstream cyclones and ceramic barrier filters,
- Eliminate the need to modulate hot gas temperatures prior to hot gas filtration, and
- Provide higher service life expectancy of the downstream turbine generator by efficiently removing micron-sized particulate matter.

1.3 Test Results

This research investigated a novel method for the removal of small flyash particles from hot gas streams in combustion systems. The mechanism of ash removal is referred to by the inventor of the device as "Boundary Layer Momentum Transfer" (BLMT). The filter system consists of a stack of annular metal disks that are rotated in a particle laden gas stream. The assumption is that the boundary layer of gas that surrounds the spinning disk pack can be penetrated by the hot gas, but will reject entrained particles. This research shows that the BLMT filter system is effective in the hot gas environment.

Table 1. Filtration Efficiency of BLMT Filter – Mass Removal Basis

Test Date	Temperature (deg. F.)	Face Velocity (m/s)	Particle Loading (ppm_volume)	Efficiency Based On PCME Readings[1]
05/23/2000	61.0	.664	24.8	99.4 %
05/24/2000	482.0	1.01	16.5	98.9 %
05/25/2000	495.4	1.11	16.6	98.7 %
05/30/2000	712.3	.98	17.8	97.7 %
05/31/2000	764.9	1.05	15.8	98.5 %

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[1] The operation and measurement accuracy of the Particle Characterization Meter (PCME) is discussed in the body of the report. In addition, the filtration efficiency stated does not take into account differences in particle size distribution in the pre and post filter ash. The efficiency reported in this table is based on a comparison of the mass of particles into the filter vessel versus the mass of particles out of the exhaust. The ash characterization charts in the appendix show that the filter is even more efficient at removing the large particles (>10 microns in diameter). See charts for ash samples 1548 (innovatch 2) and 1585 (innovatech 9).

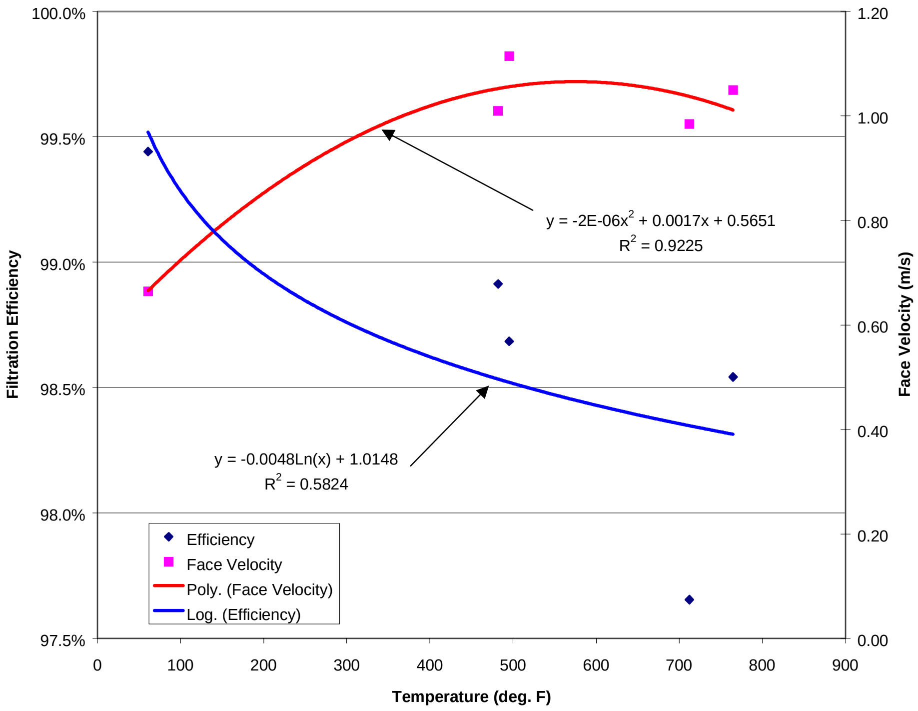

Figure 1. Filtration Efficiency Versus Particle Loading and Temperature

2 CRADA Goal/Objective

The project objective is to show the feasibility of using this new type of filtration technology in this critical application area; additional development work would still be required for implementation. The goal is to stimulate and to support U.S. industries' research and development of reliable and affordable hot gas filters for advanced coal conversion processes. The CRADA allowed prototype fabrication and assembly to be completed and the testing of a new medialess dynamic filter system redesigned to successfully operate at the high temperatures/pressures typically found in the coal-fired electric utility industry. Several engineering design and materials of construction issues were resolved to establish feasibility of its potential use at elevated temperatures / pressures, where key components of the filter must operate efficiently for long periods of time.

NETL technical personnel evaluated BLMT particle filtration in a stepwise testing protocol: (1) ambient temperature and pressure preliminary tests, (2) low temperature ramp-up to 500^{o}F at ambient pressure, (3) low temperature ramp-up to 750^{o}F to simulate higher temperatures and pressures approaching those found in a PFBC environment. Several iterations during each of these steps was used to determine particulate removal performance and pressure drop characteristics, as well as to address design issues for sustained long service life (seal, bearing and motor life). Note that typical issues of residual pressure drop buildup, media replacement, particle bridging, ceramic fracture and/or failure are precluded with BLMT technology.

Using a cantilevered design, all critical rotating components are located outside the hot gas effluent stream. Active cooling of the critical components (which required intimate collaboration with NETL technical personnel to adequately resolve this issue) increased their longevity in this environment.

After the start of the project, it became evident that attachment of the prototype inertial filter to an existing hot gas testing vessel designed to evaluate ceramic candles would not provide meaningful testing of the device. Under the CRADA, DOE technical personnel constructed a high temperature pressure vessel specifically for testing this prototype. Prototype high-temperature BLMT filter components were fabricated and assembled at NETL Morgantown and placed within the pressure vessel for subsequent testing and evaluation by DOE test engineers. Preliminary design and fabrication of some of the high temperature/pressure filter components was accomplished under a DOE Inventions & Innovation (I&I) project (formerly the Energy-Related Inventions Program or ERIP). The limited scope/budget of that program precluded high temperature testing of the unit. The CRADA would provide the means to accomplish this evaluation after I&I project completion. The targeted size and capability of the filter prototype was a unit that could operate at 1,600^{o}F at elevated pressure, handling up to 200 scfm of flow with particle loadings varying from 2 to 20 lbs/hr. The device was designed to have a mass filtration efficiency of 95% for 5 micron particles, 99% for 10 micron particles.

3 Significance of the CRADA for Industrial Interests

InnovaTech, Inc. is actively seeking joint venture and strategic partners to assist in the commercialization of the Boundary Layer Momentum Transfer (BLMT) technology, particularly for high temperature/high pressure applications as they apply to the electric power generation industry. Significant development effort will be required before this new technology is accepted as a viable alternative to existing conventional methodologies: first at reduced-scale (NETL/Morgantown testing), gradually transitioning to larger-scale (Wilsonville testing) and finally to full-scale at a designated utility site that perceives this technology to be complementary with their operations. To facilitate this type of long-range development project, teaming with a major player in this field, such a large A&E firm, is essential to successful commercialization. Preliminary data, showing concept feasibility, particularly in addressing many of the technical questions related to viability of critical BLMT components in this harsh environment, is required to move this technology up the learning curve.

4 Prior Research/Independent Technical Review

InnovaTech has successfully completed six separate Small Business Innovative Research (SBIR) research and development contracts for DOE, DOD (Army and Air Force), and EPA which use the BLMT as the basis for different ambient applications in filtration. This represents over $1.6M in Federal funding to date for R&D in this unique technological area. The primary impediment to more direct funding and support in high temperature applications is the lack of substantiated test data. This is the primary reason for independent testing, evaluation, and validation of the technology at the extensive DOE/NETL facilities in Morgantown, WV. Considerable time and effort have been expended on new designs for ambient testing of hazardous effluents, which has some overlap for HTHP applications. Specifically, since critical moving parts that may require replacement or periodic inspection/servicing in applications that might contaminate these components, the BLMT design has evolved into a cantilevered unit where only the all-metal disks extend into the effluent gas stream. All serviceable components are protected outside of the contaminated gas stream, enhancing maintainability and sustainability in harsh environments. This design scenario is also the basis for HTHP applications, where these critical rotating BLMT components must be protected from high temperatures. Active cooling and pressurization of an enclosure around these filter components appears to provide adequate protection to insure long serviceability under standard operating conditions of PFBC or other high temperature applications.

5 Technical Approach

The overall approach to meeting the CRADA project objectives entailed a systematic breakout of each critical component within the BLMT filter that could potentially fail or have significantly reduced performance at high temperatures, potentially compromising the success of the project. Each component was addressed individually to ascertain if the proposed design and/or materials change would meet longevity goals if the part were subjected to high temperature. Successful design of the prototype would provide a high temperature flyash filter that could be operated for extended periods of time, having significant long term operational cost reductions combined with enhanced reliability and performance. Successful evaluation at a DOE test facility under a simulated PFBC (oxidizing) process conditions would lead to a full scale commercialization effort with different OEMs and larger A&E firms (i.e., Black & Veatch, Bechtel, Foster Wheeler, etc.). The design engineers at these firms will not place themselves at risk on untested new technology until a body of knowledge is available about the operational envelope in which the device performs adequately for extended periods of time. This commercialization path is anticipated to take several years to accomplish. Concurrent to this high temperature filtration commercialization path, beta testing will continue on ambient temperature BLMT filters in other applications, establishing a data baseline for future comparisons. Similar filtration performance characteristics at high temperature are anticipated when compared to ambient temperature data.

The following modifications were made in the ambient-temperature prototype design:

(a) the materials of construction was changed from aluminum to Hastelloy,
(b) a non-contacting labyrinth seal was used to separate filtered from unfiltered gas, bridging an actively-cooled pressurized chamber opposite the hot gas chamber to minimize differential pressures across the seal,
(c) the actively-cooled drive shaft bearings were positioned exterior to the hot gas plenum,
(d) the cantilevered rotating disk pack was suspended from the top of the particle collection plenum, and
(e) the actively cooled electric drive motor was placed within the pressurized chamber opposite the hot gas chamber to enhance survivability.

6 BLMT Technology Assessment

The successful mass filtration efficiency test results at elevated temperatures and pressures without experiencing any serious engineering or technical problems or complications demonstrates the feasibility of using this concept in many varied high temperature and/or high pressure hot gas particulate cleanup applications. Specific intended applications for the fossil-fuel electric utility industry include pressurized fluidized bed combustion (PFBC), where the filter components are in an oxidizing atmosphere, and integrated gasification combined cycle (IGCC), where the filter components are in a reducing atmosphere. Both of these utility applications require extremely large hot gas filtration systems (e.g., hundreds of thousands-to-millions of CFM volumetric throughput flow rates), a considerable increase from the size and flow rate of the prototype system tested under this CRADA. There are, however, many non-utility industrial processes that require much smaller hot gas particulate filtration systems, on the order of thousands of CFM, for which this technology can be introduced into the marketplace and gradually expanded to accommodate higher flow rate applications.

6.1 Conceptual Design of a Commercial-Scale BLMT Filter

A conceptual design of a modular commercial-scale BLMT filter is envisioned for hot gas particulate cleanup applications based on the final prototype design (with appropriate enhancements) evaluated in this CRADA. Each filter module would have a nominal flow rating of 1,000-ACFM, allowing a parallel flow configuration to accommodate larger incremental flow requirements. Initially, for smaller industrial hot gas filtering applications in the thousands-to-tens-of-thousands of CFMs flow range, this module size would be sufficient for a large variety of processing operations, such as small industrial coal-fired boilers. However, when extremely large flow rates are required, such as those found in the electric utility industry, larger sized modules using BLMT filters having much larger diameters would need to be constructed and evaluated.

As an example, consider a 5,000-ACFM filtration system for a small commercial coal-fired boiler operation. Five (5) 1,000-ACFM BLMT filtration modules would be placed in a parallel flow arrangement (i.e., incoming dirty hot gas flow from the combustor would be equally split 5 ways). To decrease the costs of individual containment vessel for each module, it would be more cost effective to arrange the 5 separate modules in one large cylindrical pressure vessel, with the units arranged equidistant from each other around its inside perimeter, mounted on a common plenum divider. The upper actively cooled section for the drive train, motors, bearings and shafts would be open for easy access to the upper modules for periodic servicing and maintenance. Below the plenum divider (between hot and cooled sections of the modules), individual inverted cones (lower section of a cyclone) would empty into a common expansion plenum for collection and removal of the rejected flyash. Individual cyclone housing collectors below each rotating filter module would maintain flow characteristics similar to that found in the tested prototype of this CRADA, insuring that flow conditions would be comparable to those already tested during scale-up.

6.2 Capital/Operational/Maintenance Costs of a Commercial-Scale BLMT Filter System

Assuming modular fabrication of the basic BLMT design, scale up to larger flow rates is required in industrial/commercial high temperature applications. The modular design establishes commonality of parts, significantly reducing fabrication costs. A series of standard "off-the-shelf" modules in various incremental size ranges (i.e., perhaps as low as 250-ACFM, up to 10,000-ACFM) is envisioned, whether InnovaTech is either manufacturing them or licensing out the technology to a joint venture partner for construction, marketing, and distribution. To look at other costs associated with the implementation of this type of technology in the marketplace, the economics of the device can best be established by splitting the costs into various elements and analyzing each separately for a more precise evaluation:

- initial capital costs;
- installation costs;
- day-to-day operating costs;
- periodic maintenance/repair;
- filter/component life expectancy (replacement costs);
- disposal costs;
- health/safety/liability costs.

Initial Capital Costs

The capital costs of a single low-flow high-temperature prototype for this project was expensive, due to the iterative design and fabrication costs of manufacturing components out of Hastelloy (a high-cost alloy). Since the prototype of this CRADA is still several orders of magnitude smaller (according to volumetric flow rate of the application) than even a small sized unit would need to be for commercial applications, a concise cost estimate for a typical unit will need to be assessed after the next increase in prototype size. Some relative cost estimates with conventional filtration systems already commercially used can be qualitatively compared with a proposed conceptual BLMT system, however, which is outlined below. Accurate meaningful quantitative cost data is precluded at this early prototype stage, since annual production quantities in a particular industrial/commercial application, necessary to incorporate significant price breaks in the manufacturing of these units, can only be "guestimated."

The proposed BLMT filtration device is expected to have an initial capital cost slightly above the capital cost of conventional barrier filters used in this application. If the costs are being estimated for a new facility, then system costs could be significantly lessened if upstream roughing cyclones could be eliminated. A similar high-pressure filtration containment vessel(s) is required in either case, so the cost would be the same for that particular filter component. It is anticipated that the cost of the conventional ceramic filter elements alone would partially offset the higher costs of the BLMT refractory metal disks used in the prototype filtration system. The cost of the BLMT bearing/seal and motor thermal environment protection system would also be partially offset by the cost of eliminating the traditional back-pulse cleaning system use in conventional candle filter systems.

Small horsepower motors would be used to spin the disks in the individual modules of the BLMT system; the total cost for these is small, since they would be standard off-the-shelf components, as are the bearings. Cooling of the bearings/seals can be accomplished with forced air and/or water at the clean air plenum interface, assuming a vertical column of rotating disks suspended from plenum near the top of the pressure housing, as in the final prototype design. This would allow flyash to fall to the bottom of the containment vessel (as in conventional filtration systems) for collection and disposal.

Using the bill of materials (BOM) generated for the 100-ACFM prototype of this CRADA, an approximate BOM shown below can be estimated for fabrication and assembly of a single 1,000-ACFM filter module, incorporating a common housing for five units in parallel to create a 5,000-ACFM filter system.

Approximate Bill of Materials for a Single 1,000-ACFM BLMT Filter

Units Needed	**BLMT Parts Description**
300	10-12 mil thick annular disks (16” OD; 14” ID)
3,000	0.5 mm spacers
10	1/8” rods (16” length)
20	5/40 nuts (attach to threaded ends of rods)
40	Belleville lock washers (hi-temp); 2 per rod end
1	1.5” dia. shaft x 48”
1	2” nut (lock on shaft)
1	disk end plate (16” dia. x ¼” thick)
1	stator seal plate (20” dia. x 3/4” thick)
1	upper plenum seal plate (20” dia. x ½” thick)
1	rotor seal/spoke assembly (16” dia. x ½” thick)
1	dust collection cone (20” dia. tapered to 4” dia. exit)
1	plenum outlet flow diverter cone (2.5” dia. x 10” dia.)
2	shaft locking collars
3	bearing/shaft enlargement tubes (press fit)
3	sealed (high RPM) bearings sets
1	motor mount
1	motor mount adapter
1	3 HP/3 phase motor (3450 RPM)
2	shaft couplers (7/16” & 1.5”) & connecting spider
4	12” long x 1” solid square supports (ends tapped)
8	½” fine thread bolts & washers
1	20” dia. x ¼” mounting plate

A water-jacketed pressure vessel housing for a BLMT filter module, whether singly or for a cluster of 5 modules, need only be constructed of normal steel alloys as is the case with other actively cooled commercial high-temperature filters. Only the non-cooled BLMT filter components in direct contact with the hot gases would need to be fabricated from high temperature metal alloys such as Hastelloy.

Installation Costs

BLMT installation costs would be comparable to that of conventional filtration systems, perhaps slightly less costly. There would be considerable savings in plant floor space due to elimination of any upstream cyclone(s). More electrical connections due to the bank of BLMT filter motors would be envisioned; but this would be offset by elimination of the extensive high pressure piping necessary for the conventional back pulse cleaning system. All in all, the BLMT system would conceivably have a much smaller footprint than existing systems.

Day-to-Day Operating Costs

The BLMT filtration system would have an annualized cost of electricity for operating the disk motors above that utilized for conventional back pulse cleaning. This would be more than offset by the steady-state pressure drop across the BLMT filter that would entail no periodic resetting of downstream blowers to optimize performance. The cyclic (sawtooth pattern) pressure profile of conventional systems as the filters load with particles that must eventually be back pulsed causes much consternation with plant managers; this operational headache would be eliminated.

Moreover, periodic changeout of spent filter elements is eliminated in our BLMT design, perhaps the biggest cost savings over the life of the filter when compared to conventional media-based filters. Furthermore, periodic down time for conventional filter replacement is curtailed, as well as labor costs in this task.

Periodic Maintenance/Repair Costs

Since the BLMT filtration technology requires rotating components in a high temperature environment, scheduled maintenance to optimize filter performance may be more than is currently required with conventional static (i.e., non-rotating) systems. Since the backpulse cleaning systems on traditional static filter systems must also be maintained with as much care as anticipated for the BLMT system, this cost should be comparable to those encountered today. The modular BLMT system would have component attributes similar to conventional filtration systems: replacement of potentially defective disks would be comparable to broken ceramic candle replacement. However, by compartmentalizing the BLMT components, individual disk stacks within the larger pressure module could potentially be isolated without shutting down operations to the rest of the filter. Repair and/or scheduled maintenance could be conducted easily without any undue environmental exposure to the maintenance personnel, effectively reducing possible hazard litigation.

Filter/Component Life Expectancy (Replacement) Costs

Whereas conventional ceramic filter elements have a life expectancy measured in weeks or months (assuming adequate backpulse cleaning and no catastrophic failures due to thermal cycling or fatigue), the BLMT filter disks have an indefinite life expectancy measured in multiple years. Use of appropriate refractory metals will eliminate corrosion and/or erosion tendencies. Since BLMT filter disks only come into contact with flyash particles on their outside edge (i.e., the perimeter of the disk pack), any wear or erosion would be in the radial direction. Even though BLMT disks are thin (typically 15 to 20 mils), in the radial direction they would appear to be over an inch thick. The boundary layers established by the rotating disk pack actively keeps particles away from the device. Whereas the high temperature porous ceramic filters of conventional systems will frequently foul or clog up and would then be discarded, BLMT disks would not have this conventional characteristic.

The most sensitive components in the BLMT filtration system (requiring active protection) are bearings and seals, which can be engineered to last extended periods of time, as well as the filter disk drive motor. For example, for a higher initial cost, the units could be equipped with more expensive bearings having greater MTBF, requiring less frequent periodic change out during normal operations. Furthermore, there are many off-the-shelf industrial electric motors having high thermal capabilities at very reasonable costs. Since the motors will be located on the clean air side of the plenum and outside the hot gas envelope, active cooling and a clean operational environment can be easily provided, guaranteeing a long service life.

Disposal Costs

In this context, we are speaking of the disposal costs of the spent filter elements (not the flyash), a problem and additional cost with conventional filtration systems, but a moot issue with the BLMT filter. If any of the BLMT disks or components should fail and require replacement, the metal could be recycled (i.e., melted and reused); spent conventional ceramics would have to be landfilled.

Health/Safety/Liability Costs

Finally, there is the issue of worker safety and health, potential corporate liability costs if the flyash is considered hazardous (e.g., high mercury or heavy metal concentrations). Since there is significantly reduced periodic maintenance where workers must come into contact with spent filters, potential exposure of the plant workers to hazardous dust is mitigated with the BLMT filtration system. Evidence to date from commercial ceramic filters in operation requires the filter candles to be removed from the pressure vessel, leading to significant exposure to a hazardous dusty environment typically every few weeks to months during change out. The BLMT system could be maintained/serviced external to the dust collection system (i.e., remotely with the use of appropriate sensors, etc.) without having to systematically replace all the filter elements as is the case with conventional systems. Additionally, the added cost of landfilling traditional spent ceramic filter elements is avoided, alleviating some environmental concerns over traditional filtration technology.

Anticipated Problems and Solutions

Several typical problem areas associated with the use of the BLMT exclusion filter in this type of high temperature application have been anticipated. For instance, periodic lubrication of the cantilevered shaft bearings of the rotating disk set must be occasionally performed. However, with judicious choice of bearings (i.e., self-lubricating designs or easy accessibility to the pressurized and actively cooled section of the motor section of the housing) incorporating adequate engineering design precautions, this potential problem area can be mitigated. The cantilevered prototype design places all actively cooled bearings outside of the hot gas chamber of the containment vessel.

Particle bridging between filter elements, a common failure mode in most conventional porous ceramic filters, should not be a problem due to the dynamic nature of this type of filter. No build-up of residue flyash in the hot gas chamber was observed during the limited testing of the prototype. Scale up of the disks and chamber would not increase the likelihood of this occurrence. At elevated temperatures, sufficient to cause sticky and/or agglomerating flyash, there has been no evidence of interdisk fouling or clogging in this self-cleaning design. Any potential accumulation on the disks would also tend to be constantly discharged back into the collection chamber once the centrifugal forces on the conglomeration reached a mass sufficient to centrifugally overcome the adherence forces on the surface. Empirical assessment during the post-project analysis of the test components at NETL/Morgantown showed no evidence of this potential phenomenon.

The particle collection vessel portion of the housing in the hot gas section of the BLMT filter prototype is similar to that of a conventional cyclone for particle collection. The disk pack is located in the central core, while rejected flyash travels around the perimeter wall, gradually falling into the attached collection module at the bottom of the cyclone funnel. The pressurized collection module consists of a cylindrical expansion vessel where the vortices of the particle-ladened hot gas slow down, allowing the entrained particles to settle out under the influence of gravity. In a continuous system, an auger or other removal device would periodically remove accumulated flyash from this housing. Any potential buildup of flyash in this section of the collection vessel would be countered by traditional means employed with conventional hot gas cyclones (i.e., steeply inclined and smooth cyclone walls, smooth flow transitions into the collection vessel, relatively large exit throat to eliminate potential bridging across the exit, etc.).

Slight over-pressurization of the actively cooled motor/bearing section of the containment vessel would eliminate any possible bypass of flyash from the hot gas section of the housing, reducing the possibility of accumulation in the rotating seal area of the device. Flow of cooler gas from this section past the rotating non-contacting labyrinth seals would guarantee minimal servicing of this critical area of the device. Volume of the over-pressurized flow would be sufficiently small to minimally affect a perceptible temperature drop of the main hot gas flow stream.

Conclusions and Recommendations for Commercial Development

Patented dynamic medialess filters have previously been constructed of stacked sets of hollow metal disks (e.g., spaced annuli) designed to remove fine particulate matter from industrial process gas streams *at ambient temperatures*. By fabricating these filter components in high temperature metal alloys within this CRADA and redesigning critical rotating components to operate at elevated temperatures/pressures, this novel filtration technology can be applied to hot gas cleanup (HGCU) downstream of a simulated coal-fired combustor. Other types of processes applicable to this technology include conventional direct coal-fired furnaces or boilers, waste incinerators and on other high-temperature industrial processes.

For this filter technology to be utilized successfully at elevated temperatures and pressures, four critical BLMT components were modified in this project to operate for long periods of time in this harsh environment:

(1) all filter components that come in contact with hot gas must be fabricated from high temperature alloys and be actively cooled;

(2) the non-contacting, rotating seal must bridge an actively cooled pressurized chamber opposite the hot gas chamber to minimize differential pressures across the seal, minimizing particle bypass;

(3) the bearings and hollow drive shaft must be actively cooled within this pressurized chamber (outside of the hot gas chamber) to enhance component survivability (i.e., long MTBF service life);

(4) the actively cooled electric drive motor must also be protected from the heat, requiring its placement within the pressurized chamber opposite the hot gas chamber.

A compact prototype incorporating the above enhancements was designed under a separate DOE contract (No. DE-FG36-98G010314) with InnovaTech, with final construction, assembly and testing under this CRADA to establish its particle filtration performance at elevated temperatures and pressures at the DOE/NETL test facility in Morgantown, WV. The data collected from testing the prototype at elevated temperatures and pressures establishes a 98-to-99% overall particle filtration efficiency by mass. No major problems were experienced during the operation and testing of the prototype. These results establish the feasibility of using this technology for many high temperature hot gas filtration applications.

Successful implementation of the BLMT filtration technology as a major hot gas clean-up (HGCU) device could conceivably result in an overall power conversion cycle efficiency increase from 42% (current power plants) to over 45%, by allowing for an increase in inlet gas turbine temperatures, which must currently be held in the 1650^{o}F (900^{o}C) to 2350^{o}F (1290^{o}C) range. This could be accomplished by merely firing a topping fuel (natural gas) after flue gas filtration by our BLMT device, but prior to the gas turbine inlet to significantly increase the flue gas temperature. Removal of essentially all particulate matter above 2 microns before firing the natural gas is essential to obtain this 3% overall power conversion gain.

According to DOE Clean Coal Technology documents, nearly 52% of all electric power generation in the U.S. in 1994 was from coal (representing 1,694 billion kilowatt-hours of the total 3,271 billion kilowatt-hours generated). If we extend a 3% increase in coal power conversion across the board to all coal-fired power stations (admittedly a high estimate), this potentially represents 50 billion kilowatt-hours annually that could be saved (assuming $0.07/kwh, this equates to $3.5 billion energy savings every year). Note that as of 1988, there were 370 operable U.S. coal-fired power plants. Last year (FY00), 44% of the U.S. coal-fired power capacity was 30 years old or older requiring retrofits of new, more efficient clean coal technology, like the BLMT hot gas filter.

The proposed BLMT exclusion filter based on the design evaluated in this CRADA would dramatically reduce the cost of generating electricity from coal, which will lessen U.S. dependence on foreign oil. This unique filtration concept can also be adapted to biomass gasification, dust filtration in mines and granaries, inlet air filtration for turbine and reciprocating engines (i.e., aircraft, agricultural/construction/off-road vehicles) and EPA emission compliance for high temperature industrial processes, incinerators, and furnace exhausts.

The following recommendations are suggested for future (larger scale) BLMT prototype designs and commercialization.

- Continued testing at higher temperatures/pressures at NETL-Morgantown, incorporating further design enhancements recommended by the DOE engineers;
- Continued refinement of the single-module BLMT filter at Morgantown for non-utility applications, with subsequent BETA testing at several commercial facilities
- Commercialization of the smaller BLMT filtration systems via licensing;
- Collaboration with large A&E firms servicing the electric utility industry, incorporating their design suggestions for larger scale units;
- Design, fabrication and evaluation of a much larger scale, multi-module BLMT filtration system for subsequent testing at the DOE facility in Wilsonville, AL, specifically for application in coal-fired electric utilities;
- Slip-stream testing of the Wilsonville system at a commercial electric utility plant;
- Replacement of a conventional media filtration system with a BLMT filtration system at a commercial coal-fired electric utility plant.

7 Motivation for Testing

The filtration of coal ash particles from a gas stream under high temperature and high pressure conditions is a challenging engineering problem. There are many alternative ash filters, e.g. bag type, rigid ceramic, rigid metal mesh, rigid composite, electrostatic precipitators, etc… However, each of these methods has both strengths and drawbacks that make them only applicable under specific operating conditions. The rotating BLMT filter system is a novel filtration technique that promises to deliver adequate filtration efficiency under a broad range of operating conditions. In addition, the BLMT addresses some of the physical limitations regarding fracture toughness or fatigue life that plague other filtration technologies.

8 Description of Experimental Apparatus

Figure 3 shows the basic experimental setup that was used to test the InnovaTech filter system. Figure 4 provides a cutaway view of the motor drive assembly, pressure vessel, and filter system. The filter vessel and filter assembly was designed and built at NETL.

8.1 Filter System Design and Dimensions

The filter pack consists of a stack of disks held together by tensioning rods. Small washers act as spacers between the disks. This allows gas to pass between the gaps in the disks. The whole disk pack is attached to a wagon-wheel like structure that has openings that will allow filtered gas to pass by the spokes of the wheel and continue out of the exhaust. The disk pack is located at the end of an approximately 4’ long steel shaft that is connected to a 220 volt, 3-phase motor. The shaft is mounted vertically and is supported on the top with a thrust bearing and on the bottom with conventional load type bearing.

8.2 Physical Dimensions

The following are the physical dimensions of the filter pack. Photographs of the filter pack are shown later in the report. The dimensions in Table 2 are used to calculate face velocity of gas flowing through the filter pack. The results of these calculations are shown in the spreadsheets in the Data Appendix.

Table 2. Dimensions of Filter Pack

Disk Pack Dimensions						
outside diameter (in)	inside diameter (in)	number of disks	Interdisk Spacing (in)	Calculated filter area (in^2)	calculated filter area (ft^2)	calculated filter area (m^2)
6	4	90	0.026	43.6108	0.3028	0.02814

8.3 Filter Vessel

The filter vessel is made of steel and is water cooled. The inside diameter of the filter vessel is approximately 12”. The filter vessel has three sections. The top section is pressurized slightly above the main filter vessel to maintain air cooling of the motor. It is approximately 5’ high and serves to house the motor. The main body of the filter vessel is approximately 3’ high and provides a ledge on which the filter pack assembly (including pack, drive shaft, and motor) rest. The assembly is welded into position once it is lowered into the main body. The main section of the filter vessel is the location where the filter pack rotates. Ash is filtered from the gas in this section and the clean gas exits through the exhaust ports of the main body section. The ash eventually settles to the bottom of the 1’ high, lower section of the filter vessel where it slides into a small ash hopper. The ash hopper is periodically emptied.

8.4 Materials Used in Construction

The disks, disk spacers, and spacer rods are made of hastelloy. The shaft on which the disk pack is mounted, the metal labyrinth seals, and the wagon-wheel like structure on which the disks are mounted are steel. The filter vessel is made of steel.

8.5 Operation

The filter vessel is pressurized with hot combustion gas. The ash feeder meters a set amount of coal ash into the hot gas stream. The first Particle Characterization Meter (PCME) reads the ash flow into the filter vessel. The second PCME reads the amount of ash that has managed to pass through the filter. The motor that drives the spinning filter pack is in a pressurized, and air cooled, part of the vessel. To protect the motor from heat, a drive shaft assembly is used to spin the filter pack. A pressurized metal labyrinth seal is used to separate the ash side from the clean side of the spinning filter pack. The drive motor is set to spin at a constant speed of 3600 rpm.

Figure 2. Filter Drive Assembly

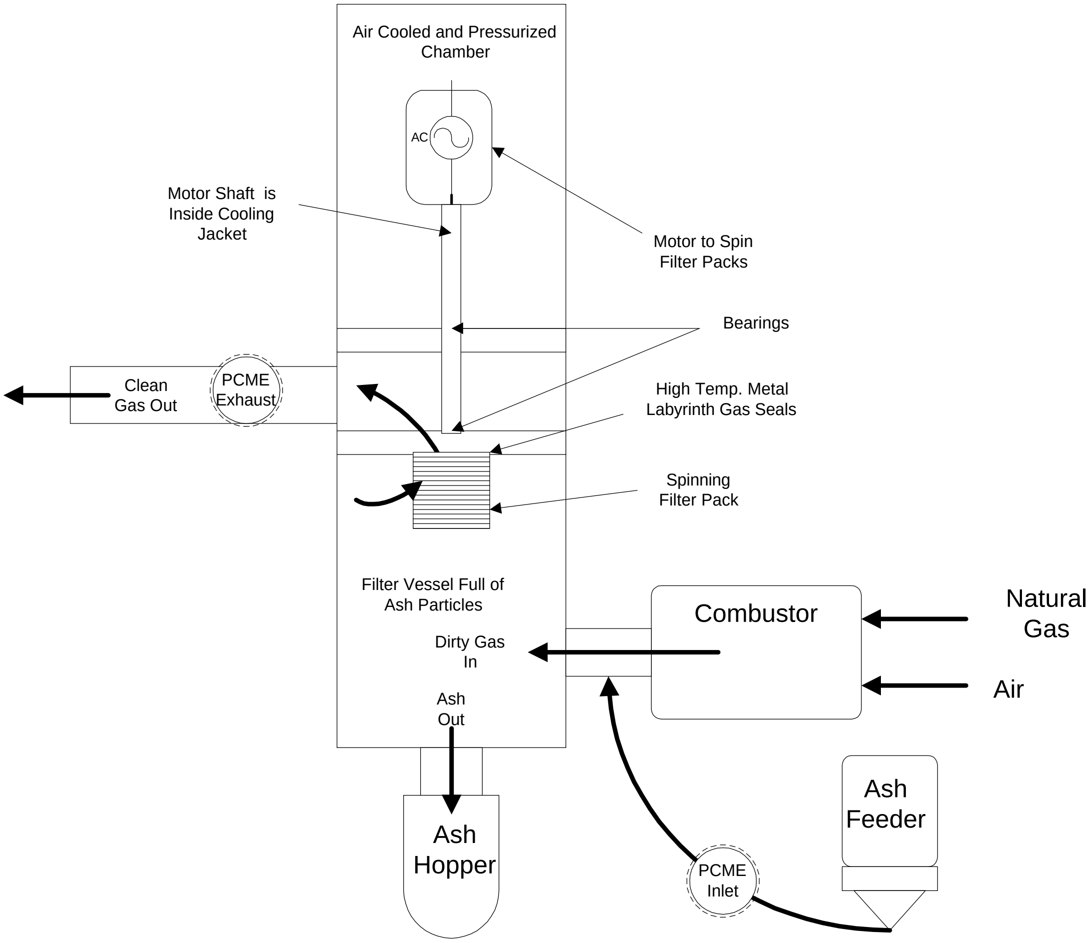

Figure 3. Schematic of Test Apparatus

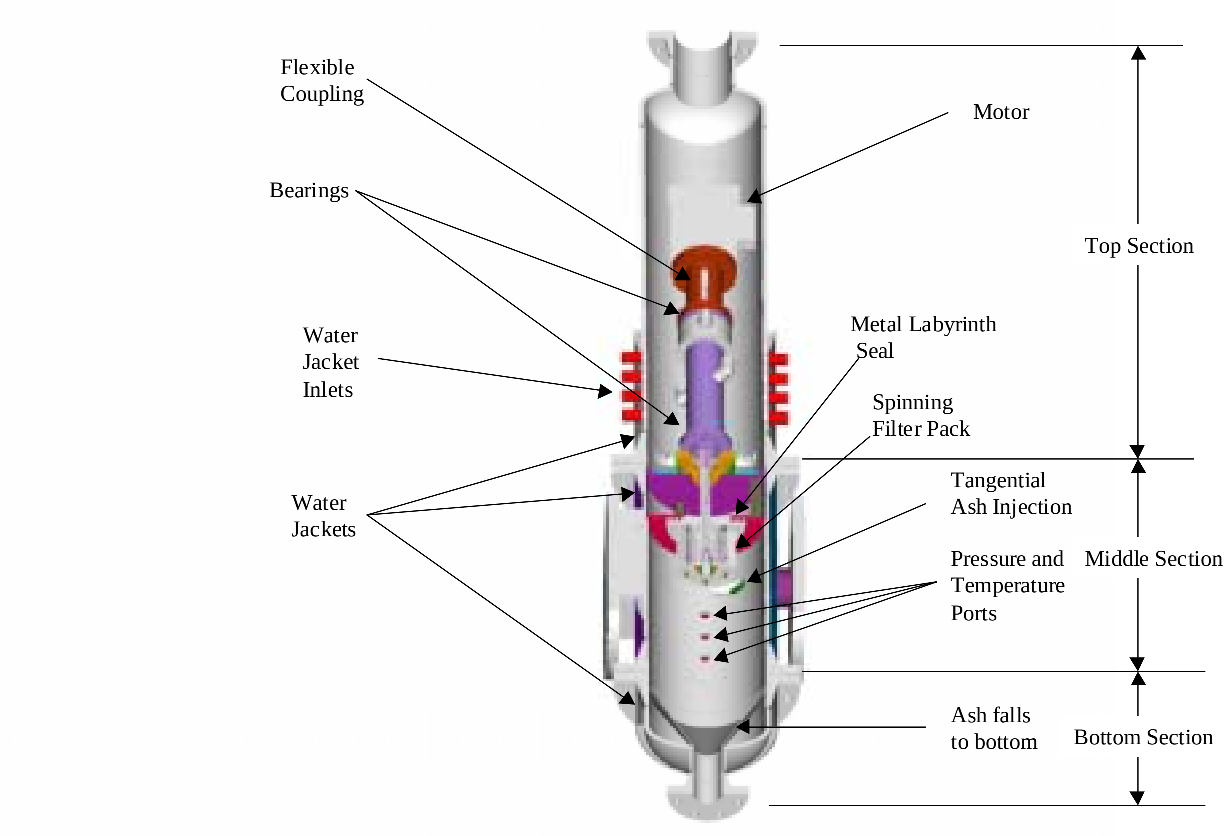

Figure 4. Annotated Cross Section View

Figure 5. Metal Labyrinth Seal

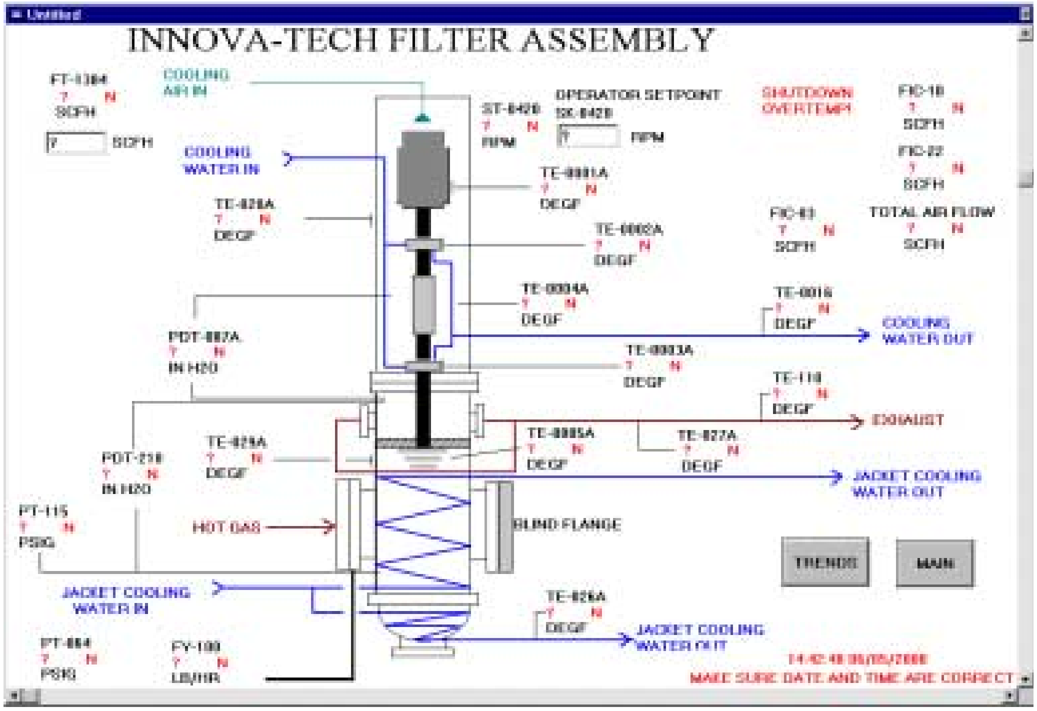

Figure 6. One of the Data Acquisition Screens Used During the Runs

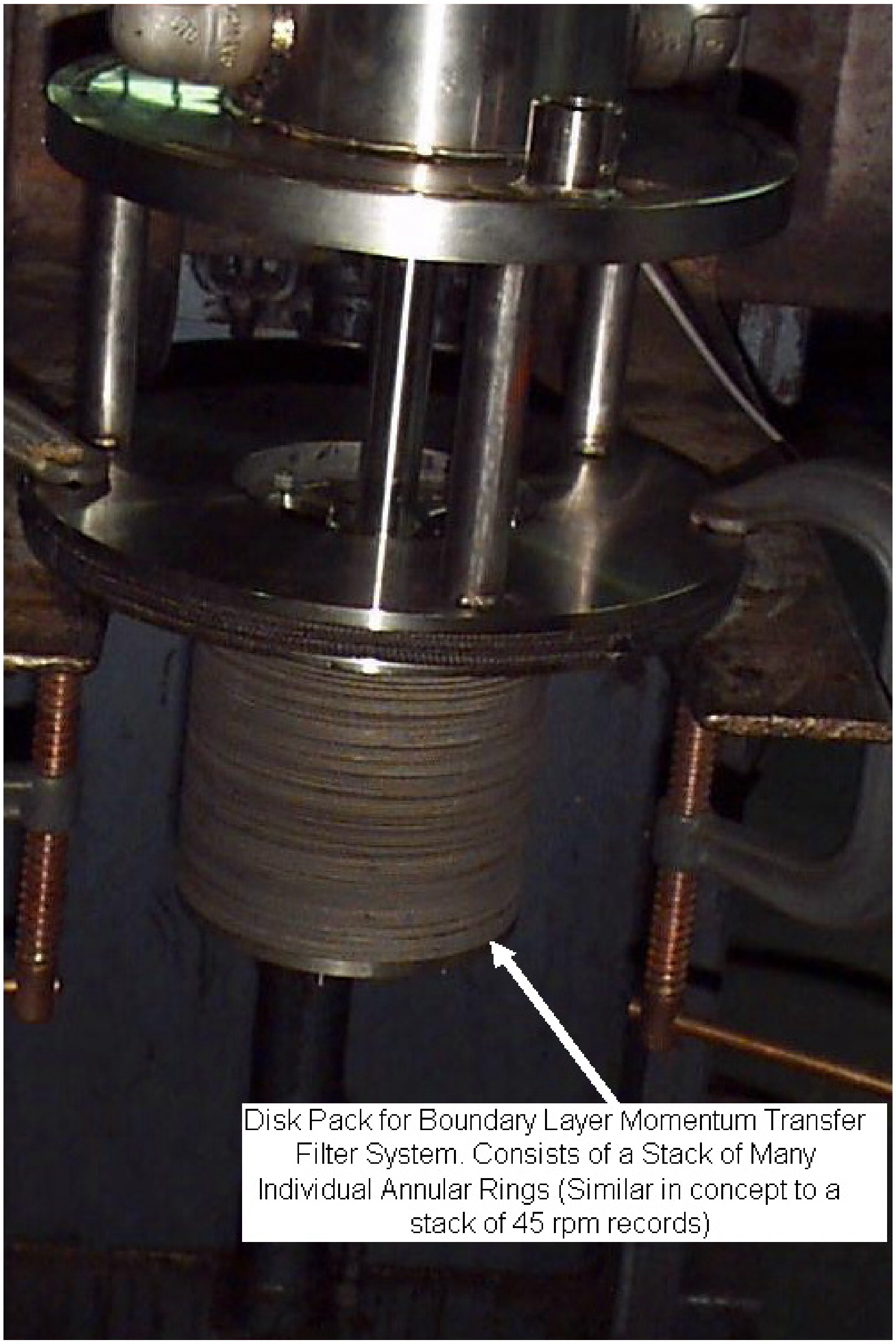
Disk Pack for Boundary Layer Momentum Transfer Filter System. Consists of a Stack of Many Individual Annular Rings (Similar in concept to a stack of 45 rpm records)

Figure 7. Boundary Layer Momentum Transfer (BLMT) Filter Disk Pack

Figure 8. Installation of Disk Pack Into Filter Vessel

Figure 9. Upper Half of Filter Assembly on Right, Mid-Section Center

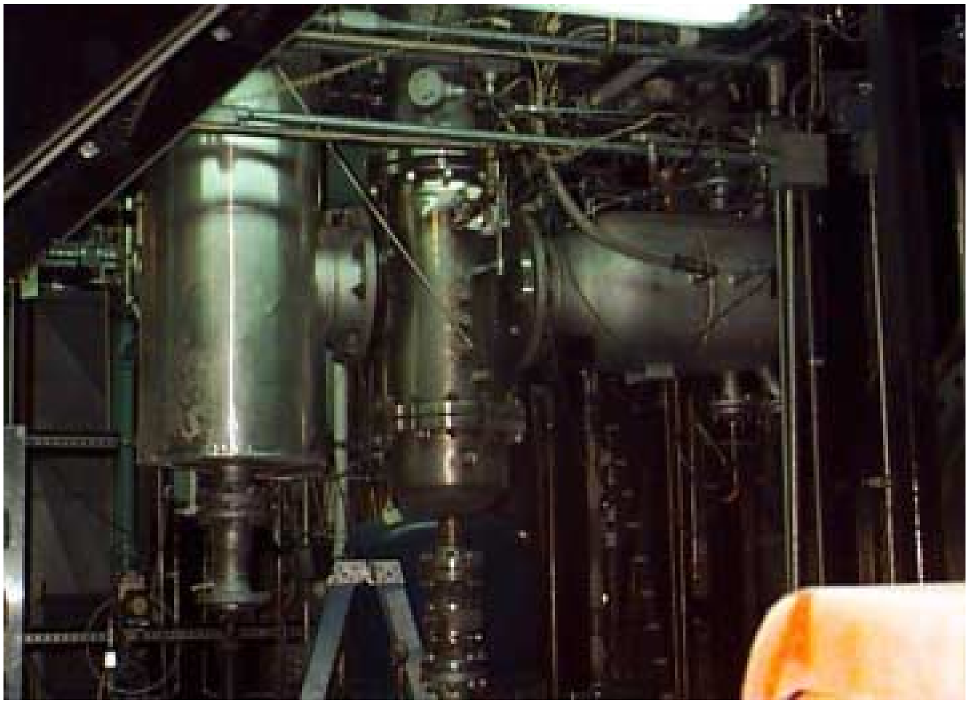

Figure 10. Filter Vessel Installed in Test Rig (center)

Figure 11. Large Blue Vessel is Pressurized Ash Feeder.

K-tron Loss-in-Weight Feeder is Inside Vessel.

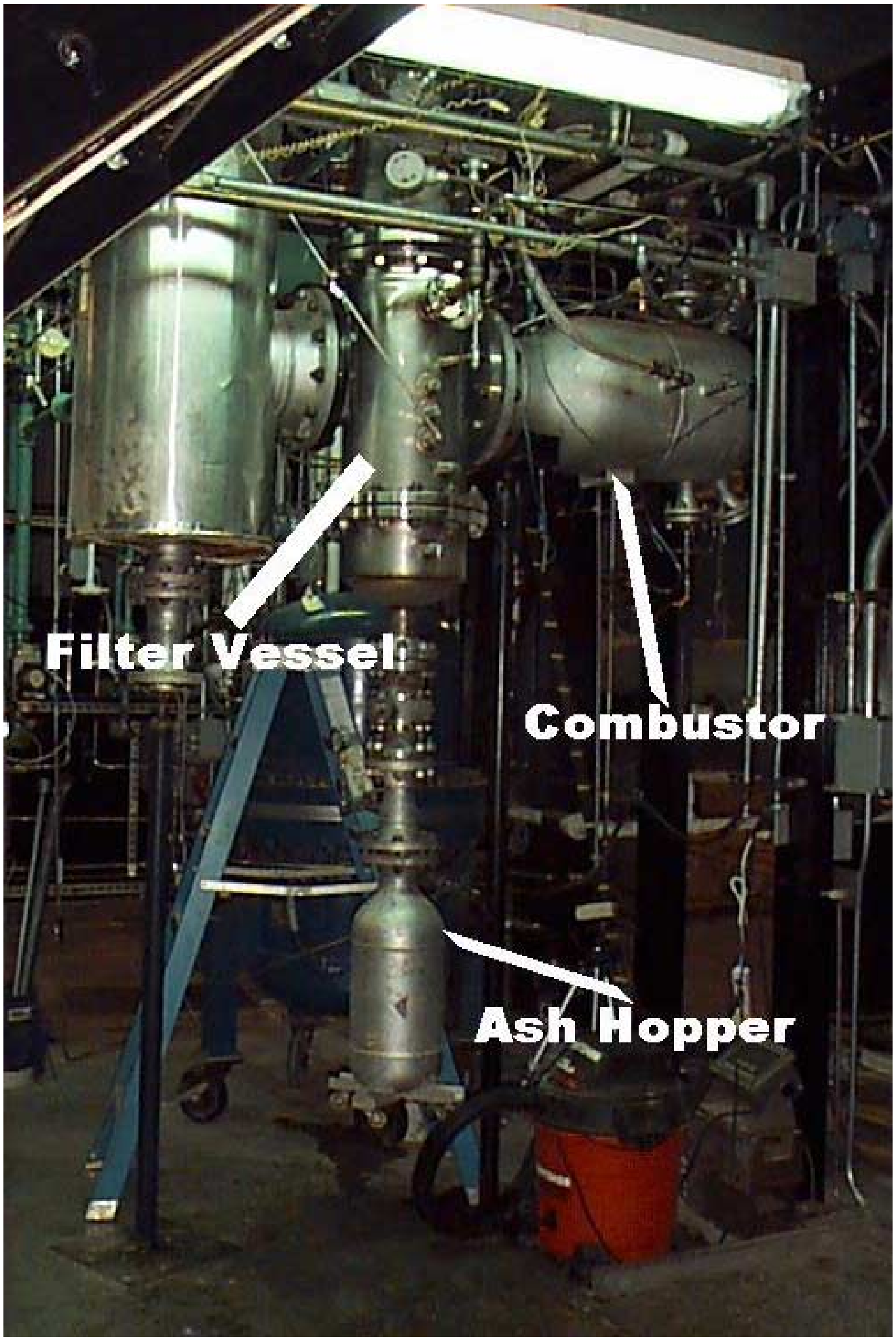

Figure 12. Vessel Assembled With Hopper (Ash Pot) In Place

9 Important Observations Regarding Testing and the Results

There are several ways to evaluate filter efficiency. One way would be to inject a known quantity of ash into the filter vessel, then measure the amount collected in the ash hopper. The difference would be what passes through the filter. The ratio of ash collected to ash injected would be the filter's efficiency[2]. Another way of calculating efficiency would be to directly measure, real time, the ash flow into the system and the ash flow out of the system. This is done in this case with a particle counter called a Particle Characterization Meter (PCME). The PCME measures the change in an induced electrical field. In operation, particles pass through a ring shaped spool piece that generates the electric field. The charge carried by the particles as they pass through the ring shaped spool piece changes the electrical field and generates a signal, read by the PCME, that is proportional to the mass flow of particles divided by the mass flow of gas. The efficiency of the filter would therefore be the ratio of the post-filter PCME reading to the pre-filter PCME reading. Problems with each of these methods of calculating filtration efficiency are discussed below.

9.1 Efficiency Calculation Using Control Mass Basis

It is very difficult to perform a control mass analysis and account fully for all of the ash that enters and leaves the system. For example, with a known amount fed into the system, the amount of ash collected in the ash pot could be weighed and the difference between what is fed in to what is collected is presumably the amount of ash that passed through the filter and out the exhaust. However, on the interior of the filter vessel there are many nooks, crannies, and ledges that hold ash. In addition, due to the tangential injection of the ash in the filter vessel (vessel acts like a cyclone) the wall builds up a cake of ash over time and a thick layer forms on the slanted bottom of the filter vessel before sliding into the ash pot. Therefore, it is erroneous to assume that the amount not accounted for in the hopper leaves the system. A crude check of how much ash adheres to the inside of the vessel was conducted after the conclusion of the 1st day of testing (05/23/00) under cold conditions.

Prior to the cold run, the vessel was vacuumed clean. After the cold run, the feeder indicated that a total of 17.2 pounds of ash fed into the system. The ash in the hopper was weighed and found to be 14.4 pounds. This indicates that 2.8 pounds had left the system (16.3% of the total weight). If this were correct, then the filter would only be 83.7% efficient in removing ash (weight basis). However, a steel rod was scrapped on the inside of the vessel while holding a clean plastic bag under the ash hopper outlet. By doing this, 2 pounds of ash was recovered in the plastic bag. This means that only .8 pounds of ash was unaccounted for. If only .8 pounds of ash passed through the filter, then the filter would be 95.3% efficient in removing ash (weight basis). This control mass result is consistent with the PCME readings. The PCME showed 99.4% filtration efficiency (again weight basis).

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[2] This method would not take into account differences in particle size distribution. That is, a filter might remove 100% of the particles above a certain diameter. The method discussed is for illustration purposes only.

9.2 Efficiency Calculation Using PCME Readings

The accuracy of the PCME reading is subject to a number of variables, some of which we could not control during the test. For example, the manual says to set the instrument gain on "high sensitivity" to detect highly dispersed solids (as is the case in this experiment). However, there is no indication of how accurate the instrument is on the high sensitivity setting. The factory representative stated that to calibrate the instrument, a known quantity of solids is passed through the instrument, and the process is repeated a second time for a different mass flow and assume a linear response. Therefore, the slope of the line is a "constant" that you can use to evaluate any other mass flow setting.

It is not known how accurate this measurement is for flows much more dispersed than those on which the instrument was calibrated. The inlet ash feeder can calibrate the PCME on one side of the system. However, there is no equivalent calibration for the second PCME (don't know for sure how many particles passed through the exhaust). In addition, a confounding problem with this procedure is that the solids must have the same general particle size distribution, or the calibration is inaccurate. The reading is dependent on the charge of the particles, which is in turn dependent on the diameter and shape of the particles passing through the sensor rings.

In this case, for the ash entering the system, two points are easily determined by feeding ash through the system at two different flow rates. The ash size distribution is the same, so "k" (a PCME reading constant) can be determined for any mass flow on the inlet side. However, there are two problems on the outlet side. First, the flow is two orders of magnitude more dispersed (mass basis, far fewer ash particles in the exhaust versus the inlet) and second, the size distribution that flows through the sensor ring of the second PCME is different from the size distribution of the ash on the inlet side (see ash samples inlet-sample #1548 and exhaust-sample #1585 in Data Appendix).

9.3 Solution to Efficiency Calculation Problem

Simply using the PCME by itself, with no other means of checking its accuracy, was not a viable option. The cold test mass balance can be used to check whether the assumptions we are making regarding the PCME accuracy are valid. As stated earlier, a true mass balance is difficult to do because of settlement of ash in the vessel. It is neither a clean or easy job to scrape the inside of the filter vessel to try to collect the ash that tends to adhere to the interior surfaces. However, this was done for the cold test. The cold test mass balance showed that 95.3% of the ash fed into the system was collected either in the ash pot or adhered to surfaces inside the system. The PCME showed an average filtration efficiency of approximately 99.4% efficiency (ratio of outlet to inlet reading). The PCME efficiency reading is higher than the mass balance, but both readings are consistent with the observations of the exhaust line of the filter system upon disassembly, i.e. there was not very much ash in the bends and crannies of the exhaust system. Therefore, we feel much more confident that, although the absolute accuracy of the filter system can not be determined without further calibrations, and modifications of the test apparatus, the efficiencies stated in this report are accurate enough to prove the concept of the BLMT under high temperature conditions.

9.4 Design Problems, Suggestions for Improvement, and Operation Notes

There are several challenges in designing a rotational filter for high temperature environments. The motor must be protected from overheating, the bearings must be protected, and the system must be properly balanced to avoid vibrations that can cause the filter assembly to become damaged or seize. However, the biggest challenge is designing a seal system that will work in the harsh, hot, particle laden environment of a coal combustor. The design employed in this test depends on a slight over pressurization of the section of the filter vessel that houses the motor, thereby forcing cooling air through the seals and bearing spaces into the hotter section.

10 Data Collection and Assumptions

There are a number of tradeoffs that were made during this experiment due to physical limitations of the test apparatus and limitations in the time available for testing. For example, the best way to test the filter system would be to match the flow and ash characteristics to those present in real power plants. This was done, but some tradeoffs were made for particular desired pressures, temperatures, ash loadings, and gas flow rates because the test equipment could not physically operate in the ranges necessary to duplicate all the desired experimental test points.

Temperature is primarily a function of fuel/air ratio, secondary coolant air, and ash conveying nitrogen flow. The desired temperature points of 1000 deg. F and 1500 deg. F. could not be reached under the operational constraints. Primarily, the water inside the coolant jacket was getting too hot. The coolant jacket was not designed to operate in a super-heated fashion. If we had continued to raise the temperature, we were afraid that we could start to build up unwanted pressure in the water jacket due to the presence of superheated steam. Therefore, the tests were conducted at two temperatures that could be achieved (500 deg. F. and 750 deg. F.) without totally vaporizing all of the coolant water.

Face velocity is a function of the dimensions of the filter system (and the gap between the disks). This is a constant and was set by how the filter pack was constructed. Ash loading on the filter, in ppmv, is a function of the density of the ash, mass feed of the ash, and volume flow of combustion gas. The desired ash loading would be approximately 5 ppmv to closely simulate PFBC conditions. Unfortunately, the ash feeder can not feed at rates low enough to duplicate the desired conditions. The loadings therefore range from 15-25 ppmv.

10.1 Calculations

The following are the calculations used to determine face velocity, ash loading in ppmv, and gas flow.

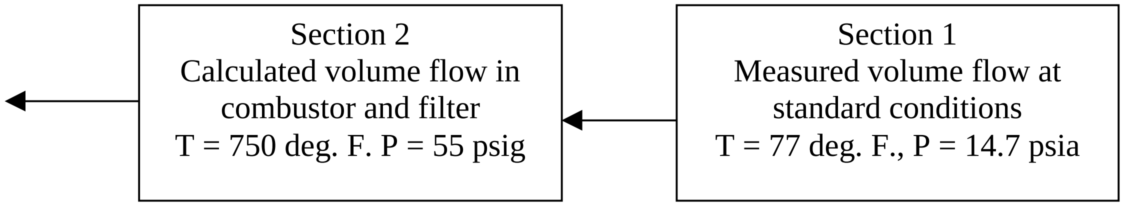
Gas Flows

Standard conditions: 77 deg. F, 25 deg. C., and 14.7 psia, 101.3 kPa. Assume steady flow process once vessel is brought up to temperature.

$$p \bullet \dot{v} = R \bullet T \qquad R = .287 \frac{kPa \bullet m\text{^}3}{kg \bullet K}$$

Where:
P = pressure (kPa)
$\dot{v}$ = specific volume flow of gas (m^3/kg s)
R = gas constant for air
T = absolute temperature (K)

Gas flows into the combustor are given by the instruments at standard conditions. However, after going through the combustion process, the gas is at a much higher temperature. In addition, the vessel operates at much higher than ambient pressures (up to 100 psig). Therefore, corrections to the gas flow must be made in the filter vessel to accurately calculate face velocity.



Use the equation below to calculate specific volume corrections. For specific volume "flows," determine the gas flow rate into the system from the instruments.

$$\frac{p1\bullet\dot{v}1}{T1} =. \frac{p2\bullet\dot{v}2}{T2}$$

Ash Feed Rate in ppmv

Assume density of ash is approximately 2.7 g/cm^3 (from ash characterization). Therefore, with known mass of ash into system from k-tron feeder reading, volume flow of ash can be calculated. Volume flow of gas was already calculated, therefore ratio of ash to gas can be determined.

10.2 Equipment and Software

The following describes some of the equipment used in the test.

Ash Characterization

Ash is analyzed to determine the particle size distribution. We use a Quantachrome Autosorb6 (Model AS-6B-KR) for BET[3] Surface Area. The samples are prepared by degassing on a Quantachrome Degasser (Model AD-3) at 105C overnight. For BET surface areas in the range of the samples in this test, the accuracy is about 10% relative. The smallest cut size the instrument is capable of handling, as currently configured, is particles 10 microns in diameter or larger.

Particle Counting

The PCME consists of a ring shaped sensor that creates an electrical field. Particles pass through this electrical field. The interaction of the slightly charged ash particle with the electric field generates a signal that can be used to calculate the mass of particles versus mass of gas flowing through the system.

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[3] BET refers to Brunauer-Emmet-Teller. This is the most widely used procedure for the determination of the surface area of solid materials.

The Particle Characterization Meter system is used to determine the proportion of solids to gas flow (kg solid/kg gas) in the ash feed stream. It operates by creating an induction field through which particles flow and measuring, in pico-amps, the change in the field due to the presence of particles. The reading of the device is somewhat dependent on the particle size distribution of the solids because the change in the induction field is dependent on the diameter of the particles that pass through the field. Further, the units of measurement must be calibrated with a known particle distribution and known amount (mass) of flow. This is done in this instance through the use of the k-tron loss in weight feeder system. The k-tron feeder has a metered mass flow rate. One of the PCME monitors is installed on the ash feed line just downstream of the k-tron feeder. This provides the real-time calibration of the device (in kg ash/kg gas).

There is also a PCME monitor on the exhaust stream to determine the amount of ash that passes through the filter (i.e. to determine filter efficiency). Strictly speaking, the ash distribution on the exhaust side of the system is not the same as that on the feed side (see ash characterization sample 1548 – feed side, and 1585 - exhaust side). Therefore, the interaction of the ash particles with the induction field on the exhaust side is slightly different from what is present on the feeder side. The calibration therefore will not be as accurate for the exhaust side as for the feed side. For the purposes of this experiment, it is assumed that the change in particle size distribution from feed to exhaust side does not materially affect the determination of the filter efficiency estimates based on the two PCME readings.

Model: Flowmasster;
Range: .01 milligram solid to m^3 of gas (approximate, depends on gas and solid density)
Accuracy: +-10% (approximate, depends on particle distribution and method of calibration)
PCME, Inc. Attn: Bruce Kemp, Pete Watson,
9324 Gulfstream Road
West Unit, Frankfort, IL 60423-0423
Phone: (815) 464-8705 Fax: (815) 464-8717

Ash Feeding

The ash is fed to the filter vessel by using a loss-in-weight feeder manufactured by k-tron. This feeder system is widely used in industry for feeding small solid particles and feeders of this type have been used at NETL for many years. A hopper contains the ash to be fed and rests on a scale. As counter-rotating screws turn, a small amount of ash is fed from the hopper. The amount of ash fed through the screws is determined by the loss in weight on the scale. The ash falls past the screws into a funnel. The hopper, scale, funnel, etc... are contained in a large pressure vessel that is pressurized with nitrogen. Nitrogen is used as an ash conveying gas because it is non-reactive, dryer than air, and is available as a site utility at higher pressure than process air. When a block valve is opened between the combustor and the ash feeder vessel, the pressure difference between the feeder vessel pushes ash through the funnel into the combustor.

Data Acquisition Hardware and Software

The filter vessel is monitored by a data collection and control system built around individual data collection modules and Paragon TNT data collection software. Data is collected by OPTO-22 data modules. Each of these modules has it’s own analog to digital converter and communicates data at rates around 10 Hz. A “Brain Board” or processor capable of spanning and linearization signals connects these modules. The brain board then communicates with a PC running Paragon TNT software for data collection, graphical operator interface and some operating controls. More Products Process Controllers (Moore 352) are the primary method of providing PID loop control for the flow loops (note: most of the control loops are run in parallel so that they can also be controlled from the computer as well as the controllers). Flow loops consist of the following: Primary air, secondary (combustion coolant) air, natural gas, ash conveying nitrogen, motor cooling and labyrinth seal pressurizing air. Relay logic is used for safety controls (block valves, open/close valves). The process variables are recorded. These consist of the following: gas temperatures, surface temperatures, position of valves (open/closed), ash feed rates, coolant water inlet and outlet temperatures and pressures, motor speed, motor current draw, natural gas flow rate, combustion temperature, and many system pressures.

Pressure Measurement

In general, Rosemount “Smart” pressure transmitters are used throughout the system. Each transmitter is dead weight calibrated yearly. Typical frequency response is 10 Hz.

Flow Measurement

Gas flow is calculated by using calibrated orifice plates, thermocouples, and pressure transmitters.

Temperature Measurement

Thermocouples are generally Omega type “k” for most measurements. Type “r” are used for combustion gas temperatures (higher range).

Figure 13. PCME Sensor Box

Figure 14. PCME Ring Shaped Sensor Installed on Exhaust Line

11 Experimental Procedure

There were basically three parts of the test:

- Cold testing on 23 May, 2000.
- Hot testing at approximately 500 degrees Fahrenheit on 24 and 25 May, 2000
- Hot testing at approximately 750 degrees Fahrenheit on 30 and 31 May, 2000

12 Operating Procedure

The following are the approximate sequence of events that occur during a test.

Pretest

1. Install rotational filter system
2. Screen and dry ash for use in experiment
3. Load ash hopper
4. Take sample of ash for particle characterization
5. Pressurize ash feeder to 150 psig and prepare for ash feeding. Block valve remains closed to isolate feeder from combustor
6. Start the rotation of the filter system
7. Begin airflow through combustor

Test – Cold

1. If it is a cold test, no natural gas is used
2. The block valve will be opened and ash will start to flow through the combustor and filter vessel toward the filter
3. The ash is rejected by the filter system and eventually settles to the bottom of the filter vessel and falls into the ash hopper
4. The readings from the particle monitors (PCME) are logged

Test – Hot

1. If it is a hot test, natural gas will be slowly brought online while an igniter system sparks to ignite the gas mixture
2. Once the gas is ignited, it takes about 2 hours (minimum) for the combustor and filter vessel to reach quasi-equilibrium temperature
3. Once filter vessel is hot enough, the ash block valve is opened and ash flows into the combustor and filter vessel

4. The ash is rejected by the filter system and eventually settles to the bottom of the filter vessel and falls into the ash hopper
5. The readings from the particle monitors (PCME) are logged

Post-Test

1. The ash flow is stopped
2. The combustor is shut off (flame extinguished)
3. The motor to the filter is turned off (rotation stopped)
4. The vessel and ash hopper are allowed to cool
5. After the filter vessel and ash hopper have cooled, a sample is taken from the ash hopper the next morning prior to lighting off again
6. The ash hopper is weighed to see how much ash is retained in the system
7. The hopper is replaced with a clean hopper

13 Test Summary

Day 1 – Cold testing at approximately 68 deg. F - Tuesday, 05/23/2000

Pretest: Took sample of ash before run – sample number 1548 – innovatech 2
Test: Fed ash from approximately 10:00 to 15:00. Totalizer on the feeder said that 17.2 # of ash had been fed. An average feed rate of about 3.43#/hour (desired feed rate of 3#/hour)
Posttest: Shut down filter system

Day 2 – Hot testing at 500 deg. F – Wednesday, 05/24/2000

Pretest: Added more ash to k-tron (39.1#'s). Scraped ash from the inside of the filter vessel with a metal rod. Wanted to get a more accurate measurement of the amount of ash removed from the gas stream. The ash in the hopper weighed 14.4 pounds. This indicates that 2.8 pounds had left the system (16.3% of the total weight). If this were correct, then the filter would only be 83.7% efficient in removing ash (weight basis). However, a steel rod was scrapped on the inside of the vessel while holding a clean plastic bag under the ash hopper outlet. By doing this, 2 pounds of ash was recovered in the plastic bag. This means that only .8 pounds of ash was unaccounted for. If only .8 pounds of ash passed through the filter, then the filter would be 95.3% efficient in removing ash (weight basis). This control mass result is consistent with the PCME readings. The PCME showed 99.4% filtration efficiency. Took sample of ash in the hopper including the scrapings from the inside of the vessel – sample number 1549 – innovatech 3
Test: Lit off the combustor at 10:00 and began test. Total time of hot test approximately 3.5 hours. Total ash fed is 11.5 #. Average of 3.3#/hour (desired feed rate of 3#/hour)
Posttest: Let filter cool down.

Day 3 – Hot testing at 500 deg. F – Thursday, 05/25/2000

Pretest: Took sample of ash after it passed through k-tron feeder feed screws to see if the action of the feed screws changed the particle size distribution (crushed the ash) sample 1550, innovatech 4

Test: Lit off combustor at 6:30 am. Test time of approximately 8 hours (hot exposure). Fed approximately 17# if ash before a hole developed in the ash feed line. This cause the test to stop to replace the feed line that was worn through. We have found ash to be very abrasive at high gas flow rates.

Posttest: Let filter cool down.

Day 4 – Hot testing at 750 deg. F – Tuesday, 05/30/2000

Pretest: Weighed ash in hopper from two days of hot testing (05/24 to 05/25) test – weight of 22# of ash in the hopper and took sample #1551 – innovatech 5.

Test: Total time of hot test approximately 3.5 hours.

Posttest: Let filter cool down.

Day 5 – Hot testing at 750 deg. F – Wednesday, 05/31/2000

Pretest:

Weighed ash in hopper from yesterday's (05/30/00) test – weight of 6# in hopper. Sample 1553 taken innovatech 7

Test: Total time of hot test approximately 3. hours.

Posttest: Let filter cool down. Took sample #1584 of ash in hopper innovatech 8, and sample # 1585
of ash in exhaust line, innovatech 9.

14 Test Results

Overall, the tests serve as a proof of concept of the filter system in operation in a high temperature environment. Though this test apparatus was complicated in concept, a second design or subsequent testing should be much simpler. The slight pressurization scheme used to keep ash from intruding into the bearing areas worked, the idea of using a long two piece shaft to isolate the filter from the bearings and motor worked and both the motor and bearings survived 5 days of testing at 3600 rpm with no apparent ill effects.

14.1 Motor Drive Assembly

During initial shakedown of the motor drive assembly, the filter pack developed three problems: 1) the filter assembly was not adequately balanced, which led to wobbling, 2) the entire assembly was not stiff enough. When the motor was spinning up from 0 rpm to 3600 rpm, the filter pack passed through a critical frequency. Because the assembly was not stiff enough, the metal seal would severely drag sometimes as we tried to accelerate through the critical frequency. This would load the motor, overheat it, and shut it down and, 3) the lack of strength of the assembly led to damage as the assembly was removed from the main body of the vessel. All of these problems went away after proper balancing of the disk pack on the shaft and stiffening of the assembly.

14.2 Filter Efficiency

A number of caveats were discussed earlier with respect to how to interpret the PCME readings. It is important to note that the true filtration efficiency would be calculated by determining a “beta” ratio that is based on the particle size distributions and mass of ash fed to the system versus ash that passes through the system.

14.3 Cold Testing Results

It was found that doing a mass balance to determine the quantity of particles that have passed through the system was not as simple as first thought. The ash trapped in the system amounted to a rather substantial quantity, when compared to the total amount fed into the system during a test.

14.4 Ash in Exhaust Line

There was very little ash in the exhaust line. This indicated to us that even though the system ran essentially for 5 days, very little ash was getting through the filter. If more ash was getting through, the PCME would have registered a high reading and we would have seen evidence of ash where the exhaust system was disassembled and the vessel was removed. We saw very little ash. Figure 13 shows some ash that was trapped between two flanges in the exhaust after the tests. This ash was sampled and is presented as test number 1589, innovatech 9. Unfortunately, there was so little ash available that is was totally consumed in particle characterization making further tests on the ash was not possible.

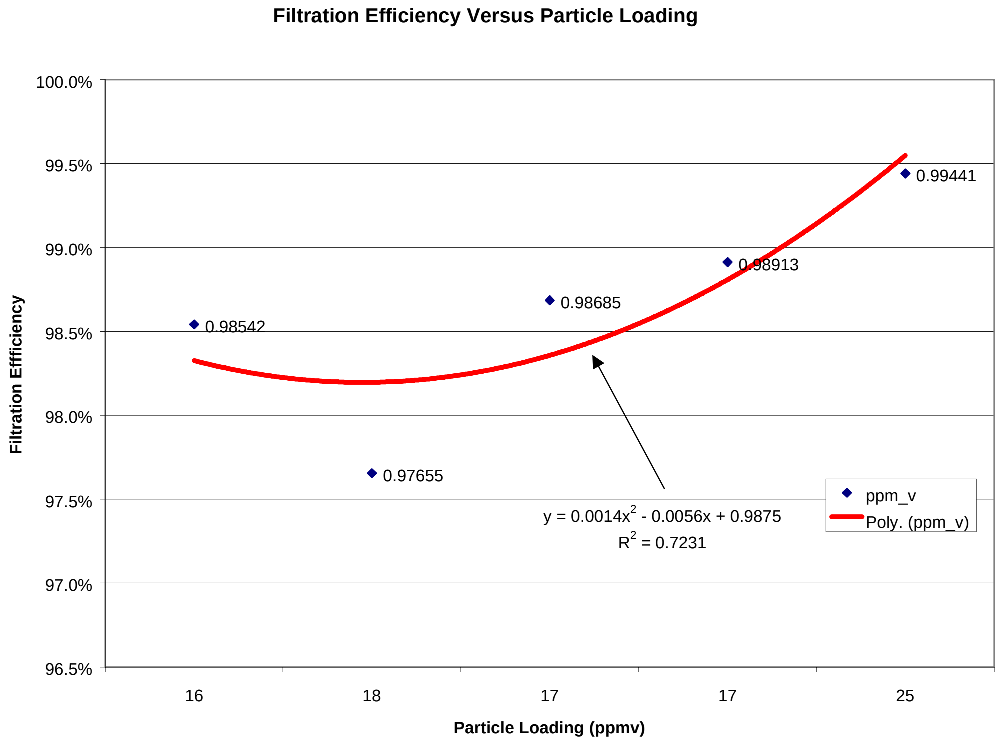


Figure 15. Filtration Efficiency Versus Particle Loading (ppmv)

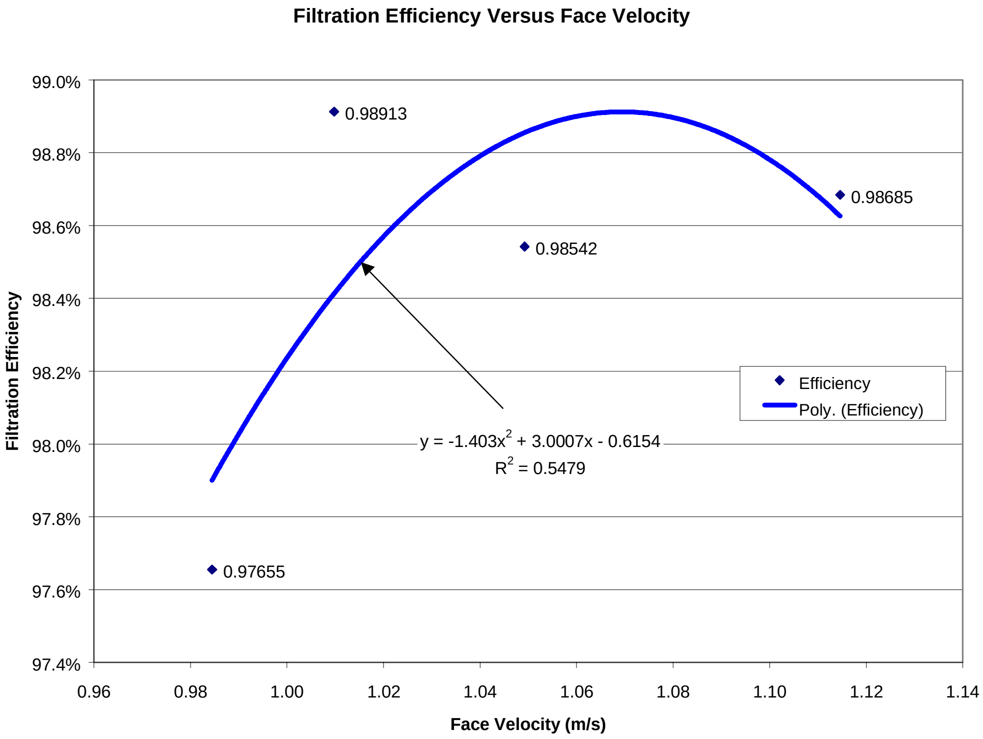


Figure 16. Filtration Efficiency Versus Face Velocity (m/s)

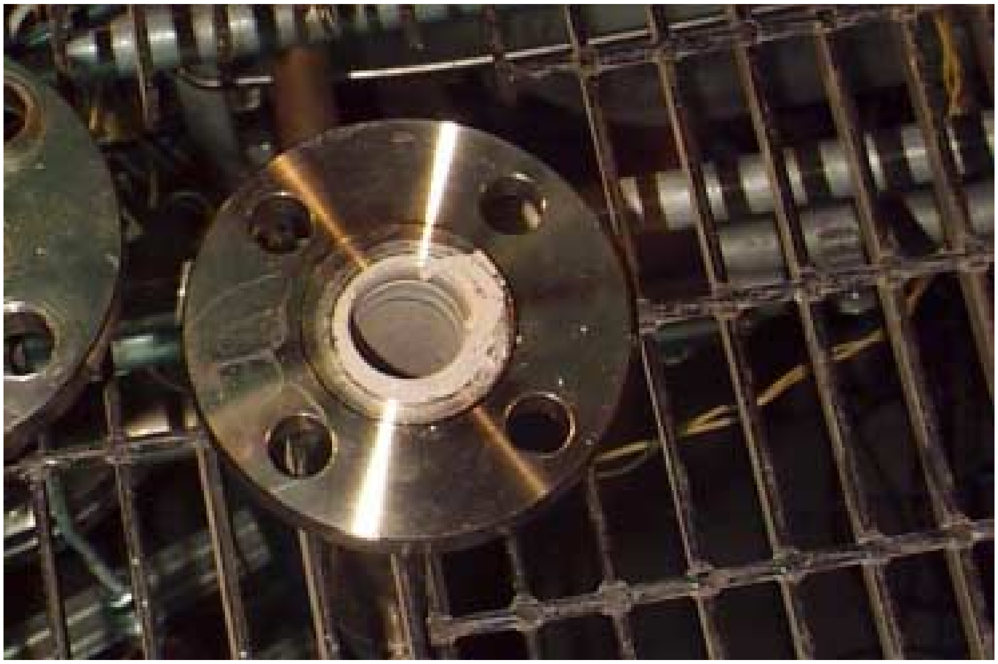


Figure 17. Ash From Exhaust Line

15 Suggestions for Improvement in Construction, Testing, and Operation

The following are some suggestions regarding how to perform further testing and some recommended improvements in the design of the filter system.

15.1 Problems Encountered During Construction

Perhaps the biggest problem encountered during construction of the device was devising a means or method to seal rotating filter element from the clean side of the vessel in such a high temperature environment. Other potential problems are noted below.

- Shaft length, i.e. the length of cantilever – Should perhaps rethink whether it is necessary to have so much standoff from the hot environment. Makes the system very wobbly. Could correct by using stiffer, one-piece shaft.
- Rigidity of the system - Entire filter assembly must be made as rigid as possible. The metal labyrinth seals dragged because of too much slack in the filter assembly.
- Ease of removal and insertion - Welding is not a good way to secure the filter assembly. Suggest a re-design that will allow a plate that supports the assembly to be sandwiched between the flanges of the top and middle section of the filter vessel.

15.2 Problems Encountered During Testing

- Seizing of the pack due to rotational imbalance. This happened early on several times. It was corrected by balancing the filter pack on the shaft (live balancing) at a local electric motor repair shop.
- Plugging of pressure ports (See figure below). It is believed that the swirl action caused by tangentially introducing the ash led to ash buildup on the interior walls of the filter vessel. This caused ash to often plug the pressure transmitter impulse lines. Very small pressure differences (delta-p’s) must be maintained in order to ensure cooling air is going in the right direction. Therefore, plugging of pressure impulse lines should be corrected.

15.3 Design of Device

The following are some suggestions to improve the design of the rotational filter system if further hot testing is conducted.

- Shroud - Install a shroud around the top of the spinning disk pack to divert ash from the labyrinth seal area. This would further ensure that no ash bypasses the filter.
- Labyrinth seal - Re-think the labyrinth, high temperature seal. There may be an easier method of constructing a seal than the one used here.

Figure 18. Ash Plugging of Pressure Ports

- Sturdier bearings – The bearings used to support the shaft were not study enough to lend confidence in extended testing. Suggest refitting the shaft with a new, more robust, set of bearings.
- Stiffer structure - The installation and removal of the filter system resulted in bending the original structure. A chain hoist was used to remove the assembly. The assembly caught on some weldment inside the vessel. As the chain hoist was raised, it torqued the whole assembly sideways, bent the seal plate standoffs, and racked (sideways) the whole assembly. The assembly was cold worked (used a BIG hammer) back into rough alignment, then 3 additional standoffs were welded into position. It is believed that the original design was too delicate for the conditions faced in real-world installations.
- Dynamically balance filter pack – The filter pack was not dynamically balanced prior to installation. This caused severe problems during 3 weeks of initial trials and shakedowns. A severe wobble was found to occur at various rotational speeds, which actually caused the filter pack to drag and sometimes seize, overheat the motor, and cause the motor to shut down. The combination of stiffening the assembly and dynamically balancing did 2 things: 1) changed the critical frequency at which the shaft wobbled, 2) made the wobble of the shaft/pack much smaller. After stiffening and balancing, the assembly never seized again during the 5 days of testing.

16 Patent Disclosure

During construction and testing of the BLMT, a number of times it was noted that there may be a better method of removing particles with a rotational filter. In addition, the BLMT is difficult to construct, relatively fragile (disks are thin and can be bent or warped), and not fault tolerant (if a disk is bent and creates a gap, the boundary layer can not be maintained). This led to the invention disclosure and patent application at NETL for another rotational filter system that NETL believes is an improvement over the BLMT. This patent disclosure is included after the Data Appendix. The name of the invention is the Brush Shaped Rotational Filter (BSRF). The inventors are John Shultz (NETL), John VanOsdol (NETL), Steven Wright (Innovatech).

17 Acknowledgements

Many people contributed to the successful completion of this testing effort.

U.S. Dept. of Energy, NETL employees

John Shultz – Responsible Person (RP) and lead engineer for the test, primary author of the final report, and co-inventor of the Brush Shaped Rotational Filter (BSRF)
Tim Floyd – Primary designer of the filter vessel and motor internals
TK Chiang – Team leader for NETL filter research
John VanOsdol - Contributed to the final report write-up, made suggestions regarding how to improve the BLMT filter system and is co-inventor on the Brush Shaped Rotational Filter (BSRF)
Erik Saab – Designed exhaust spool pieces used to connect the filter system to the existing exhaust stack
Gary McDaniel – DOE technician, operated the filter vessel system
Karl Warnick – DOE technician, operated the filter vessel system

Onsite contractor employees

Brad Linton – Primary machinist – did excellent work manufacturing the designs that Tim Floyd and Steve Wright came up with.
Dan Johnson – Did all of the welding
Allan Shoaff – Did sheet metal work
Stacy Fike – Set up data acquisition system screens and set up PID controllers
Todd Worstell – Helped set up data acquisition screens
Greg Faber - Installed motor, pressure transmitters and troubleshot project
Bob Kalakewich – Monitored the PCME, dried out and screened the ash, and took ash samples
Don Floyd – Ash characterization
Mike Beer – Fabricator and installer
Donny Martin – Fabricator and installer
Terry McKisic – Set up Paragon TNT data acquisition software

18 Data Appendix

Table 3. Cold Test Results - 23 May, 2000

General observations:													
1. Standard conditions: 77 deg. F, 25deg. C, 298 deg k, 14.7 psia, 101.3 kpa also, the feeder was set at 3#/hr													
2. The PCME readings are 2 sec readings for the "point" reading. A 1-minute average is displayed for the "average" reading.													
3. The impulse line for pdt-210 appeared to plug. This may account for the decrease in delta-p over time													
date 23 may 2000		**PCME**	**PCME**	**PCME**	**PCME**	**TE-005A**	**fy-100**	**inflow**	**pt-115 or 119**	**pdt-210**			
		exhaust	**exhaust**	**feed**	**feed**	**Approx.**	**Approx.**	**Approx.**	**Approx.**	**Approx.3**			
		point	**average**	**point**	**average**	**Filter**	**Ash**	**Total Gas**	**System**	**Filter**			
		reading	**reading**	**reading**	**reading**	**Temp**	**Loading**	**In Flow**	**Pressure**	**Delta-P**	**Removal**		
notes	**time**	**ch1**	**ch2**	**ch1**	**ch2**	**(Fahrenheit)**	**(#/hr)**	**(SCFH)**	**(Psig)**	**(in of H2O)**	**Efficiency**		
test	11:00	6.01	4.85	918.00	1050.00	61.60	3.64	4546.00	12.18	3.92	0.995		
test	11:30	11.30	7.75	979.00	1210.00	61.60	3.75	4562.00	12.09	3.36	0.994		
test	11:45	14.70	8.72	1250.00	1340.00	60.50	4.05	4542.00	12.27	2.85	0.993		
test	12:00	3.44	8.42	1420.00	1450.00	60.57	3.57	4562.00	12.23	2.48	0.994		
test	12:30	5.49	7.07	1030.00	1550.00	60.50	3.37	4562.00	12.32	2.01	0.995		
test	13:00	6.21	10.30	1290.00	1420.00	60.50	3.58	4542.00	12.23	1.31	0.993		
test	14:00	8.26	9.71	1540.00	1810.00	61.59	3.21	4521.00	12.23	1.42	0.995		
ash feeder off	14:52	4.13	7.89	1400.00	1870.00	62.94	3.14	4528.00	12.09	0.77	0.996		
average		7.44	8.09	1228.38	1462.50	60.98	3.54	4545.63	12.21	2.27	0.994		
		Approx.	**Post Comb.**	**TE-005A**	**Approx.**	**Approx.**	**Approx.**	**Approx.**				**Approx.**	**Approx.**
		Post Comb.	**Face**	**approx.**	**Ash**	**Total Gas**	**System**	**Post Comb.**	**Face**	**Gas**	**Gas**	**Particle**	**Particle**
		Gas Flow	**Velocity**	**Filter Temp**	**Loading**	**In Flow**	**Pressure**	**Gas Flow**	**Velocity**	**Density**	**Mass Flow**	**Loading**	**Loading**
notes	**time**	**(ft^3/HR)**	**(ft/s)**	**(Kelvin)**	**(kg/hr)**	**(M^3/HR)**	**(kpa)**	**(M^3/HR)**	**(m/s)**	**(kg/m^3)**	**(kg/hr)**	**(PPM_mass)**	**(PPM_volume)**
test	11:00	2406.35	2.18	289.44	1.65	128.73	185.33	68.14	0.67	2.23	152.03	10883.30	23.95
test	11:30	2422.93	2.20	289.44	1.70	129.19	184.71	68.61	0.67	2.22	152.56	11172.87	23.09
test	11:45	2391.15	2.17	288.83	1.84	128.62	185.95	67.71	0.66	2.24	151.89	12119.83	21.66
test	12:00	2405.57	2.18	288.87	1.62	129.19	185.67	68.12	0.67	2.24	152.56	10636.57	24.43
test	12:30	2397.23	2.17	288.83	1.53	129.19	186.29	67.89	0.66	2.25	152.56	10040.68	25.96
test	13:00	2394.70	2.17	288.83	1.63	128.62	185.67	67.81	0.66	2.24	151.89	10713.33	24.47
test	14:00	2388.62	2.17	289.44	1.46	128.03	185.67	67.64	0.66	2.24	151.19	9650.71	27.36
ash feeder off	14:52	2411.06	2.19	290.19	1.43	128.22	184.71	68.28	0.67	2.22	151.42	9425.66	27.71
average		#####	2.179	289.236	1.609	128.724	185.501	68.026	0.664	2.235	152.014	10580.371	24.827

Table 4. Hot Test Results - 500 °F - 24 May, 2000

General observations:

1. Standard conditions: 77 deg. F, 25deg. C, 298 deg k, 14.7 psia, 101.3 kpa also, the feeder was set at 3#/hr

2. The PCME readings are 2 sec readings for the "point" reading. A 1 minute average is displayed for the "average" reading.

date 24 may 2000		**PCME**	**PCME**	**PCME**	**PCME**	**TE-005A**	**Fy-100**	**inflow**	**pt-115 or 119**	**pdt-210**			
		exhaust	**exhaust**	**Feed**	**feed**	**Approx.**	**Approx.**	**Approx.**	**Approx.**	**Approx.**			
		point	**average**	**Point**	**average**	**Filter**	**Ash**	**Total Gas**	**System**	**Filter**			
		reading	**reading**	**Reading**	**reading**	**Temp**	**Loading**	**In Flow**	**Pressure**	**Delta-P**	**Removal**		
notes	**time**	**ch1**	**ch2**	**ch1**	**ch2**	**(Fahrenheit)**	**(#/hr)**	**(SCFH)**	**(Psig)**	**(in of H2O)**	**Efficiency**		
test	13:36	24.00	20.00	2180.00	1550.00	474.00	3.20	4384.00	15.04	2.09	0.987		
test	13:45	18.10	22.80	3980.00	2460.00	483.00	3.41	4403.00	16.67	0.21	0.991		
test	14:00	13.90	22.80	2730.00	2660.00	480.00	3.49	4417.00	16.53	malfunction	0.991		
test	14:15	21.40	23.20	2450.00	2630.00	482.00	3.62	4396.00	16.09	malfunction	0.991		
test	14:30	23.90	29.80	2260.00	2420.00	483.00	3.42	4380.00	16.33	malfunction	0.988		
test	14:45	22.30	26.50	2750.00	2410.00	481.00	3.50	4379.00	16.09	malfunction	0.989		
test	15:00	24.50	24.90	2280.00	2450.00	485.00	3.54	4381.00	16.62	malfunction	0.990		
test	15:15	19.00	28.50	2510.00	2570.00	482.00	3.50	4351.00	16.09	malfunction	0.989		
test	15:30	28.90	32.90	2400.00	2500.00	485.00	3.50	4397.00	16.09	malfunction	0.987		
off	16:00	25.10	28.90	3450.00	2530.00	485.00	3.57	4402.00	16.48	2.55	0.989		
average		22.11	26.03	2699.00	2418.00	482.00	3.48	4389.00	16.20	1.62	0.989		

		Approx.	**Post Comb.**	**TE-005A**	**Approx.**	**Approx.**	**Approx.**	**Approx.**				**Approx.**	**Approx.**
		Post Comb.	**Face**	**Approx.**	**Ash**	**Total Gas**	**System**	**Post Comb.**	**Face**	**Gas**	**Gas**	**Particle**	**Particle**
		Gas Flow	**Velocity**	**Filter Temp**	**Loading**	**In Flow**	**Pressure**	**Gas Flow**	**Velocity**	**Density**	**Mass Flow**	**Loading**	**Loading**
notes	**time**	**(ft^3/HR)**	**(ft/s)**	**(Kelvin)**	**(kg/hr)**	**(M^3/HR)**	**(kpa)**	**(M^3/HR)**	**(m/s)**	**(kg/m^3)**	**(kg/hr)**	**(PPM_mass)**	**(PPM_volume)**
test	13:36	3757.66	3.41	518.56	1.45	124.15	205.05	106.41	1.04	1.38	146.61	9921.29	17.44
test	13:45	3612.35	3.28	523.56	1.55	124.68	216.29	102.30	1.00	1.44	147.24	10526.75	17.03
test	14:00	3628.49	3.29	521.89	1.59	125.08	215.32	102.75	1.00	1.44	147.71	10739.57	16.56
test	14:15	3671.20	3.33	523.00	1.65	124.49	212.25	103.96	1.02	1.41	147.01	11192.82	15.78
test	14:30	3632.70	3.29	523.56	1.55	124.03	213.95	102.87	1.00	1.42	146.47	10613.06	16.88
test	14:45	3653.12	3.31	522.44	1.59	124.01	212.25	103.45	1.01	1.42	146.44	10863.80	16.41
test	15:00	3607.68	3.27	524.67	1.61	124.06	215.94	102.16	1.00	1.43	146.51	10982.94	16.42
test	15:15	3633.62	3.30	523.00	1.59	123.21	212.25	102.90	1.00	1.41	145.50	10933.71	16.49
test	15:30	3683.74	3.34	524.67	1.59	124.52	212.25	104.32	1.02	1.41	147.04	10819.33	16.27
off	16:00	3641.25	3.30	524.67	1.62	124.66	214.98	103.11	1.01	1.43	147.21	11023.18	16.14
average		3652.18	3.31	523.00	1.58	124.29	213.05	103.42	1.01	1.42	146.78	10761.65	16.54

Table 5. Hot Test Results - 500 °F - 25 May, 2000

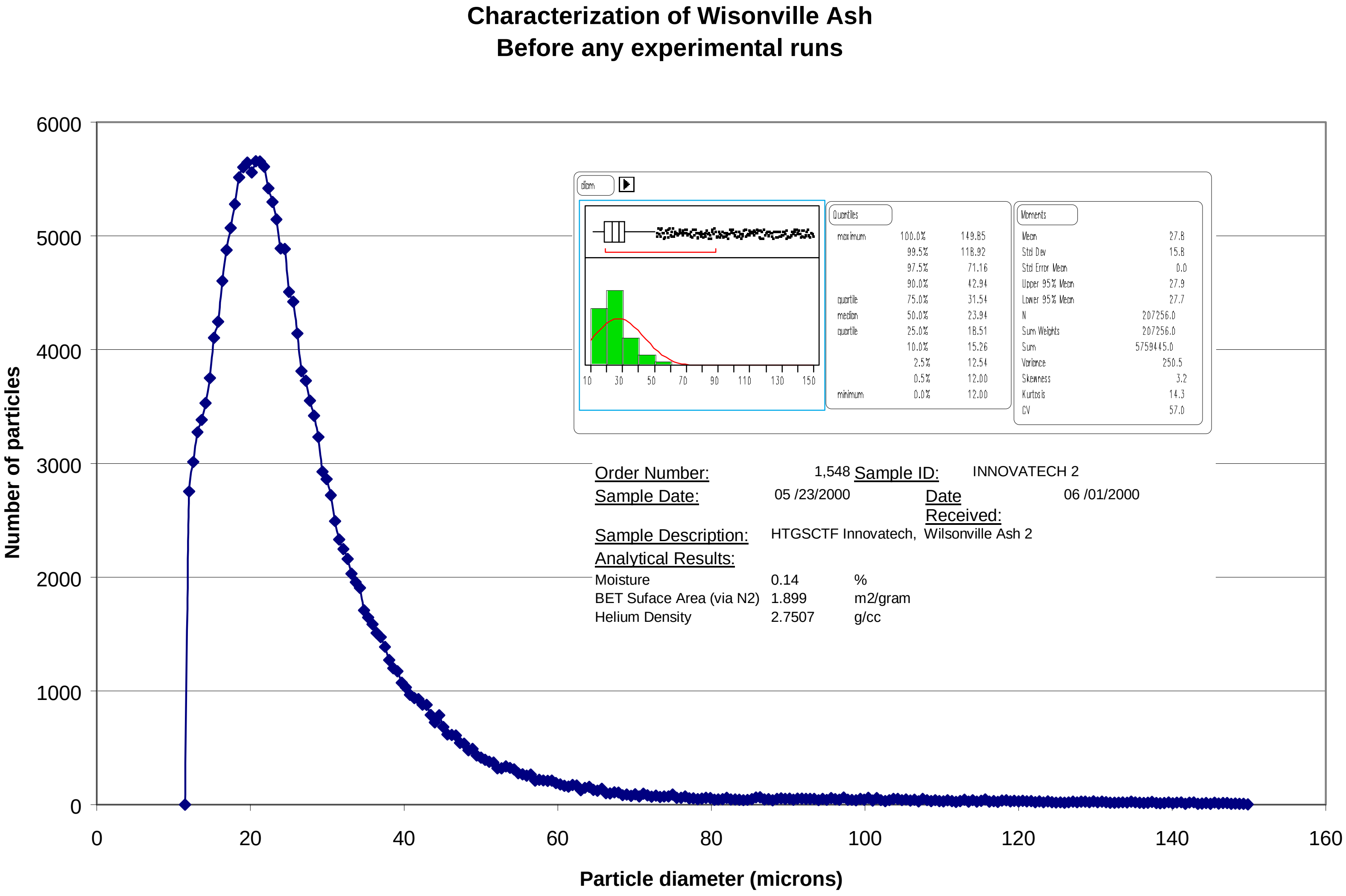
General observations:													
1. Standard conditions: 77 deg. F, 25deg. C, 298 deg k, 14.7 psia, 101.3 kpa													
2. The PCME readings are 2 sec readings for the "point" reading. A 1-minute average is displayed for the "average" reading.													
date 25 may 2000		**PCME**	**PCME**	**PCME**	**PCME**	**TE-005A**	**fy-100**	**inflow**	**pt-115**	**pdt-210**			
		exhaust	**exhaust**	**feed**	**feed**	**Approx.**	**Approx.**	**Approx.**	**Approx.**	**Approx.**			
		point	**average**	**point**	**average**	**Filter**	**Ash**	**Total Gas**	**System**	**Filter**			
		reading	**reading**	**reading**	**reading**	**Temp**	**Loading**	**In Flow**	**Pressure**	**Delta-P**	**Removal**		
notes	**time**	**ch1**	**ch2**	**ch1**	**ch2**	**(Fahrenheit)**	**(#/hr)**	**(SCFH)**	**(Psig)**	**(in of H2O)**	**Efficiency**		
test	9:30	27.10	24.40	2530.00	2140.00	492.00	3.55	4332.00	13.00	missing	0.989		
test	###	30.10	24.40	2830.00	2150.00	489.00	3.24	4289.00	13.23	missing	0.989		
test	###	22.00	24.10	1930.00	2110.00	493.00	3.15	4334.00	13.37	missing	0.989		
test	###	24.80	45.20	2150.00	2330.00	500.00	3.12	4308.00	13.28	missing	0.981		
test	###	22.40	27.60	1700.00	1990.00	498.30	2.63	4305.00	13.14	missing	0.986		
off	###	22.80	25.50	2350.00	2220.00	500.00	3.34	4285.00	13.00	5.15	0.989		
average		24.87	28.53	2248.33	2156.67	495.38	3.17	4308.83	13.17	5.15	0.987		
		Approx.	**Post Comb.**	**TE-005A**	**Approx.**	**Approx.**	**Approx.**	**Approx.**				**Approx.**	**Approx.**
		Post Comb.	**Face**	**approx.**	**Ash**	**Total Gas**	**System**	**Post Comb.**	**Face**	**Gas**	**Gas**	**Particle**	**Particle**
		Gas Flow	**Velocity**	**Filter Temp**	**Loading**	**In Flow**	**Pressure**	**Gas Flow**	**Velocity**	**Density**	**Mass Flow**	**Loading**	**Loading**
notes	**time**	**(ft^3/HR)**	**(ft/s)**	**(Kelvin)**	**(kg/hr)**	**(M^3/HR)**	**(kpa)**	**(M^3/HR)**	**(m/s)**	**(kg/m^3)**	**(kg/hr)**	**(PPM_mass)**	**(PPM_volume)**
test	9:30	4063.42	3.69	528.56	1.61	122.67	190.98	115.07	1.12	1.26	144.87	11138.55	14.54
test	###	3977.38	3.61	526.89	1.47	121.46	192.57	112.63	1.10	1.27	143.43	10267.81	16.28
test	###	4015.93	3.64	529.11	1.43	122.73	193.53	113.72	1.11	1.27	144.94	9878.94	16.58
test	###	4034.11	3.66	533.00	1.42	121.99	192.91	114.24	1.12	1.26	144.07	9843.91	16.67
test	###	4044.40	3.67	532.06	1.20	121.91	191.95	114.53	1.12	1.26	143.97	8303.69	19.72
off	###	4053.14	3.68	533.00	1.52	121.34	190.98	114.78	1.12	1.25	143.30	10594.60	15.49
average		4031.40	3.66	530.44	1.44	122.02	192.15	114.16	1.11	1.26	144.09	10004.58	16.55

Table 6. Hot Test Results - 750 °F - 30 May, 2000

General observations:													
1. Standard conditions: 77 deg. F, 25deg. C, 298 deg k, 14.7 psia, 101.3 kpa													
2. The PCME readings are 2 sec readings for the "point" reading. A 1-minute average is displayed for the "average" reading.													
date 30 may 2000		**PCME**	**PCME**	**PCME**	**PCME**	**TE-005A**	**fy-100**	**inflow**	**pt-115**	**pdt-210**			
		exhaust	**exhaust**	**feed**	**feed**	**Approx.**	**Approx.**	**Approx.**	**Approx.**	**Approx.**			
		point	**average**	**point**	**average**	**Filter**	**Ash**	**Total Gas**	**System**	**Filter**			
		reading	**reading**	**reading**	**reading**	**Temp**	**Loading**	**In Flow**	**Pressure**	**Delta-P**	**Removal**		
notes	**time**	**ch1**	**ch2**	**ch1**	**ch2**	**(Fahrenheit)**	**(#/hr)**	**(SCFH)**	**(Psig)**	**(in of H2O)**	**Efficiency**		
test	###	74.00	78.00	1590.00	1220.00	742.00	4.76	7434.00	55.22	malfunction	0.936		
test	###	12.30	17.70	1110.00	952.00	700.92	2.94	6711.00	44.92	malfunction	0.981		
test	###	6.20	6.97	1050.00	1190.00	672.91	3.18	6707.00	42.49	malfunction	0.994		
test	###	4.01	5.48	796.00	1010.00	733.32	2.90	6963.00	48.99	malfunction	0.995		
average		24.13	27.04	1136.50	1093.00	712.29	3.45	6953.75	47.91	#DIV/0!	0.977		
		Approx.	**Post Comb.**	**TE-005A**	**Approx.**	**Approx.**	**Approx.**	**Approx.**				**Approx.**	**Approx.**
		Post Comb.	**Face**	**approx.**	**Ash**	**Total Gas**	**System**	**Post Comb.**	**Face**	**Gas**	**Gas**	**Particle**	**Particle**
		Gas Flow	**Velocity**	**Filter Temp**	**Loading**	**In Flow**	**Pressure**	**Gas Flow**	**Velocity**	**Density**	**Mass Flow**	**Loading**	**Loading**
notes	**time**	**(ft^3/HR)**	**(ft/s)**	**(Kelvin)**	**(kg/hr)**	**(M^3/HR)**	**(kpa)**	**(M^3/HR)**	**(m/s)**	**(kg/m^3)**	**(kg/hr)**	**(PPM_mass)**	**(PPM_volume)**
test	###	3488.42	3.16	667.44	2.16	210.52	482.07	98.79	0.96	2.52	248.61	8703.08	12.63
test	###	3566.92	3.24	644.62	1.34	190.04	411.06	101.01	0.99	2.22	224.43	5954.55	20.00
test	###	3626.55	3.29	629.06	1.45	189.93	394.31	102.70	1.00	2.18	224.29	6444.47	18.19
test	###	3561.10	3.23	662.62	1.32	197.18	439.12	100.84	0.98	2.31	232.85	5660.96	20.31
average		3560.75	3.23	650.94	1.57	196.92	431.64	100.83	0.98	2.31	232.55	6690.77	17.78

Table 7. Hot Test Results - 750 °F - 31 May, 2000

General observations:													
1. At 8:40, right after starting the test, the PCME exhaust reads a very high number. This may indicate that ash was trapped in the exhaust and was blown out at the start of the test.													
2. The data that is plotted for "filtration efficiency" has a light gray background. It took until approx. 13:00 to reach equilibrium													
3. Standard conditions: 77 deg. F, 25deg. C, 298 deg k, 14.7 psia, 101.3 kpa													
4. The PCME readings are 2 sec readings for the "point" reading. A 1-minute average is displayed for the "average" reading.													
5. Density of ash is approximately 2.7 g/cm^3 or 2700 kg/m^3													
date 31 may 2000		**PCME**	**PCME**	**PCME**	**PCME**	**TE-005A**	**fy-100**	**Inflow**	**pt-115**	**pdt-210**			
		exhaust	**exhaust**	**feed**	**feed**	**Approx.**	**Approx.**	**Approx.**	**Approx.**	**Approx.**			
		point	**average**	**point**	**average**	**Filter**	**Ash**	**Total Gas**	**System**	**Filter**			
		reading	**reading**	**reading**	**reading**	**Temp**	**Loading**	**In Flow**	**Pressure**	**Delta-P**	**Removal**		
notes	**time**	**ch1**	**ch2**	**ch1**	**ch2**	**(Fahrenheit)**	**(#/hr)**	**(SCFH)**	**(Psig)**	**(in of H2O)**	**Efficiency**		
	11:12	20.10	23.00	492.00	440.00	743.00	3.49	8602.00	64.24	malfunction	0.948		
plugged	12:30	33.60	29.90	2950.00	3150.00	723.76	3.83	7801.00	56.00	malfunction	0.991		
feeding 3.6#/hr	14:10	70.00	41.10	2910.00	2840.00	750.31	3.40	7817.00	55.27	malfunction	0.986		
feeding 3.5#/hr	15:10	47.70	41.30	2960.00	2710.00	753.00	3.59	8011.00	56.36	malfunction	0.985		
feeding 3.5#/hr	15:40	37.80	38.70	3020.00	2760.00	791.26	3.50	7870.00	53.16	malfunction	0.986		
average		51.83	40.37	2963.33	2770.00	764.86	3.50	7899.33	54.93	#DIV/0!	0.985		
		Approx.	**Post Comb.**	**TE-005A**	**Approx.**	**Approx.**	**Approx.**	**Approx.**				**Approx.**	**Approx.**
		Post Comb.	**Face**	**approx.**	**Ash**	**Total Gas**	**System**	**Post Comb.**	**Face**	**Gas**	**Gas**	**Particle**	**Particle**
		Gas Flow	**Velocity**	**Filter Temp**	**Loading**	**In Flow**	**Pressure**	**Gas Flow**	**Velocity**	**Density**	**Mass Flow**	**Loading**	**Loading**
notes	**time**	**(ft^3/HR)**	**(ft/s)**	**(Kelvin)**	**(kg/hr)**	**(M^3/HR)**	**(kpa)**	**(M^3/HR)**	**(m/s)**	**(kg/m^3)**	**(kg/hr)**	**(PPM_mass)**	**(PPM_volume)**
	11:12	3578.26	3.25	668.00	1.59	243.59	544.26	101.33	0.99	2.84	287.67	5514.61	16.80
plugged	12:30	3565.29	3.23	657.31	1.74	220.91	487.45	100.96	0.99	2.58	260.88	6673.25	15.36
feeding 3.6#/hr	14:10	3690.88	3.35	672.06	1.55	221.36	482.42	104.52	1.02	2.50	261.41	5911.91	16.72
feeding 3.5#/hr	15:10	3732.74	3.39	673.56	1.63	226.86	489.93	105.70	1.03	2.53	267.90	6091.11	15.65
feeding 3.5#/hr	15:40	3961.14	3.59	694.81	1.59	222.86	467.87	112.17	1.10	2.35	263.19	6044.80	15.13
average		3794.92	3.44	680.14	1.59	223.69	480.07	107.47	1.05	2.46	264.17	6015.94	15.83



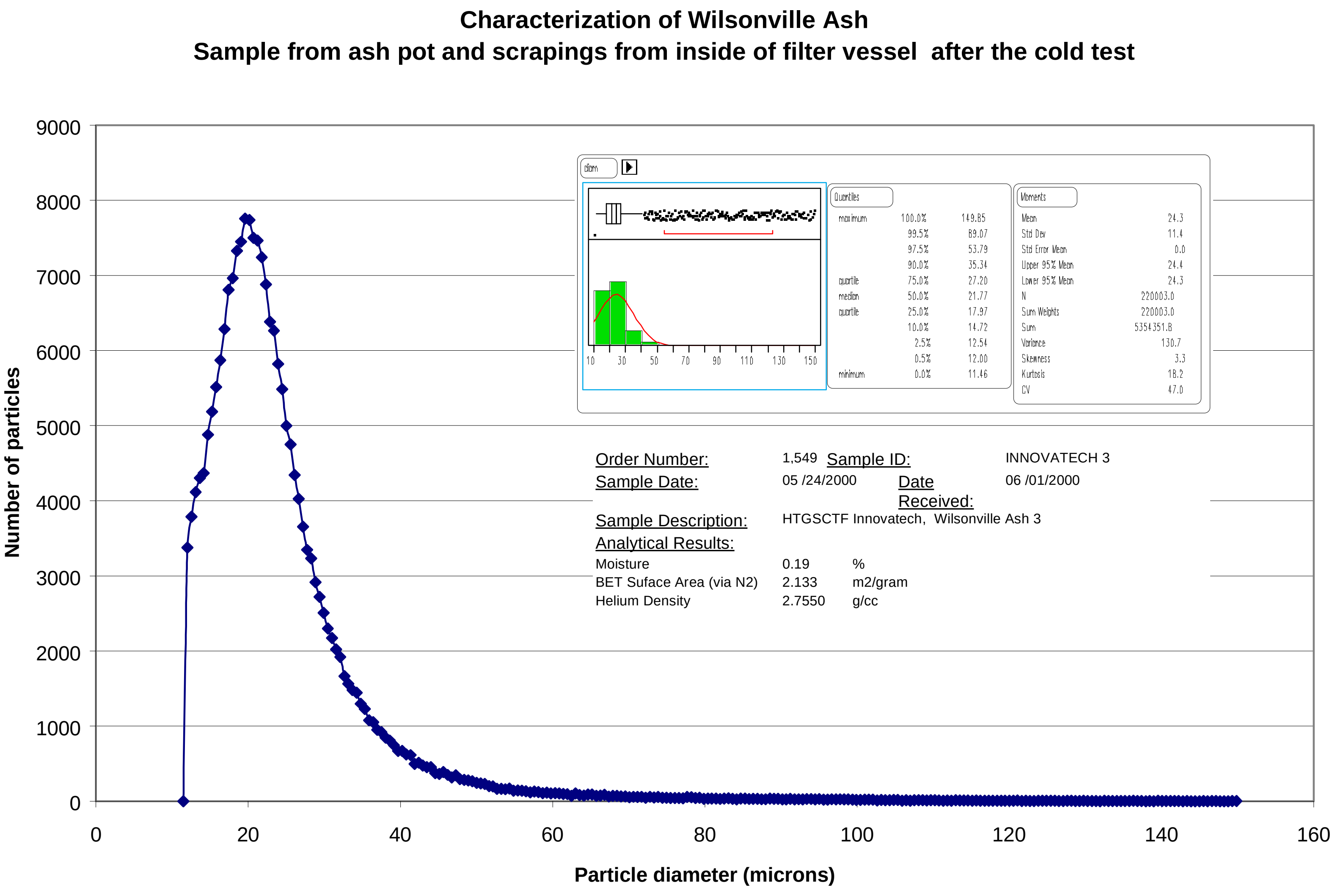
```
Quantiles
maximum    100.0%    149.85
            99.5%    118.92
            97.5%     71.16
            90.0%     42.94
quartile    75.0%     31.54
median      50.0%     23.94
quartile    25.0%     18.51
            10.0%     15.26
             2.5%     12.54
             0.5%     12.00
minimum      0.0%     12.00
```

```
Moments
Mean                 27.8
Std Dev              15.8
Std Error Mean        0.0
Upper 95% Mean       27.9
Lower 95% Mean       27.7
N                207256.0
Sum Weights      207256.0
Sum             5759445.0
Variance            250.5
Skewness              3.2
Kurtosis             14.3
CV                   57.0
```

Order Number: 1,548 Sample ID: INNOVATECH 2
Sample Date: 05 /23/2000 Date Received: 06 /01/2000
Sample Description: HTGSCTF Innovatech, Wilsonville Ash 2
Analytical Results:

Moisture	0.14	%
BET Suface Area (via N2)	1.899	m2/gram
Helium Density	2.7507	g/cc

Figure 19. Pretest Ash Characterization



Characterization of Wilsonville Ash
Sample from ash pot and scrapings from inside of filter vessel after the cold test

Quantiles		
maximum	100.0%	149.85
	99.5%	89.07
	97.5%	53.79
	90.0%	35.34
quartile	75.0%	27.20
median	50.0%	21.77
quartile	25.0%	17.97
	10.0%	14.72
	2.5%	12.54
	0.5%	12.00
minimum	0.0%	11.46

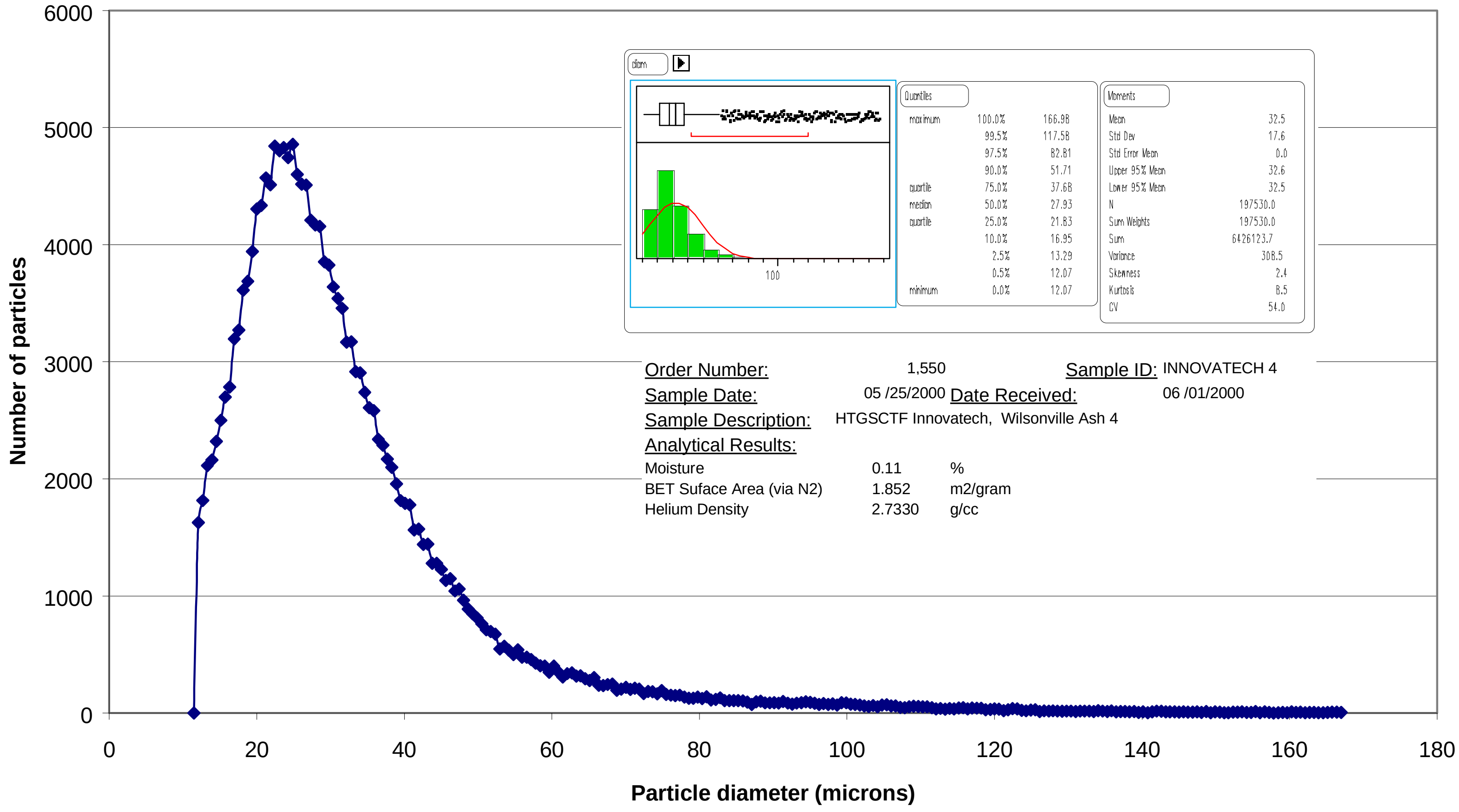
Moments	
Mean	24.3
Std Dev	11.4
Std Error Mean	0.0
Upper 95% Mean	24.4
Lower 95% Mean	24.3
N	220003.0
Sum Weights	220003.0
Sum	5354351.8
Variance	130.7
Skewness	3.3
Kurtosis	18.2
CV	47.0

Order Number: 1,549 Sample ID: INNOVATECH 3
Sample Date: 05 /24/2000 Date Received: 06 /01/2000
Sample Description: HTGSCTF Innovatech, Wilsonville Ash 3
Analytical Results:

Moisture	0.19	%
BET Suface Area (via N2)	2.133	m2/gram
Helium Density	2.7550	g/cc

Figure 20. Ash Characterization After Cold Flow Test

Characterization of Wilsonville Ash
Just after feed screws to see if k-tron crushes the ash and affects the particle size distribution



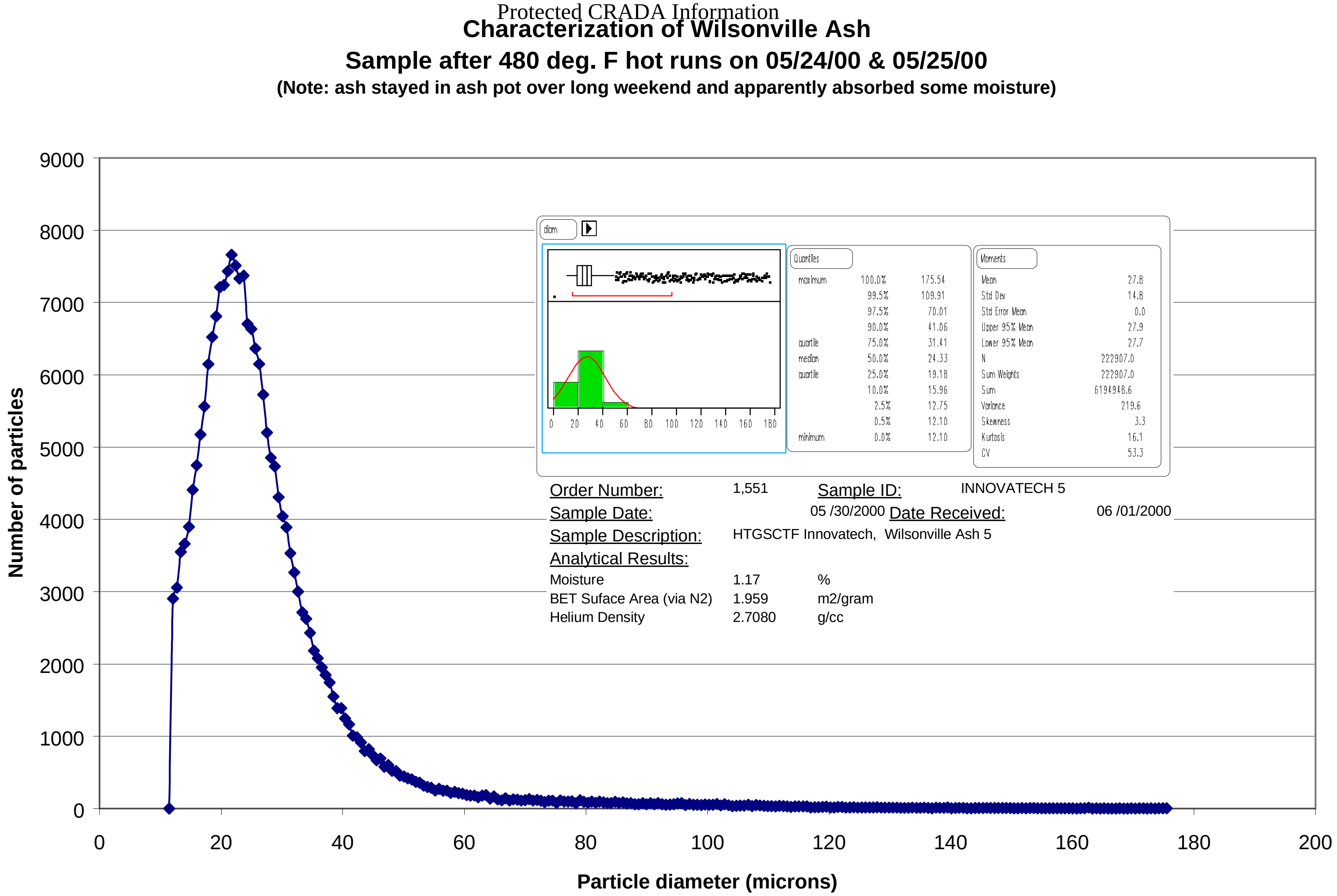
Quantiles		
maximum	100.0%	166.98
	99.5%	117.58
	97.5%	82.81
	90.0%	51.71
quartile	75.0%	37.68
median	50.0%	27.93
quartile	25.0%	21.83
	10.0%	16.95
	2.5%	13.29
	0.5%	12.07
minimum	0.0%	12.07

Moments	
Mean	32.5
Std Dev	17.6
Std Error Mean	0.0
Upper 95% Mean	32.6
Lower 95% Mean	32.5
N	197530.0
Sum Weights	197530.0
Sum	6426123.7
Variance	308.5
Skewness	2.4
Kurtosis	8.5
CV	54.0

Order Number: 1,550 Sample ID: INNOVATECH 4
Sample Date: 05 /25/2000 Date Received: 06 /01/2000
Sample Description: HTGSCTF Innovatech, Wilsonville Ash 4
Analytical Results:

Moisture	0.11	%
BET Suface Area (via N2)	1.852	m2/gram
Helium Density	2.7330	g/cc

Figure 21. Ash Characterization After Passing Through Feed Screws



Characterization of Wilsonville Ash

Sample after 480 deg. F hot runs on 05/24/00 & 05/25/00

(Note: ash stayed in ash pot over long weekend and apparently absorbed some moisture)

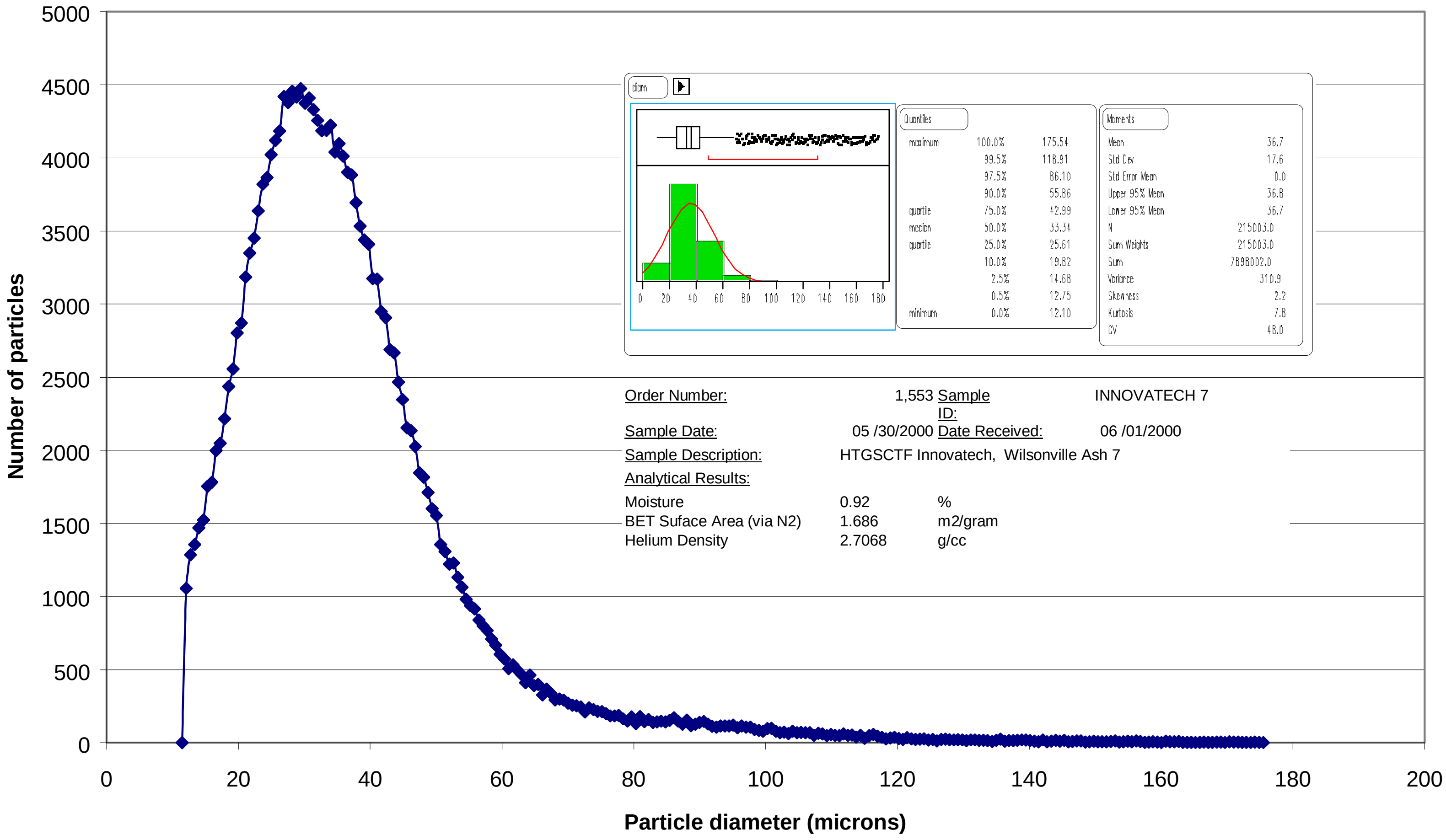
Quantiles		
maximum	100.0%	175.54
	99.5%	109.91
	97.5%	70.01
	90.0%	41.06
quartile	75.0%	31.41
median	50.0%	24.33
quartile	25.0%	19.18
	10.0%	15.96
	2.5%	12.75
	0.5%	12.10
minimum	0.0%	12.10

Moments	
Mean	27.8
Std Dev	14.8
Std Error Mean	0.0
Upper 95% Mean	27.9
Lower 95% Mean	27.7
N	222907.0
Sum Weights	222907.0
Sum	6194948.6
Variance	219.6
Skewness	3.3
Kurtosis	16.1
CV	53.3

Order Number:	1,551	Sample ID:	INNOVATECH 5
Sample Date:	05 /30/2000	Date Received:	06 /01/2000
Sample Description:	HTGSCTF Innovatech, Wilsonville Ash 5		
Analytical Results:			
Moisture	1.17	%	
BET Suface Area (via N2)	1.959	m2/gram	
Helium Density	2.7080	g/cc	

Figure 22. Ash Characterization After First Series of Hot Tests at 500 °F

Characterization of Wilsonville Ash
Sample of ash as it is being loaded into k-tron feeder



Quantiles

maximum	100.0%	175.54
	99.5%	118.91
	97.5%	86.10
	90.0%	55.86
quartile	75.0%	42.99
median	50.0%	33.34
quartile	25.0%	25.61
	10.0%	19.82
	2.5%	14.68
	0.5%	12.75
minimum	0.0%	12.10

Moments

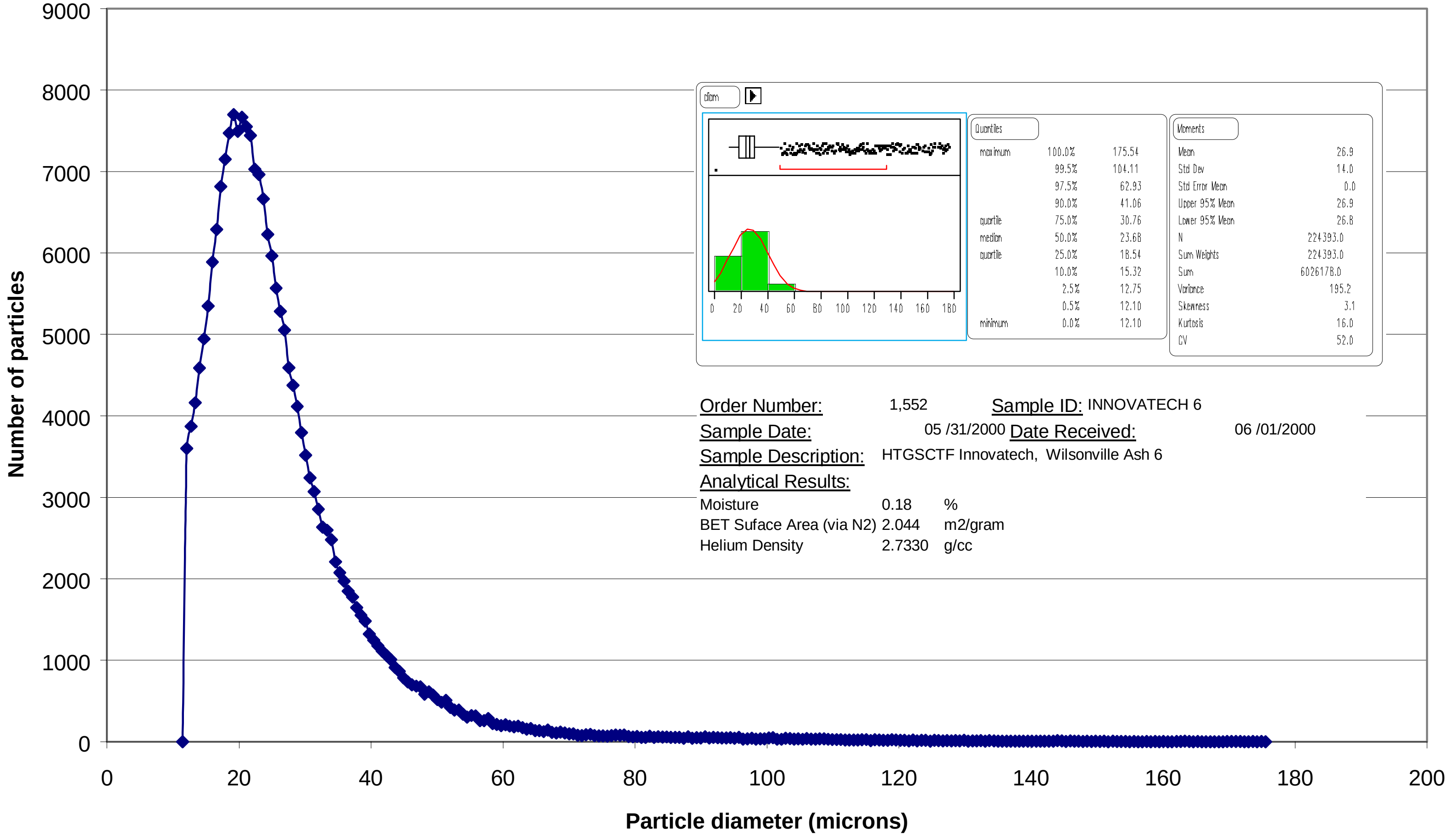
Mean	36.7
Std Dev	17.6
Std Error Mean	0.0
Upper 95% Mean	36.8
Lower 95% Mean	36.7
N	215003.0
Sum Weights	215003.0
Sum	7898002.0
Variance	310.9
Skewness	2.2
Kurtosis	7.8
CV	48.0

Order Number:	1,553	Sample ID:	INNOVATECH 7
Sample Date:	05 /30/2000	Date Received:	06 /01/2000
Sample Description:	HTGSCTF Innovatech, Wilsonville Ash 7		

Analytical Results:

Moisture	0.92	%
BET Suface Area (via N2)	1.686	m2/gram
Helium Density	2.7068	g/cc

Figure 23. Ash Characterization Before 750 °F Tests



Quantiles

maximum	100.0%	175.54
	99.5%	104.11
	97.5%	62.93
	90.0%	41.06
quartile	75.0%	30.76
median	50.0%	23.68
quartile	25.0%	18.54
	10.0%	15.32
	2.5%	12.75
	0.5%	12.10
minimum	0.0%	12.10

Moments

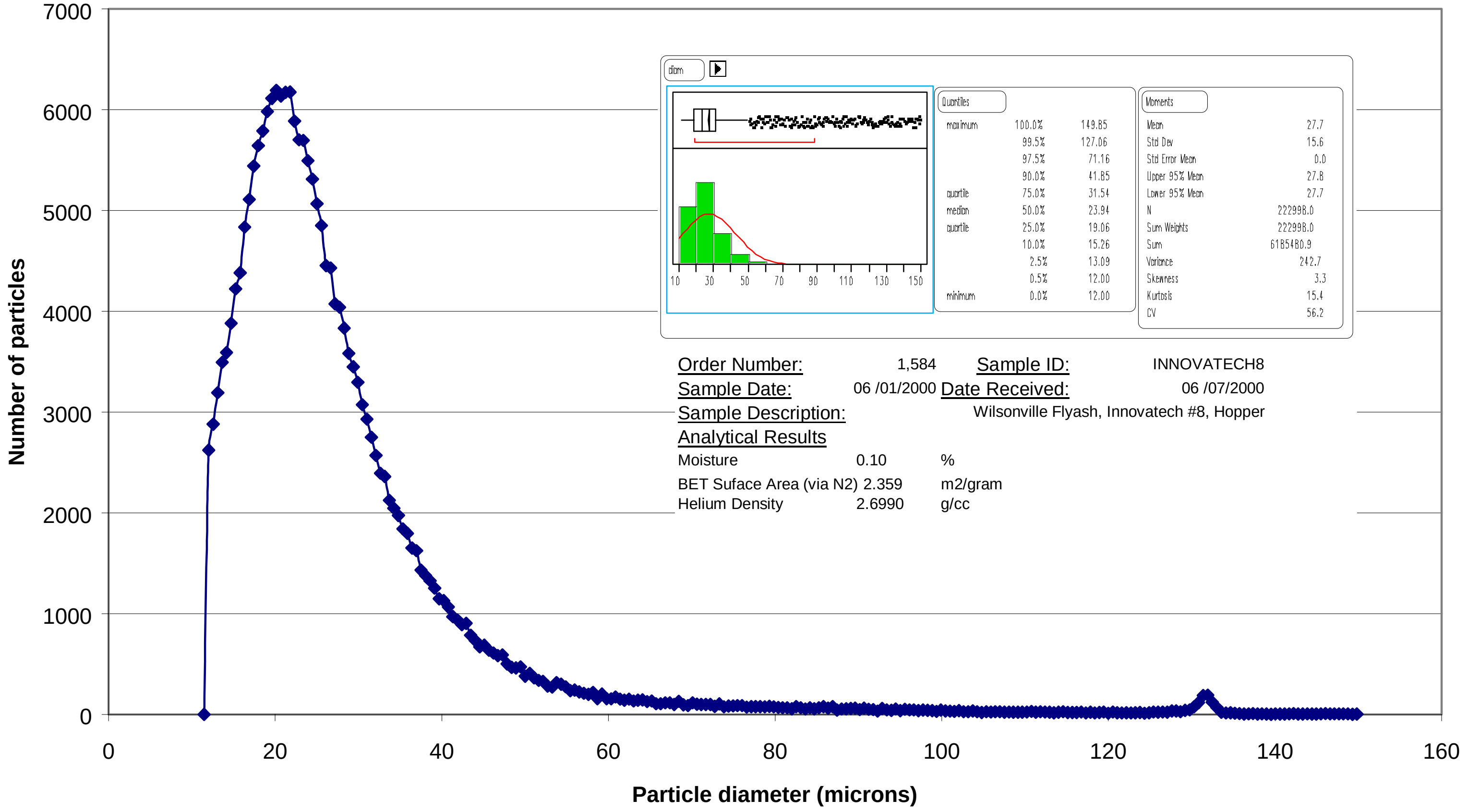
Mean	26.9
Std Dev	14.0
Std Error Mean	0.0
Upper 95% Mean	26.9
Lower 95% Mean	26.8
N	224393.0
Sum Weights	224393.0
Sum	6026178.0
Variance	195.2
Skewness	3.1
Kurtosis	16.0
CV	52.0

Order Number: 1,552 Sample ID: INNOVATECH 6
Sample Date: 05 /31/2000 Date Received: 06 /01/2000
Sample Description: HTGSCTF Innovatech, Wilsonville Ash 6
Analytical Results:

Moisture	0.18	%
BET Suface Area (via N2)	2.044	m2/gram
Helium Density	2.7330	g/cc

Figure 24. Ash After First Day of Testing at 750 °F

Characterization of Wilsonville Ash
Sample of ash in hopper after both hot (750 deg. F.) runs on 05/30/00 & 05/31/00



Quantiles

maximum	100.0%	149.85
	99.5%	127.06
	97.5%	71.16
	90.0%	41.85
quartile	75.0%	31.54
median	50.0%	23.94
quartile	25.0%	19.06
	10.0%	15.26
	2.5%	13.09
	0.5%	12.00
minimum	0.0%	12.00

Moments

Mean	27.7
Std Dev	15.6
Std Error Mean	0.0
Upper 95% Mean	27.8
Lower 95% Mean	27.7
N	222998.0
Sum Weights	222998.0
Sum	6185480.9
Variance	242.7
Skewness	3.3
Kurtosis	15.4
CV	56.2

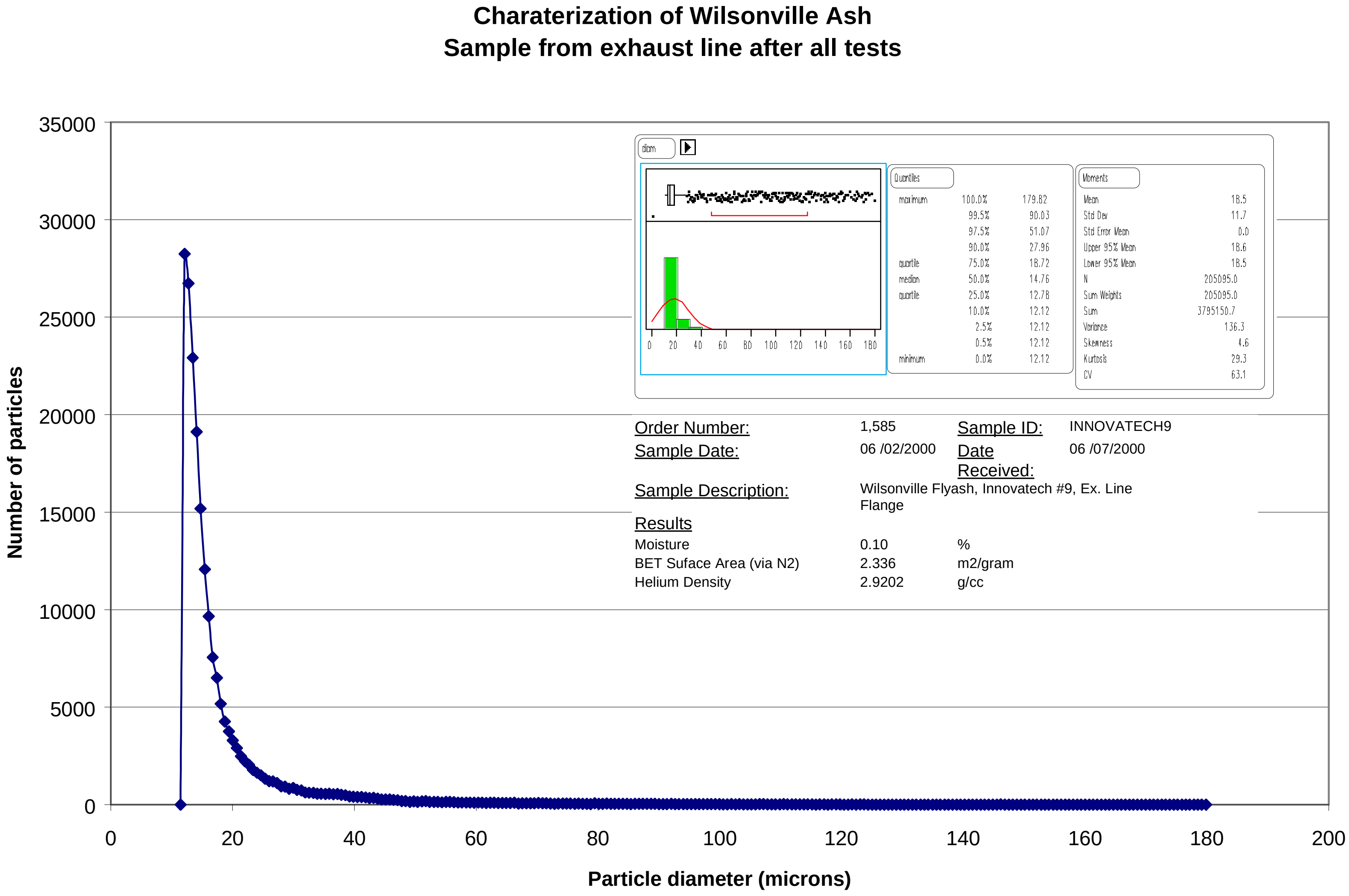
Order Number:	1,584	Sample ID:	INNOVATECH8
Sample Date:	06 /01/2000	Date Received:	06 /07/2000

Sample Description: Wilsonville Flyash, Innovatech #8, Hopper

Analytical Results

Moisture	0.10	%
BET Suface Area (via N2)	2.359	m2/gram
Helium Density	2.6990	g/cc

Figure 25. Ash From Hopper After Completion of Two Tests at 750 °F



Quantiles

maximum	100.0%	179.82
	99.5%	90.03
	97.5%	51.07
	90.0%	27.96
quartile	75.0%	18.72
median	50.0%	14.76
quartile	25.0%	12.78
	10.0%	12.12
	2.5%	12.12
	0.5%	12.12
minimum	0.0%	12.12

Moments

Mean	18.5
Std Dev	11.7
Std Error Mean	0.0
Upper 95% Mean	18.6
Lower 95% Mean	18.5
N	205095.0
Sum Weights	205095.0
Sum	3795150.7
Variance	136.3
Skewness	4.6
Kurtosis	29.3
CV	63.1

Order Number:	1,585	Sample ID:	INNOVATECH9
Sample Date:	06 /02/2000	Date Received:	06 /07/2000
Sample Description:	Wilsonville Flyash, Innovatech #9, Ex. Line Flange		

Results

Moisture	0.10	%
BET Suface Area (via N2)	2.336	m2/gram
Helium Density	2.9202	g/cc

Figure 26. Ash From Exhaust Line

PATENT COUNSEL USE ONLY

NATIONAL ENERGY TECHNOLOGY LABORATORY

NETL No.: ____________________

S-No.: ____________________

REPORT OF POSSIBLE INVENTION

1. Descriptive title of invention in less than 10 words.

A Brush Shaped Rotational Filter (BSRF)

2. Problem the invention overcomes.

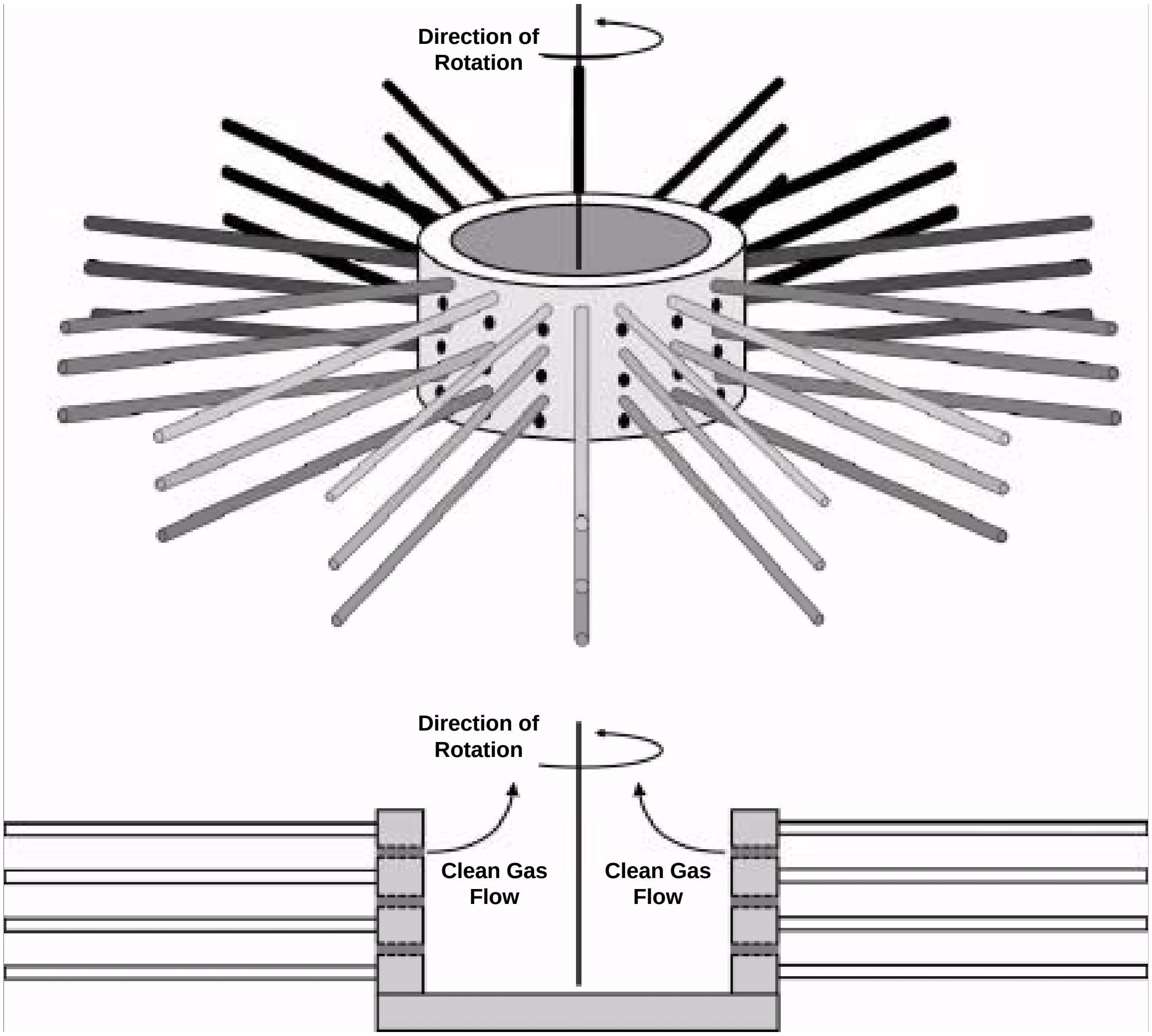
1. **Durability in High Temperature Applications** - Current high temperature filter technologies rely heavily on ceramic materials. These ceramic materials often fracture and thereby cease to be effective filters. The proposed filter system is constructed in a manner, and using materials, so that complete failure of the filter will not occur.
2. **Cleaning of Filter Not Necessary** - Current high temperature filtration technologies must be cleaned in order to continue to function. The proposed filter system is inherently self-cleaning. Therefore, it does not require periodic cleaning. This reduces the complexity of the filtration system greatly, thereby increasing filtration system reliability.
3. **Serviceability of Filter System During Power Plant Operation** - Current filtration systems require that the power production system producing the hot, particle laden gas be taken out of service for maintenance. The proposed filter system maintains all equipment requiring periodic maintenance outside of the hot, dirty, particle laden environment. Therefore, routine maintenance can be performed with the power production system still online. This greatly reduces maintenance costs and system downtime.

3. Detailed description of the invention (include examples and sketches).

The rotational filter system consists of a cylinder, or other hollow shape that has holes through which clean gas passes. The filter is presented with a dirty, particle-laden environment. The filter is spun with a motor in this dirty environment. The small whiskers or wires that are attached to the cylinder cause a great deal of turbulence in the particle-laden environment. It is the combination of gas turbulence and impact of the particles against the whiskers/wires which causes the particles to de-entrain from the gas. Clean gas then passes through the holes in the filter. If the filter is used in an unconfined space, as in a vehicle air cleaner, the particles are simply rejected back into the environment. If the filter is used in a contained environment, as in a vacuum cleaner system, the particles settle to the bottom of the filter vessel where they are later removed.

(OVER)

3. Detailed description of the invention (include examples and sketches). (Continued)

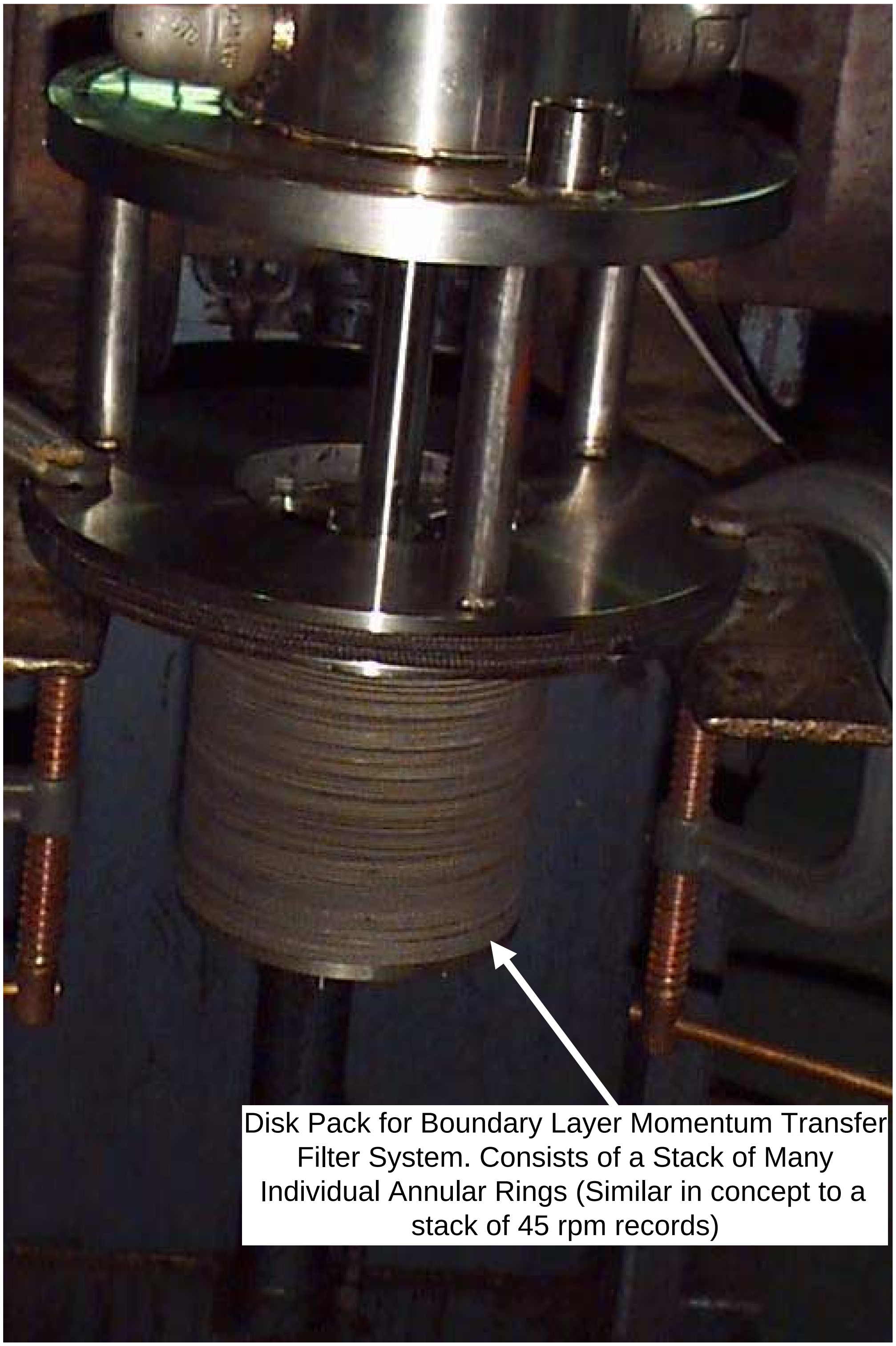


4. List all prior art references known to you and include a copy of each one.

"Novel Method and Apparatus for Ejecting Particulates From the Primary High Temperature Inlet Flow Path of a Coal-Fired Turbine Generator". Energy-Related Inventions Program. Recommendation Number 710. National Institute of Standards and Technology, U.S. Department of Commerce, Inventor: Steven R. Wright, Ph.D., NIST Evaluator: Howard E. Robb, Consultant: Kemal Tuzla, Ph.D.

Dr. Wright's invention consists of a large stack of disks (see photo - Figure 1). The disk pack is rotated, thereby creating a boundary layer of gas around the disk pack and between the individual stacked disks. The mechanism of filtration of Dr. Wright's invention is referred to by him as "Boundary Layer Momentum Transfer (BLMT)". Essentially, particles approach the disk pack surface, but are rejected by the gas boundary layer that forms due to the rotation of the filter assembly.

This sharply contracts with the physical mechanism by which particles are removed with the Brush Shaped Rotational Filter (BSRF) described in this invention disclosure. The BSRF does not rely on a boundary layer to remove particles. In fact, the exact opposite gas flow phenomena is desired. The function of the whiskers/wires is to induce turbulence in the gas flow and allow particle impact on the surfaces of the whiskers/wires to be the primary mechanism of particle de-entrainment.



Disk Pack for Boundary Layer Momentum Transfer Filter System. Consists of a Stack of Many Individual Annular Rings (Similar in concept to a stack of 45 rpm records)

Figure 27. Boundary Layer Momentum Transfer (BLMT) Filter System

5. Itemize the features or advantages you consider unique and compare those with the references listed in Item No. 4 and other previous practices.

1. **Physical means of particle de-entrainment** - The physical method by which the BSRF removes particles is likely easier to achieve and maintain than the mechanism used by the BLMT under a variety of operating conditions and design situations.
2. **Ease of manufacture** - The BLMT filter system must be manufactured to quite tight tolerances, particularly with respect to the spacing between the filter disks. The BSRF does not need tight manufacturing tolerances to be an efficient filter.
3. **Durability** - The whiskers/wires are inherently fault-tolerant. That is, the filtration efficiency of the filter does not depend on any one whisker/wire and in fact many whiskers/wires can be damaged or lost before filtration efficiency is adversely affected. This sharply contrasts with the BLMT filter system. If one or more disks of the BLMT filter system are damaged such that the intra-disk spacing is increased, a total failure of filtration efficiency can occur.
4. **Auto-plugging capability** - If the whiskers/wires are made of a flexible material, the BSRF filter can be constructed so that when rotation of the filter stops, the whiskers/wires will bend and automatically cover the holes through which clean gas normally flows. This is a very valuable, and innovative, method of providing a fail-safe method in a multi-filter installation.

6. Possible alternative versions and/or uses of the invention.

1. Street Sweepers
2. Commercial Vacuum Systems
3. Motor Vehicle Air Cleaners
4. Aircraft Air Cleaners
5. Integrated Filtration System In Home Heating/Cooling Applications - The air blower drive system in home heating/cooling systems could easily be retrofit to accommodate a rotational system such as the BSRF.

7. Anticipated use of the invention by the Government or private industry (both foreign and domestic).

1. High Temperature Flue Gas From Power Plants
2. Particulates Produced In Mixed Waste (Radioactive And Or Chemical) Storage Tanks
3. Coal Dust Removal
4. Sawdust Removal
5. Asbestos Removal
6. Any application for which the BLMT system could be used, the BSRF can be used.

(OVER)

8. Provide the following for each contributor to the invention:

Name: John R. Shultz, Ph.D. Employed by: USDOE Division/Office: EOSD
Work Address: 3610 Collins Ferry Road, Morgantown, WV 26507
County: USA Office Phone: 304-285-4861 Location/MS: C03
Specific Contribution: Sketches of device, consultation on design, and write-up of invention disclosure paperwork.

Name: John VanOsdol , Ph.D. Employed by: USDOE Division/Office: GFC
Work Address: 3610 Collins Ferry Road, Morgantown, WV 26507
County: USA Office Phone: 304-284-0167 Location/MS: NO4
Specific Contribution: Initial idea and evaluation/model of gas flow, and means of particle de-entrainment

Name: Steve Wright, Ph.D. Employed by: Innova-Tech Incorporated Division/Office: N/A
Work Address: 4608-D, Industry Lane, Durham North Carolina, 27713-5414
County: USA Office Phone: 919-544-1717 Location/MS: N/A
Specific Contribution: Assisted in technical discussions and invented the BLMT filter.

9. Facts pertaining to the invention.

Date of Conception by Inventor(s): 07/03/00 At: NETL
Date of First Sketch or Drawing: 07/03/00 Recorded in: Notebook No.: Page Nos.:
Read and Understood by: Dan Burton On: 07/03/00
Date of First Written Description: 07/03/00 Recorded in: Notebook No.: Page Nos.:
Read and Understood by: John Shultz On:
Date of First Model or Test Unit: N/A Recorded in: Notebook No.: Page Nos.:
Read and Understood by: On:
Date of First Written Disclosure to Public: N/A At:
Date of First Oral Disclosure to Public: N/A At:
First Use Date: At:

Signature of Inventor(s):	Date: