Appendix 3

This appendix contains a copy of the Summary Report of work performed by Westinghouse Electric Corporation, Science and Technology Center, under a subcontract of this program.

ADVANCED HOT GAS FILTER DEVELOPMENT

SUMMARY REPORT

M. A. Alvin
March 31, 1998

By

Westinghouse Electric Corporation
Science and Technology Center
1310 Beulah Road
Pittsburgh, PA 15235-5098

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For

DuPont Lanxide Composites
1300 Marrow Road
P. 0. Box 6077
Newark, DE 19714

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Abstract

During the past five years, the filament wound DuPont PRD-66 filter element has undergone considerable development to improve the structural integrity of the outer membrane, and to produce a nearly complete barrier vs. bulk filter element. Additional improvements have included the incorporation of a strengthened, integral flange and reinforced end cap area, and achievement of acceptable gas flow resistance through the as-manufactured filter body.

DuPont PRD-66 filters were installed and operated in the Westinghouse Advanced Particulate Filtration unit at the American Electric Power pressurized fluidized-bed combustion test facility in Brilliant, OH, in 1994 and 1995, and at the Foster Wheeler pressurized circulating fluidized-bed combustion test facility in Karhula, Finland, in 1997. Both field test operations, as well as bench-scale qualification testing conducted in Westinghouse's pressurized fluidized-bed combustion simulator test facility in Pittsburgh, PA, have identified several life limiting issues that warrant continued development prior to commercial use of the filament wound PRD-66 candle. Additional efforts remain to be focused on the development and production of a dual membrane, barrier candle filter; further strengthening of the flange; and incorporation of a chip resistant outer surface. This report provides a summary of the efforts conducted at Westinghouse which have supported the development, manufacture, and field test operation of the DuPont PRD-66 candle filters.

Introduction

Two tasks were conducted by Westinghouse in support of DuPont's DOE/FBTC program entitled "Advanced Hot Gas Filter Development" (Contract No. DE-AC2l-94MC3 1214A). These included:

Task 2- Test Plan Definition
Task 3- Development, Qualification, and Testing of Hot Gas Filters.

Initially Task 3 was identified to include:

Task 3.1 - Material Qualification

Task 3.2- Corrosion Testing

Task 3.3 - High Temperature, High Pressure (HTHP) Filter Testing.

Due to budget constraints incurred by DuPont, Task 3.2 was eliminated from Westinghouse's workscope. In the following sections, a summary of the results obtained at Westinghouse between February 9, 1995 and March31, 1998 for conduct of Task 2, Task 3.1, and Task 3.3 is provided.

Program Overview

On January 20, 1994, the dimensional tolerances and filtration characteristics that are required for retrofit of porous ceramic candle filters into Westinghouse's Advanced Particulate Filtration (APE) systems were provided to the DuPont Lanxide Corporation (DLC)[1]. During 1994, filter elements were fabricated by DLC, and were delivered for use in the Westinghouse APE slipstream test facility that was operated at the American Electric Power (AEP) pressurized fluidized-bed combustion (PFBC) Tidd Demonstration plant in Brilliant, Ohio. The Westinghouse APF system at AEP consisted of three filter clusters (i.e., nine filter arrays) which housed 384, 1.5 m filter elements.

Testing of three, 1.5 m, DLC PRD-66 filament wound candles in the PFBC environment was initiated in July 1994, and continued for a period of 1705 hours [1]. At the conclusion of testing in October 1994, the filter vessel was slow cooled and inspected. Post-test inspection indicated that all three filters elements remained intact.

Additional 1.5-m PRD-66 filter elements were fabricated for inclusion in Test Segment 5 at AEP (January through March 1995). Twenty-two PRD-66 candle filters were installed in the Westinghouse APF system, filling an entire top array. After 232 hours of operation, sections of the PRD-66 matrix were identified in the ash hopper discharge, implying that failure of an element or elements had occurred. Testing continued, and after 775 hours of operation, additional sections of the PRD-66 filter matrix were found in the ash hopper discharge.

At the conclusion of 1110 hours of operation in Test Segment 5, the filter vessel was slow cooled and inspected. Only two ERD-66 filter elements remained intact, four had suffered either mid-body fracture or failure at a location that was ~3/4 below the flange, and sixteen filters had fractured at the base of the flange. The outer surface of the intact and fractured filters was generally “ash free”, particularly along the portion of the body that was adjacent to the plenum support pipe, and to approximately mid-way down the length of each filter element. Alternately a 1-2 mm ash deposit remained along the outer surface of the PRD-66 candles, primarily near the bottom end cap. Surface “divot-like” formations resulted in lines which ran parallel down both sides of the remaining intact and fractured filter elements. Localized “divoting” was also observed below the gasket sleeve, which was installed around the filter flange, as well as in alternate, isolated areas along the filter body.

[1] Proprietary Westinghouse filter specifications served in part fulfill Task 2- Test Plan Definition.

The mechanisms leading to divoting and mid-body failure of the FRD-66 filter elements in Test Segment 5 were considered to be primarily related to delamination areas that were present within the wall of the filament wound matrix (i.e., uneven winding and/or localized drying or positioning of the elements during manufacturing of the elements). Post-test inspection indicated that ash and sorbent fines were present within the 7 mm PRD-66 filter wall. These were expected to have resulted from penetration of submicron fines through the PRD-66 outer membrane, or were back pulsed into the matrix after failure of an alternate candle(s). PFBC ash which had been shown by Westinghouse to have a high thermal coefficient of expansion in comparison to the ceramic filter matrix, may have induced localized internal failure within the filter wall during the plant shutdown and startup cycles in Test Segment 5. Mid-body failure of the element conceivably resulted once the filter wall had sufficiently weakened or thinned after "divoting" had occurred. Failure at the base of the PRD-66 filter flange was attributed to the low load bearing capability of the filter flange to support the thermal expansion loads applied by the ash, once fines became "wedged" in between the outer surface of the filter element and the metal holder.

In Task 2, Westinghouse recommended that

- The flange be densified and/or strengthened
- Modifications be made to the membrane to prevent fines infiltration into subsurface layers. In this manner, accumulated ash fines would not lead to fracture of the filament winding pattern during system startup and cooldown (i.e., higher thermal coefficient of expansion of the ash relative to the ceramic filter matrix).
- Modifications be made to the winding pattern to prevent localized internal delamination areas within the filter matrix,

in an attempt to mitigate failure of the PRD-66 filter element during continued process operation.

As a result, during conduct of the originally proposed contract with DOE/FETC, DLC supplied six, 1.5 m, PRD-66 candle filters to Westinghouse on February 28, *1995*. Production modifications which had been made by. DLC included:

- Strengthening of the flange and end cap(2 Standard or baseline filter elements identified as D-337 and D-338)
- Strengthening of the flange and end cap, and providing a higher permeability outer surface (o.d.) membrane (2 Improved membrane filter elements identified as D-325 and D-331)
- Strengthening of the flange and end, providing a higher permeability o.d. membrane, as well as an inner surface (i.d.) membrane (2 Improved dual membrane filter elements identified as D-328 and D330).[2]

Westinghouse initially performed room temperature permeability measurements on the six modified PRD-66 filter elements to confirm DLC's measurements (Task 3.1). One filter type

[2] Fabrication of the dual membrane candle was recommended by Westinghouse as a result of ash penetration along the i.d. surface of intact fitter elements (i.e., AEP Test Segments 1-3) after failure. of alternate candles had occurred within the filter array during process operation. Westinghouse patent pending.

of each element was then returned to DLC and sectioned. Sections were returned to Westinghouse for characterization of fines penetration into the matrix, as well as permeability measurements (Task 3.1). Following this effort, one element of each filter type was subjected to high temperature, high pressure (HTHP), simulated pressurized fluidized-bed combustion (PFBC) testing at the Westinghouse test facilities in Pittsburgh, PA (Task 3.3). After two hours of simulated PFBC exposure, and cooldown of the test facility, debonding of the outer membrane was evident. As a result continued HTHP testing was terminated, and DLC undertook an extensive effort to reformulate the manufacture and application of the membrane along the o.d. surface of the PRD-66 filter elements.

In 1997, DLC provided Westinghouse with newly formulated filter elements for qualification testing under simulated PFBC test conditions in Task 3.1. The viability and performance of the filter elements during qualification testing in Pittsburgh, PA, served as the basis for acceptance or rejection of elements for possible inclusion within Westinghouse's APF array which was installed at the Foster Wheeler pressurized circulating fluidized-bed combustion (PCFBC) test facility in Karhula, Finland. Twelve candles were subsequently manufactured and shipped directly to Karhula, Finland. After initial inspection, seven elements were identified for installation and operation in the PCFBC environment.

Development, Qualification, and Testing of Hot Gas Filters

Material Qualification

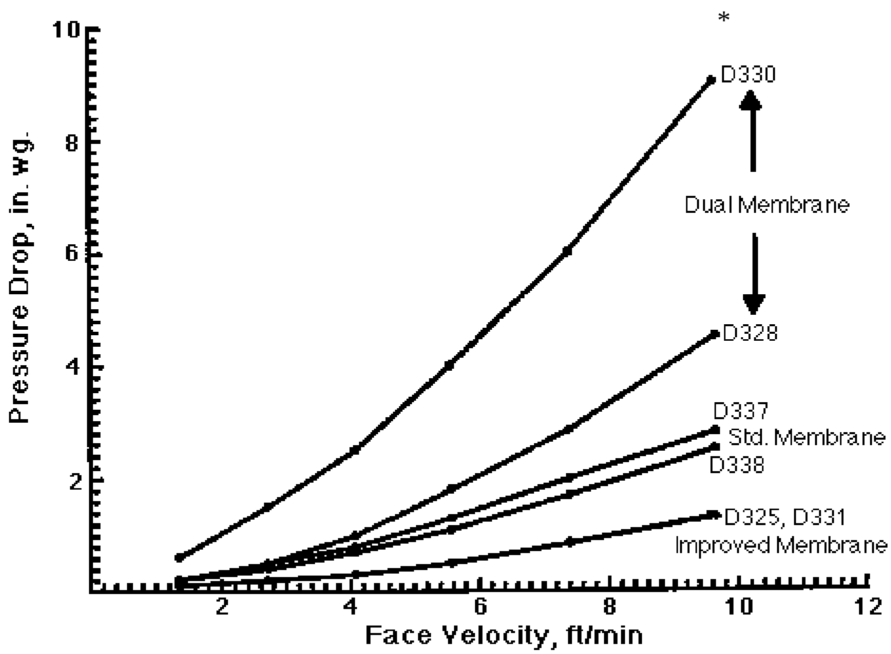
Candle Filter Permeability Measurements Task 3.1)

Westinghouse specifications for an initial pressure drop across an as-manufactured 1.5-m candle filter is 6+/-2 mbar at 52 m^3/hr/candle at 70^0F air (2.41+/-0.8 in-wg at 30.6 scfm at 70^0F air). With an outer filtration surface area of 2.76 ft^2/candle filter, and a flow of 30.6 scfm, a face velocity of 11.1 fpm results.

Initial room temperature gas flow resistance measurements were conducted on the following filter elements:

- Standard or baseline candles identified as D-337 and D-338 (Strengthened flange and end cap candles)
- Improved membrane candles identified as D-325 and D-33 1 (Strengthened flange and end cap candles with a higher permeability o.d. membrane)
- Improved dual membrane candles identified as D-328 and D-330 (Strengthened flange and end candles with a higher permeability outer surface membrane, and an inner membrane).

As shown in Figure 1, relative homogeneity resulted for the standard PRD-66 candle filters which had undergone flange and end cap strengthening or densification (i.e., D-337 and D-338). Extrapolating from the gas flow resistance measurements presented in Figure 1, the pressure drop across the standard filter elements at a face velocity of 11.1 fpm ranged between 3 and 3.4 in-wg (i.e., 7.5-8.5 mbar). Based on the room temperature gas flow resistance measurements, the standard PRD-66 candles were considered to be within the Westinghouse pressure drop specifications for as-manufactured candle filter elements.



* Westinghouse As-Manufactured Specifications

Figure 1 – Room temperature gas flow resistance measurements

With respect 10 candles that had been manufactured with an improved membrane, as well as a strengthened or densified flange and end cap (i.e., D-325 and D-331), a lower gas flow resistance resulted. As shown in Figure 1, the gas flow resistance through these elements was quite reproducible. For the improved membrane filters, the pressure drop across the candle at a face velocity of 11.1 fpm was 1.6 in-wg (i.e., 4 mbar). This was considered to be acceptable in view of the Westinghouse as-manufactured filter element pressure drop specifications.

When the improved membrane was applied to the outside surface of the PRD-66 filament wound filter element, and an internal membrane was also applied to the i.d. surface of the filter wall, the gas flow resistance across the filer matrix increased. As shown in Figure 1, a relatively wide range in gas flow resistance resulted between the two as-manufactured, dual membrane candle filters (i.e., D-328 and D-330). Based on the extrapolated gas flow resistance shown in Figure 1, the pressure drop across the dual membrane candles ranged between 5.6 and 11.0 in-wg (i.e., 14-27.4 mbar) for a gas face velocity of 11.1 fpm, which exceeded the Westinghouse pressure drop specifications for as-manufactured candle filters.

Based on these results, Westinghouse recommended:

- Establishing reproducibility in the manufacturing process for production of the dual membrane filter elements
- Further reduction of the gas flow resistance through the as-manufactured dual membrane candle filters while maintaining bulk material strength.

Coupon Gas Flow Resistance and Particle Collection (Task 3.1)

Table 1 provides a summary of the room temperature gas flow resistance measurements for twelve cylindrical PRD-66 filter samples that were supplied to Westinghouse by DLC on April 25, 1995 (i.e., D-35813, D-358C, D-358G, D-358H, D-358L, D-358M, D-359B, D-359C, D-359G, D-359H, D-359L, and D-359M). The higher gas flow resistance of samples that were designated as D-358 was supported by the visibly tighter filament winding pattern along the inner surface of the cylinders. The visibly tighter i.d. winding indicated that this series of cylinders had been manufactured with a dual membrane. In contrast, the lower gas flow resistance observed for the D-359 test sample series, as well as the open diamond weave, indicated that these samples were manufactured with only a single outer surface membrane.

The room temperature gas flow resistance of the D-359 single membrane PRD-66 cylinders was determined to be 0.51 +/- 0.08 in-wg/fpm which indicated the relative uniformity of the six samples that were removed from various locations along the length of a single candle filter body. The room temperature gas flow resistance of the dual membrane D-358 PRD-66 cylinders was determined to be l. 0l +/- 0.20 in-wg/fpm. The greater scatter in the gas flow resistance measurements for the dual membrane samples tended to indicate a reduction in production homogeneity along the length of the 1.5 m candle filter.

As shown in Table 1, four sections out of six of the D-358 cylinder series were within the Westinghouse gas flow resistance specifications (i.e., <1 in-wg/fpm), while two exceeded the as-manufactured gas flow resistance specifications. The wide range in gas flow resistance may be expected to possibly cause uneven dust cake removal. Perhaps the manner in which the membrane was applied (i.e., wetter yarn applied in one area versus another; variation in yarn

TABLE 1

GAS FLOW RESISTANCE MEASUREMENTS FOR THE IMPROVED o.d. AND i.d./o.d. MEMBRANE-COATED CYLINDERS

Filter Identification Number	System Pressure, psig	Velocity, fpm	Pressure Drop, in-wg	Gas Flow Resistance, in-wg/fpm
D-358B	8.5	12.29	16.0	1.30
D-358C	8.3	12.24	12.0	0.98
D-3580	5.7	11.51	10.0	0.87
D-358H	7.8	12.10	12.0	0.99
D-358L	5.7	11.51	8.5	0.74
D-358M	5.8	11.54	13.5	1.17
			Average +/- 1⇔	1.01 +/- 0.20
D-359B	6.0	11.58	6.0	0.52
D-359C	7.5	12.02	7.0	0.58
D-359G	5.7	11.51	5.0	0.43
D-359H	6.5	11.74	5.0	0.43
D-359L	5.6	11.48	5.5	0.48
D-359M	7.5	12.02	7.5	0.62
			Average +/- 1⇔	0.51 +/- 0.08

Cylinders: 58 mm o.d.; 50 mm length; Assumed uniform effective surface area during bonding/sealing along edge.

thickness; closer wrap positioning etc.), or possibly the extent of "sealing" which was added along the edges of each cylinder to provide an adequate test sealing surface were responsible for The gas flow resistance variations which led to what appeared to be a non-homogeneous filter body.

In an attempt to demonstrate particle collection efficiency, dust was delivered to each of the twelve cylindrical samples at room temperature for a period of 3 minutes. Both the clean inner surface appearance, as well as the absence of detectable fines in the off-gas stream indicated excellent particle collection efficiency of the PRD-66 matrix (Figure 2). When a particle challenged cylinder from the D-358 and D-359 series was fast fractured, fines were evident below the outer membrane-coated surface. As shown in Figure 3, the depth of fines penetration into the 6 mm filter wall varied from 1 to 3 mm indicating that the PRD-66 matrix had bulk rather than barrier filtration characteristics. Examination of the fast fractured surface indicated that the fines did not permeate across the entire 6 mm filter wall during the 3 minute dust exposure. Continued dust exposure testing would be needed to demonstrate the extent of fines penetration and/or plugging which may result during extended process operation.

High Temperature, High Pressure Simulated PFBC Testing (Task 3.3)

Three full length filters were subjected to high temperature, high pressure (HTHP) testing in Westinghouse's pressurized fluidized-bed combustion (PFBC) simulator in Pittsburgh, PA. These included candle filters D328 (improved, lower flow resistance dual membrane candles with a strengthened flange), D338 (standard membrane candles with a strengthened flange), and D325 (improved, lower flow resistance outer surface membrane candles with a strengthened flange). All three filter elements were mounted in the HTHP test facility, and the system was brought to temperature (1550^0F), and maintained at steady state conditions for two hours of operation with dust feed. After cool-down of the unit, areas along the outer surface of candle filter D328 and D325 were seen to have spalled off (Figure 4), while the standard outer surface membrane along candle filter D338 remained intact. The standard D338 membrane had typically been used at Tidd during the 1705 hour, Test Segment 4, and 1110 hour, Test Segment 5 campaigns. The failed membrane areas along D328 and D325 typically extended 1-2 inches, running parallel with the outer membrane winding pattern, and for 3-4 filament winding turns. Removal of the subsurface diamond pattern support structure was not evident (i.e., absence of initiation/propagation of "divoting"). Further development was recommended by Westinghouse to manufacture low gas flow resistance filter elements which maintained the integrity of the outer surface membrane.

Modified Filter Membrane Evaluation (Task 3.1)

Manufacturing modifications were undertaken to improve the bonding and integrity of the outer surface membrane of the PRD-66 candle, while maintaining the Westinghouse gas flow resistance criteria for as-manufactured filter elements. On October 16, 1996, two, 2 inch, PRD66 filter sections were received at Westinghouse. These were identified as:

- PRD-66 Combination membrane filter sample (492-5D)
- PRD-66 Particulate membrane filter sample (490-C).

Figure 5 illustrates the general appearance of both production configurations. The combination membrane consisted of:

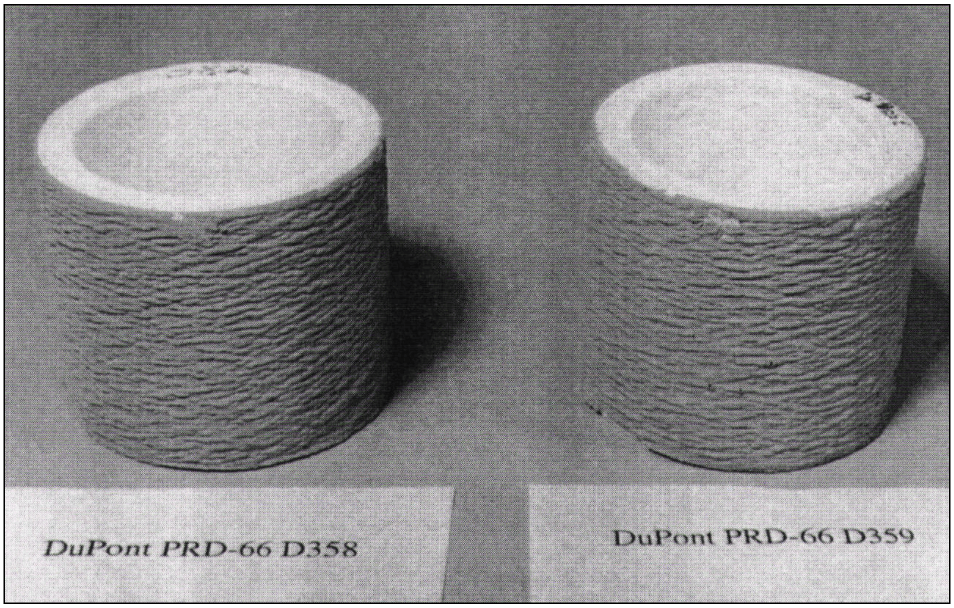


Figure 2 – DuPont PRD-66 filter matrices after room temperature particle collection and gas flow resistance testing.

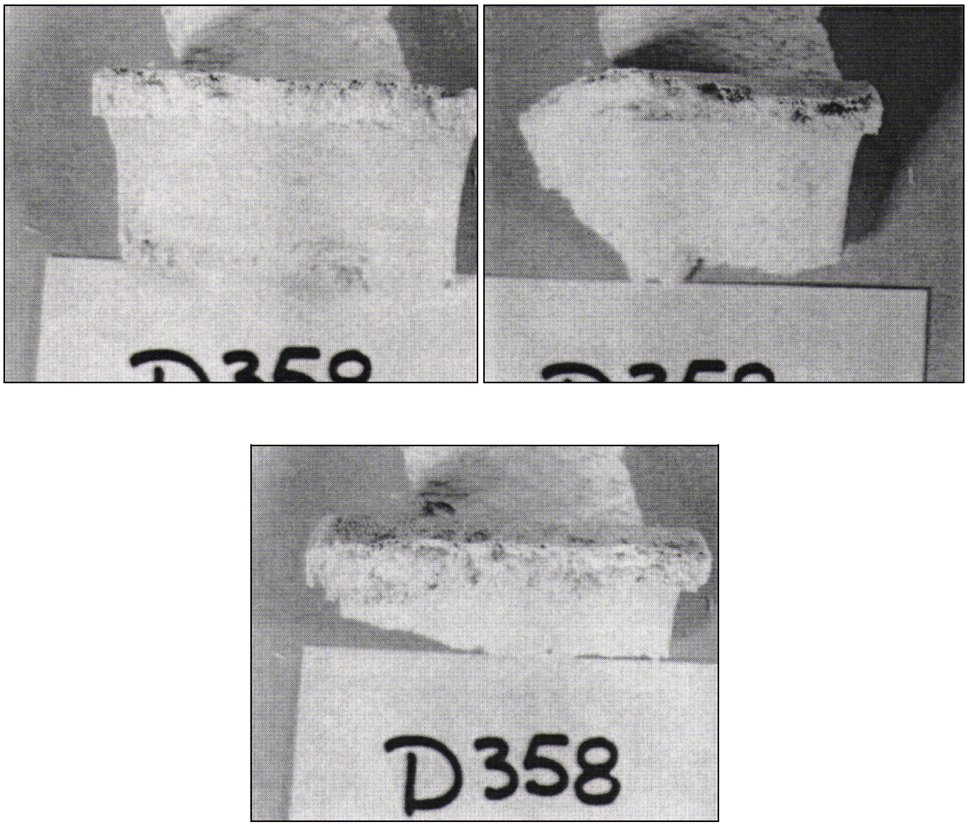


Figure 3a – Fresh fractured surface of the particle challenged D-358 filter matrix.

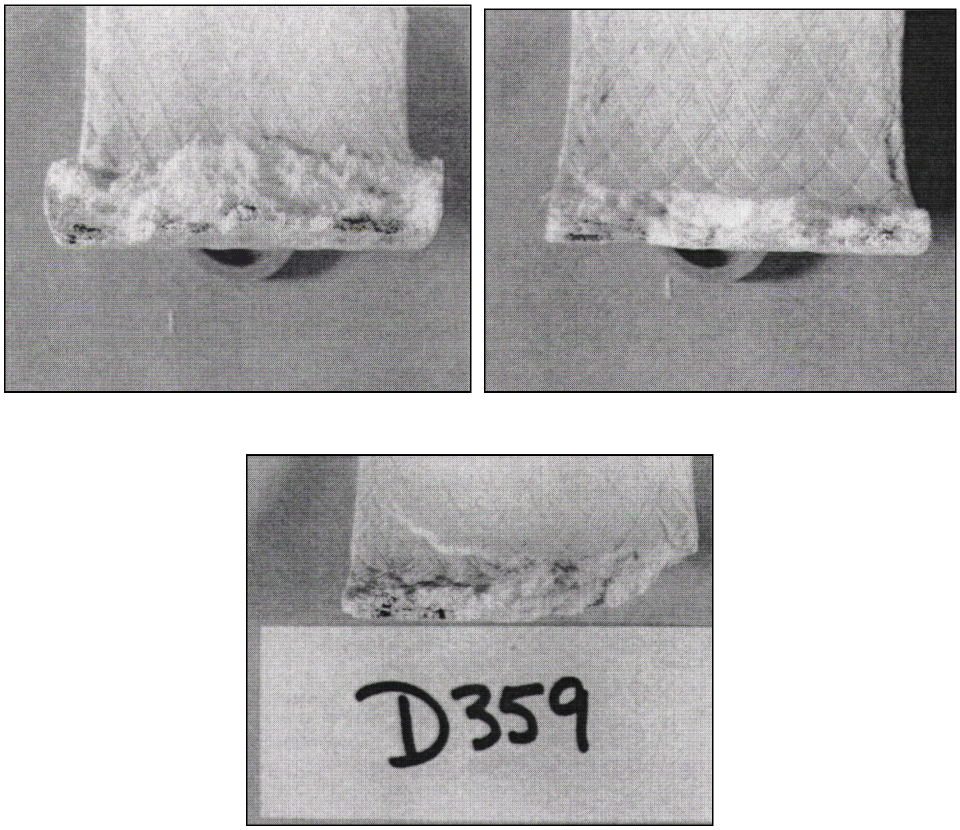


Figure 3b -- Fresh fractured surface of the particle challenged D-359 filter matrix.

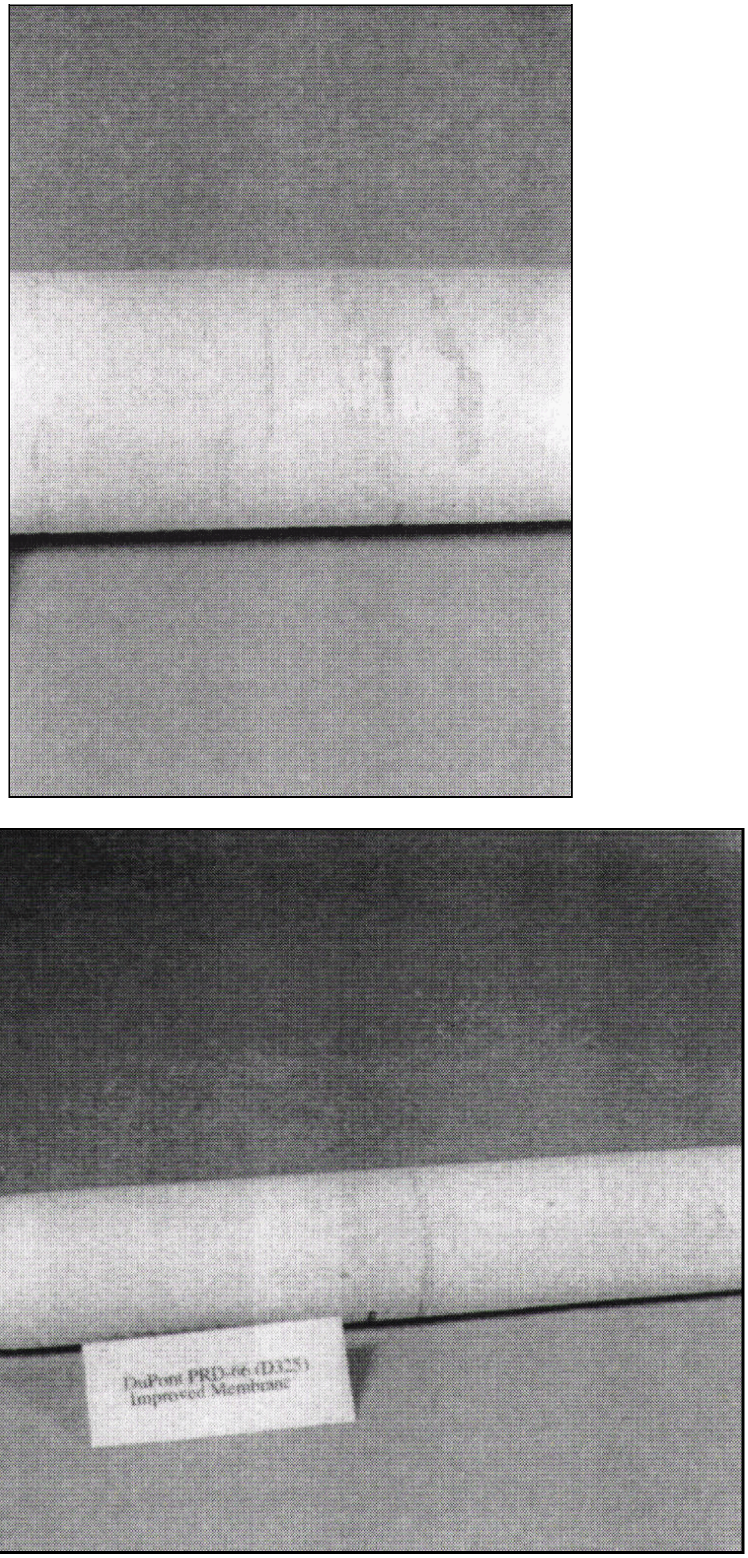


Figure 4a – HTHP-tested DuPont PRD-66 candle filter (Improved o.d. membrane; Strengthened flange).

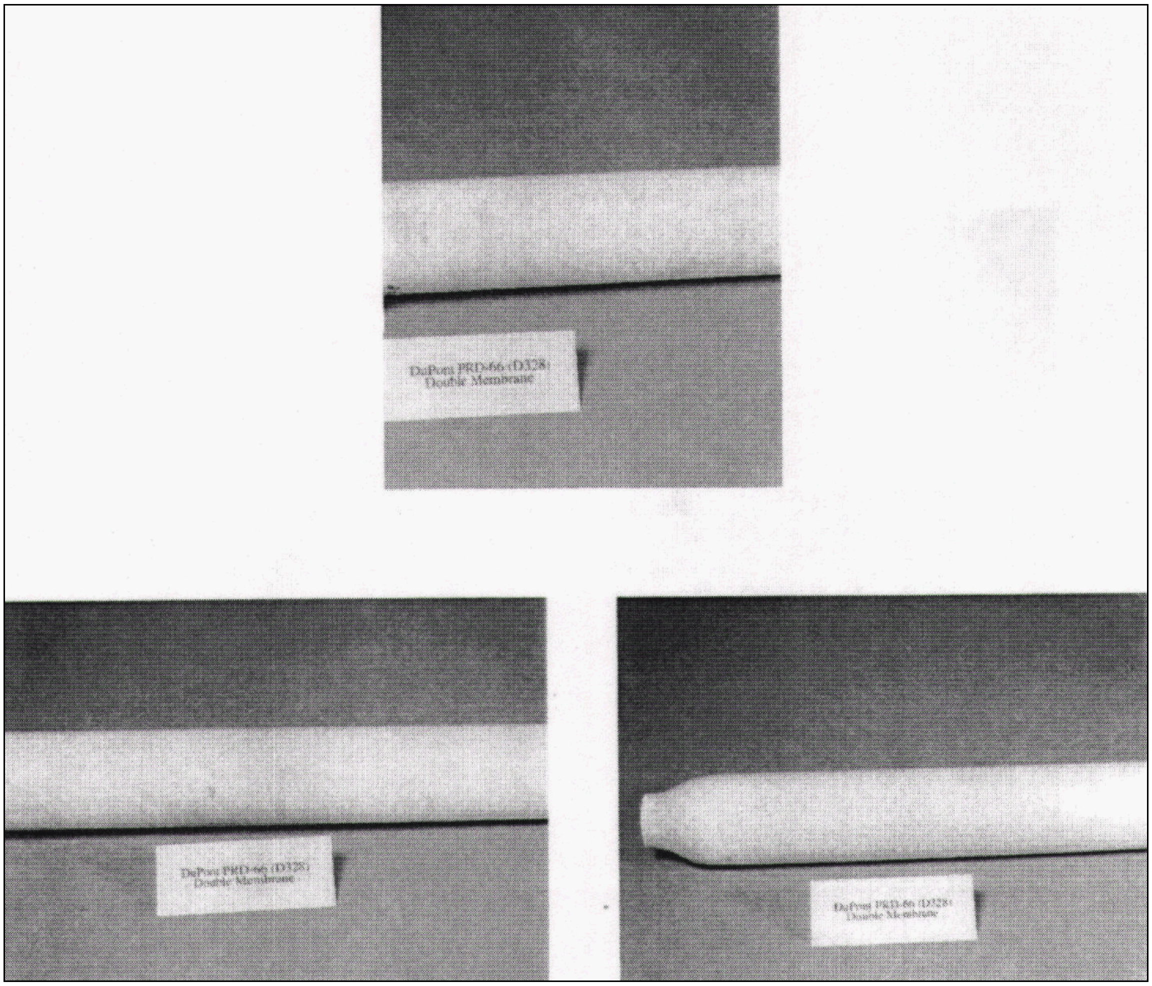


Figure 4b – HTHP-tested DuPont PRD-66 candle filter (Improved dual membrane; Strengthened flange).

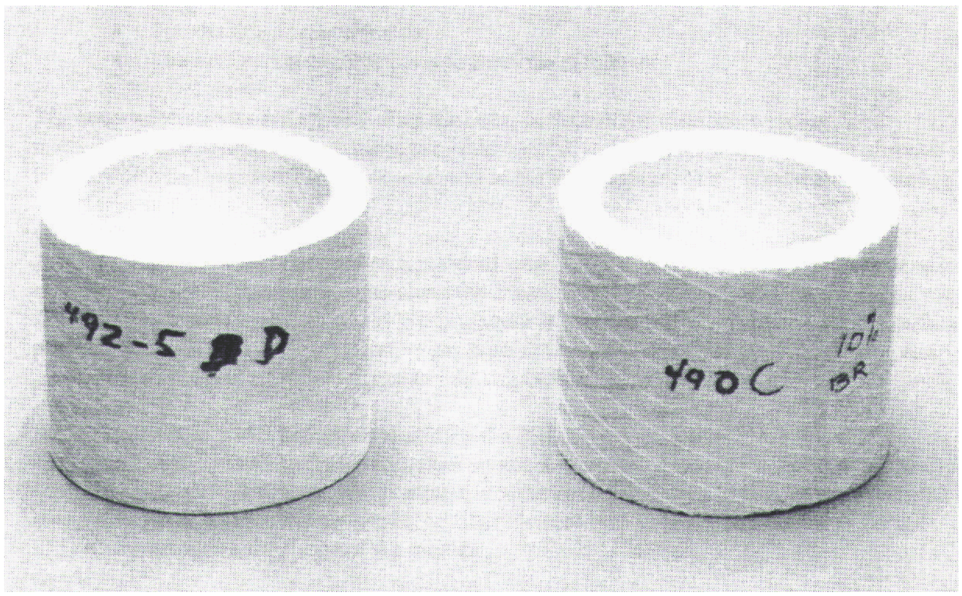


Figure 5 – PRD-66 combination membrane and particulate membrane filter concepts.

- The prior diamond winding pattern which served as the bulk or support matrix
- An additional external hoop winding which formed a smooth surface outer membrane
- The application of an additional particulate slurry infiltration which was expected to reduce the gaps between the outer hoop winding, resulting in the formation of the combined hoop wrap and particulate membrane.

In contrast the particulate membrane filter concept consisted of:

- The diamond support matrix
- The infiltration of particulates to form the membrane.

The hoop winding was not applied along the outer surface of the diamond winding. Both matrices were developed in an attempt to circumvent "divoting" and subsequent filter element failure which had previously been experienced in the Westinghouse APF system at Tidd during Test Segment 5.

Initially 8-inch sections of each material were shipped to Westinghouse for consideration and/or evaluation. The uneven edges along the 2-inch pieces which resulted from cutting of the filter sections at DLC were ground at Westinghouse in order to provide a smooth sealing surface prior to conduct of the room temperature gas flow resistance measurements. After testing and inspection, both samples were returned to DLC on October 21, 1996.

Table 2 provides comments regarding the PRD-66 combination membrane and particulate membrane filter concepts. Based on not only general appearance, but also the gas flow resistance measurements, Westinghouse recommended continued future development and manufacture of the combination membrane filter element with enhanced strengthening of the PRD-66 matrix along the flange of the candles.

Issues which remained to be addressed, however, included:

- Demonstrating the relative strength of both membrane filter concepts to identify if differences existed
- Demonstrating the relative load-to-failure for both membrane filter concepts to identify if differences existed
- Manufacturing of the filter sections and/or body with comparable o.d. dimensions. For the samples provided, the o.d. dimensions were not identical.

Based on the above information, Westinghouse supported production of the PRD-66 filter element with the combination membrane for use in future process simulation and/or field testing. Should the hoop wrap prove to be ineffective (i.e., bulk filtration vs. complete barrier filtration performance), additional modifications to the PRD-66 particulate membrane filter would be needed.

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[3] Both the diamond winding pattern and external hoop were conceptually similar to what had previously been utilized to manufacture the filter elements installed at AEP.

TABLE 2 COMPARISON OF PRD-66 FILTER MEMBRANE CONCEPTS	
Combination Membrane Hoop Wrap with Particle Infiltrate	**Particulate Membrane**
W-STC Gas Flow Resistance: 0.5 in-wg/fpm	W-STC Gas Flow Resistance: 1.07 in-wg/fpm
DLC Gas Flow Resistance: 0.9 in-wg/fpm	DLC Gas Flow Resistance: 1.2 in-wg/fpm
Gaps Between Hoop Wrap Winding Were Evident. Potential Issues Include: -- Penetration of Submicron Fines -- Divot Formation Due to Thermal Expansion of Penetrated Submicron Fines -- Divoting Leading To Failure of The Element	Particulate Infiltrate May Be More Evenly Distributed Along The External Diamond Wrap Pattern. If So, Then -- Areas For Fines Penetration Into The Matrix Which May Mitigate Or Reduce Divoting/Failure Of The Filter Elements May Be Eliminated
Relatively Smooth Outer Surface -- A Conditioned Ash Cake Layer May Not Form Which May Lead To Penetration Of Submicron Fines Into The Interior Of The Filter Wall, Potentially Causing Divoting and/or I Failure Of The Element	Stepped Surface Due To Diamond Patterns May -- Be Potential Areas To Accumulate and/or Retain Ash Fines -- Lead To The Formation Of A Conditioned Ash Layer Which Could Possess Bulk Filtration Characteristics -- Pending Accumulation Of Fines Along The Diamond Weave Edges, Localized Removal Of Fines May Not Occur Leading To A High Pressure Drop Across The Filter Element.
-- Minimal "Crumbling" Of Cut Surfaces In Contrast To Original Matrices	
-- Along Cut Surfaces, Potential Delamination Areas Still Exist Most Likely As A Result Of Bulk Substrate Winding Patterns.	

* Differences between the Westinghouse and DuPont gas flow resistance measurements may be due to variations in the uniformity of the 2-inch vs. 8-inch sections, or alternately the measurement technique.