ADVANCED REGENERABLE HEPA FILTERS BASED ON CERAMIC HONEYCOMB MATERIALS

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ABSTRACT

High efficiency particulate air (HEPA) filters are used in many industrial and governmental applications. While standard pleated fiberglass HEPA filters are adequate for many of these applications, the Department of Energy (DOE) has many nuclear air cleaning examples in which enhanced thermal, chemical, mechanical, or *in situ* filter cleaning capabilities would be useful.

The CeraMem™ HEPA filter is a membrane-coated porous ceramic honeycomb monolith modified to serve as a dead-end, wall-flow filter. CeraMem has developed new filters with lower airflow resistance as compared to those previously reported while maintaining HEPA filtration efficiency, filter cleanability, and thermal, chemical, and mechanical stability.

CeraMem has evaluated its ceramic HEPA filters in demanding applications, two of which are described. In the first, CeraMem investigated a two-step high-temperature HEPA filtration/catalytic oxidation process for reducing dioxin and furan emissions from incinerator off-gas streams. This HEPA filter process was shown to be very effective in reducing the formation of toxic dioxins and furans and to reduce the level of dioxin and furan contamination of incinerator ash. In the second, the ceramic HEPA filters were evaluated as prefilters prior to a fiberglass HEPA filter for eliminating the atmospheric discharge of fine radioactive particulate calcine from transport air in a pneumatic transport system. The filters were repeatedly cleaned and no increase in pressure drop was observed for the downstream HEPA filter.

The ceramic honeycomb HEPA filter technology provides for an alternative to conventional fiberglass HEPA filters or could be used as prefilters prior to conventional HEPA filters in applications that require enhanced ruggedness and *in situ* cleanability. These applications include nuclear materials handling and waste destruction and extend to protection against chemical, biological and radioactive weapons.

INTRODUCTION

High efficiency particulate air (HEPA) filters are used in many industrial and governmental applications. These include processing of sterile goods, hospital operating rooms, biological safety cabinets, microelectronics manufacture, and containment of radioactive particulate. Traditional fiberglass HEPA filters meet the needs of most of these applications with a variety of low-cost filter module configurations.

However, standard HEPA filters have limitations with regard to temperature stability, moisture tolerance, mechanical strength, and filter cleanability [1]. Penetration of HEPA filters starts to increase between 200ºC and 300ºC making them susceptible to fire damage and eliminates the capability to thermally oxidize organic constituents in the dust layer as part of a filter regeneration process. Wetting of the HEPA filter media can damage standard fiberglass HEPA filters. Not only does the media strength deteriorate but also if the media and/or dust cake adsorbs too much water, the pressure drop through the weakened filter material can rise leading to mechanical failure of the filter and loss of containment. This attribute eliminates the option of cleaning filters with a water wash through the filter media to remove dust cake materials. The maximum differential pressure that standard HEPA filters can withstand is between 760 mm of water column (wc) and 1,020 mm wc. While this is well above the typical operating range of 25 mm wc (clean) to 125 mm wc (loaded), the pressure differential is well below that typically used to regenerate rigid, inorganic gas filters that is in the range of 35 to 70 kPa. The inability to regenerate filters leads to filter replacement that in some cases is very expensive, generates hazardous waste, and exposes maintenance personnel to health and safety risks.

DOE's nuclear air cleaning applications have many examples in which enhanced thermal, chemical, mechanical, or filter regeneration capabilities would be useful. For example, such filters would be useful for treating headspace vent-gas from high-level radioactive waste (HLW) tanks. There are approximately 300 HLW tanks in the United States. These tanks contain up to 4,000,000 liters of liquid waste each that the DOE is presently processing into various stabilized waste forms for ultimate disposal. These tanks contain highly radioactive materials, water, and organics. Through radiolysis, hydrogen is formed by the breakdown of water and organics. The hydrogen must be continually purged from the headspace to remain below the hydrogen lower explosion limit. This vent-gas contains radioactive particles and aerosols that are not to be released to the atmosphere. Presently, standard glass fiber HEPA filters are used to filter the vent gas. The glass fiber HEPA filters may only last a few months and cannot be regenerated. The spent HEPA filters are a mixed waste that must be properly disposed of and the disposal costs are high.

DOE's Savannah River Site (SRS) has worked on the application of high-pressure-drop filter media in an *in situ* regenerative filtration system [2,3]. The *in situ* cleaning of the filter media, one type of which was from CeraMem, used an aqueous solution to regenerate the media to a new, clean filter status. Testing has indicated that an *in situ* cleanable filtration system is feasible for use on the HLW tanks.

Also, waste destruction processes such as steam reforming can benefit from high-temperature HEPA filters for the capture of hazardous and/or radioactive particulate in the off-gas. Steam reforming is a relatively mature technology being used by Studsvik [4] and ThermoChem [5] for waste destruction. In this process, steam is circulated through the waste in the absence of oxygen at modest temperature (e.g., 500°C to 600°C) producing a synthesis gas. The inorganics remain in the reformer residue although some inorganics can be volatilized and would have to be captured in the off-gas treatment system. ThermoChem reports that high-temperature HEPA filters were used in the demonstration of this technology. The reported HEPA filters were silicon carbide candle filters; however, no monodispersed aerosol test data were reported. CeraMem has been told that first generation CeraMem filters were also used with good success [6].

In general, cleanable HEPA filters can be cost effective if the cost of replacement and disposal are taken into account. A cost analysis conducted on cleanable HEPA filters showed that *in situ* cleanable filters have the potential of being cost effective when compared to conventional fiberglass HEPA filters [7]. The study estimated that the DOE complex uses an average of 11,000 filters per year at an estimated cost of $55 million. Using *in situ* cleanable HEPA filters could save the complex $42 million a year in operating cost. The study did not include costs associated with fiberglass filter breakthrough or rupture, but these additional costs increase the cost benefit of the *in situ* cleanable filters for the complex.

CeraMem started the development of honeycomb-based ceramic HEPA filters working with SRS for vent-gas from HLW tanks. CeraMem is continuing this work in order to improve the prototype products and evaluate new applications. The following describes the CeraMem HEPA filter design and characteristics and two application tests of the technology.

CERAMEM HONEYCOMB HEPA FILTER TECHNOLOGY

The CeraMem™ gas filter uses a porous ceramic monolith modified to serve as a dead-end, wall-flow filter. Porous monoliths have been modified by Corning, Inc. and others to be diesel exhaust particulate traps. In these, the inlet/outlet passageways are plugged in a checkerboard pattern. Gas flow through the trap is constrained to pass through the wall structure (e.g., wall-flow) of the monolith. The soot in the exhaust gas is removed both on the wall surface and by depth filtration within the pore structure. Particulate removal efficiency is typically 90-98%. Regeneration is often by thermal oxidation, but more recently variants utilizing passive, *in situ* catalytic oxidation have been commercialized.

CeraMem's patented improvement to this technology [8] includes the casting of a fine-pored, ceramic membrane coating onto the surfaces of the inlet wall passageways, forming a composite filter (See Figs. 1 and 2). This reduces the pore size seen by particulates from the 10-25 µm of the monolith wall structure to about 0.2-0.5 µm, the pore size of the ceramic membrane. The membrane coating acts as a high-efficiency surface filter and particulates collect as a filter cake on the membrane surface. Although there may be some diffusive capture of small particles, pore plugging is essentially absent and the membrane-coated filter is readily regenerated by compressed air backpulsing. Very high removal efficiency for submicron particulates has been demonstrated in a number of applications and prototype filters have been prepared with HEPA quality performance (>99.97% retention at 0.3 µm particle size) based on standard HEPA filter DOP aerosol challenge tests.
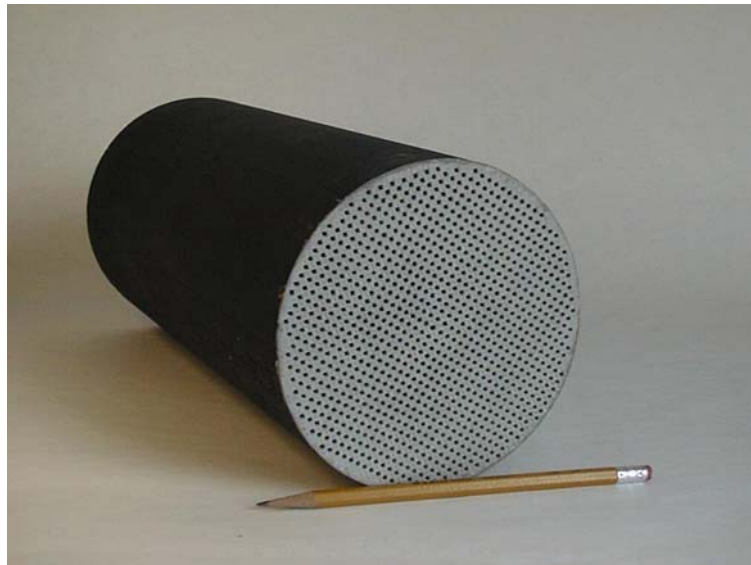

Fig. 2   Photograph of a Ceramem gas filter (142 Mm)

In industrial-scale systems, an assembly of filters is mounted onto a tubesheet within a filter vessel, the latter also containing dirty gas distribution baffles, a backpulse regeneration system similar to that used in baghouses, and a quiescent dust collection zone at the bottom of the vessel. The extraordinary compactness of the filter leads to filtration systems that are much more compact than systems containing candle filters or fabric filters of an equivalent capacity.
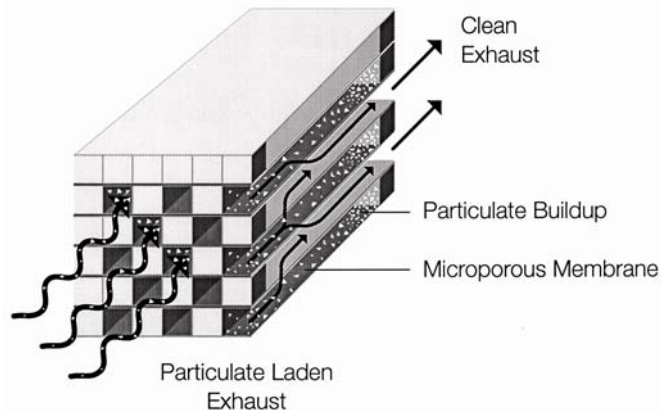

Fig. 1 Schematic of membrane-coated gas filter

HEPA Filter Development and Characteristics*

Prototype ceramic HEPA filters like the one pictured in Fig. 2 were developed for SRS. The filters were 142 mm in diameter and 305 mm long with 2-mm channels. The honeycomb monolith supports were made from 40% porous silicon carbide. Ceramic membrane coatings made from granular ceramic powders were deposited on both sides (inlet dirty side and outlet clean side) of the monolith walls. For these membrane-coated filters, average ambient airflow pressure drop and DOP filtration efficiency are given in Table I. While the DOP aerosol retention is good, the pressure drop for airflow is very high compared to traditional fiberglass HEPA filters (approximately 25 mm wc clean at 2.5 cm/s face velocity). This pressure drop was deemed acceptable for the HLW tank application but lower gas flow resistance is necessary in order to increase the number of applications to which these HEPA filters can be applied.

New ceramic HEPA filters were developed with lower airflow resistance while maintaining the requisite DOP aerosol retention. Modifications included a lower pressure drop (i.e., larger pore size) silicon carbide monolith support material, altered membrane formulation, and different number of membrane layers on the inlet and outlet channels of the monolith. Lab-scale coupons with dimensions of 25 mm square cross-section and 150 mm long were prepared for characterization. Results for a lab-scale version of the SRS prototype and two experimental versions are shown in Table I. The pressure drop has been reduced by a factor approaching three for the best experimental HEPA filter coupon (Version II). This reduction in resistance will increase the number of potential applications that these HEPA-quality filters can be used for. It is interesting to note that the filtration efficiency appears to be relatively insensitive to face velocity. This may be due to the large contribution of particle sieving to particle retention in these membrane-coated filters as compared to fiberglass HEPA filters. Additional work is necessary to determine if this effect is real.

Table I Pressure drop and DOP filtration efficiency for selected ceramic HEPA filters

Filter Type	Airflow Pressure Drop (mm wc) at Selected Face Velocities			DOP (ca. 0.3 µm) Filtration Efficiency at Selected Face Velocities[a]		
	2 cm/s	3.4 cm/s[b]	5 cm/s[b]	2 cm/s	3.4 cm/s	5 cm/s
Average prototype filter for SRS	---	597	---	---	99.985%	---
SRS filter as lab coupon	340	650	912	99.97%	---	99.99%
New filter as lab coupon, Version I	196	351	516	99.98%	---	99.98%
New filter as lab coupon, Version II	132	241	366	99.99%	---	99.99%

[a] DOP aerosol filtration efficiencies measured by Air Techniques International at the Oak Ridge Filter Test Facility or at ATI's home office in Owings Mills, MD.
[b] Pressure drops for lab coupons extrapolated to these face velocities based on best-fit power function to data measured up to 2.6 cm/s.

CERAMIC HONEYCOMB HEPA FILTER APPLICATION TESTING

Use of Ceramic HEPA Filters in Mitigation of Dioxin Formation in Incinerator Flue Gas*
Incineration is a very effective method of treating waste materials. The main purpose of incineration is to reduce the volume of the waste. Other positive attributes include the destruction of toxic and pathogenic

materials and the recovery of energy from the heat of combustion. However, this waste treatment process is very controversial at the present time due to the creation of gaseous emissions and secondary solid and liquid waste streams that must be properly handled in order to operate incinerators in an environmentally friendly manner.

The most strictly controlled emissions are dioxins and furans (D/F). These terms generally describe a family of chemicals that consist of 75 dioxins and 135 furans. The most toxic of this group is 2,3,7,8-tetrachlorodibenzo-p-dioxin, often abbreviated as TCDD. This chemical is very toxic to many different animals and may be a human carcinogen. Since TCDD is the most toxic of the dioxin and furan chemicals and the toxicity of the chemicals within the family vary from very toxic to non-toxic, a system has been put in place to rate the overall toxicity of a mixture of these chemicals. Therefore, incinerator emissions are reported as the TCDD equivalent mass of D/F based on toxicity in the gas stream.

Almost two-thirds of anthropogenic dioxin results from waste incineration [9]. The most likely sources of D/F in incinerator off-gas are from products of incomplete combustion and de novo synthesis during cool down through the air pollution control equipment [10].

In the combustion process, the formation of D/F is unintended. Cyclic carbon molecules (e.g., precursors) are formed as intermediates during the combustion of waste materials. When these precursors are formed in the presence of chlorine, they can react to form D/F chemicals. At high temperatures and excess oxygen conditions, destruction of the D/F does occur. However, if there are process upsets or non-optimum flow conditions within the combustor, the D/F can escape before being destroyed.

Even if D/F are not formed in the incinerator, they can form during cool down in the air pollution control equipment downstream of the incinerator. Considerable effort has been placed on understanding dioxin formation and it can occur when the following conditions are met: 1) gas temperature between 200ºC and 400ºC, 2) residence time within this temperature range of at least 2 seconds, 3) presence of chlorine, 4) the presence of carbon skeleton precursors, and 5) the presence of catalytic surfaces [11]. While there may be debate on particular aspects of each parameter (e.g., upper gas temperature of 500ºC), these criteria are generally accepted as required for the de novo synthesis of D/F.

The methods to reduce D/F emissions from incinerators can be split into two categories. These are 1) methods to mitigate the formation of D/F and 2) methods to remove D/F from off-gas streams. Methods to decrease the generation of D/F include improved combustion, gas quenching, and hot gas filtration. Methods to remove D/F from off-gases include scrubbing, sorption, and oxidation. D/F mitigation and processes that remove D/F without secondary waste stream generation (e.g., catalytic oxidation) are preferred.

CeraMem investigated a two-step mitigation/removal process for reducing D/F emissions from incinerator waste streams [12]. The first step was high-temperature HEPA filtration of the off-gas to remove particulate thereby essentially eliminating de novo synthesis of D/F downstream and contamination of ash particles with D/F that could then become a secondary solids waste stream. Hot gas filtration has been evaluated before for D/F mitigation but the filters used did not have the right combination of high filtration efficiency and high temperature capability [13,14,15]. In addition, hot gas filtration by itself may not reduce D/F emissions to below regulatory limits because homogeneously formed D/F or D/F precursors are not sorbed onto the dust cake particulate at high filtration temperatures.

The second step, which was downstream of the hot gas HEPA filter, was catalytic oxidation of D/F and carbon-based D/F precursors created and not subsequently destroyed in the incineration process.   This could minimize if not eliminate any gas phase D/F coming through the filter and the possibility of D/F formation downstream of the catalyst. The most often-used metal oxide compositions are single or mixed

oxides of Ti, V, W, and Fe usually supported on Al_2O_3, SiO_2, or zeolitic materials. The catalysts are exposed to the contaminated gas stream using typical methods such as beds or honeycomb supports. Operating temperatures typically range between 150ºC and 550ºC and space velocities range between 2000 hr^{-1} to about 50,000 hr^{-1}. These catalysts work well with reported oxidation efficiencies of over 95% [16]. One drawback to the use of these catalysts is that particulates in the off-gas may abrade, foul, or poison the active catalyst materials thereby considerably reducing catalyst lifetime and catalyst effectiveness. The use of high-temperature HEPA filtration prior to the oxidation catalyst will minimize these problems. The filtration and catalytic oxidation unit operations could potentially be located between the secondary combustion chamber and downstream HCl and Hg removal systems.

Due to the complexities in handling D/F and their analysis, experimental evaluation was conducted with the assistance of the Rensselaer Polytechnic Institute (RPI) and Professor Elmar Altwicker. CeraMem supplied a filter and catalyst coupon in housings for incorporation into the RPI bench scale test system. The HEPA filter element was the same size and type as Version II of the lab-scale coupons listed in Table I. The catalyst was V_2O_5/TiO_2 material supported on a 35-cell-per-square-centimeter cordierite monolith, 25 mm diameter by 150 mm length, provided by Süd Chemie Prototech. The catalyst size corresponded to a space velocity of 10,000 hr^{-1} at 15 liters per minute (lpm) gas flow. In order to test the filter and catalyst, an experimental system was constructed where the key parameters could be compared between a process stream treated via the filter and catalyst and a comparable process stream subject to a similar time/temperature history, but in the absence of the filter and catalyst.

The overall process flow schematic for the test system is shown in Fig. 3. Fly ash was fed in batch mode using a vertically mounted fluidized bed particle feeder. Up to 2.2 lpm (STP) of 10% O_2 in N_2 gas flow was used to fluidize a bed of glass beads and ash. Typically, the bed contained one gram of ash for each run. The particulate-laden gas from the particle feeder was combined with 12 to 16 lpm of 10% O_2 in N_2 that was preheated prior to mixing. Preheating the majority of the gas stream minimized the amount of heat exchange surface and therefore the amount of particulate lost prior to entering the furnace at the desired process temperature (ca. 550ºC). The particulate loading at temperature was approximately 100 to 200 mg/m^3. System run times were between 60 and 90 minutes.

Prior to entering kiln #2, a syringe pump was used for injecting 2,4,6-trichlorophenol (TCP) as a D/F precursor and then a Y-junction was used to direct the particulate-laden gas flow to either the filter unit and catalyst process train (FU/CAT) or the parallel empty tube and constant temperature oven (ET/CTO) train. The system was operated with one side or the other by capping off the out-of-service end of the Y-junction. The gas velocity in the tubing of about 12.2 m/s was typical of particulate-laden flue gas systems. Due to the high Reynolds number flow ($>10^5$), particle holdup and losses in the tubing between the feeder and the entrance of kiln #2 were typically much less than 10% of the total charge. The dimensions of the catalyst, filter, and empty tube housings were identical.

Temperatures and pressure drop were measured for both the filter and empty tube reactor. Catalyst temperature was held using a clamshell heater and the CTO had its own temperature control. A glass wool plug was used in the CTO to trap particulate prior to entering the downstream sampling equipment. Typically, the wool plug was set at about 200ºC (dioxin formation minimized) or 300ºC (dioxin formation maximized).
Approximately one third of the exit gases from either the catalyst or the oven entered a large ice-cooled impinger containing 500 ml of toluene. This "Swedish trap" serves to collect D/F and other volatiles; it was originally developed by Prof. C. Rappe and his group at the University of
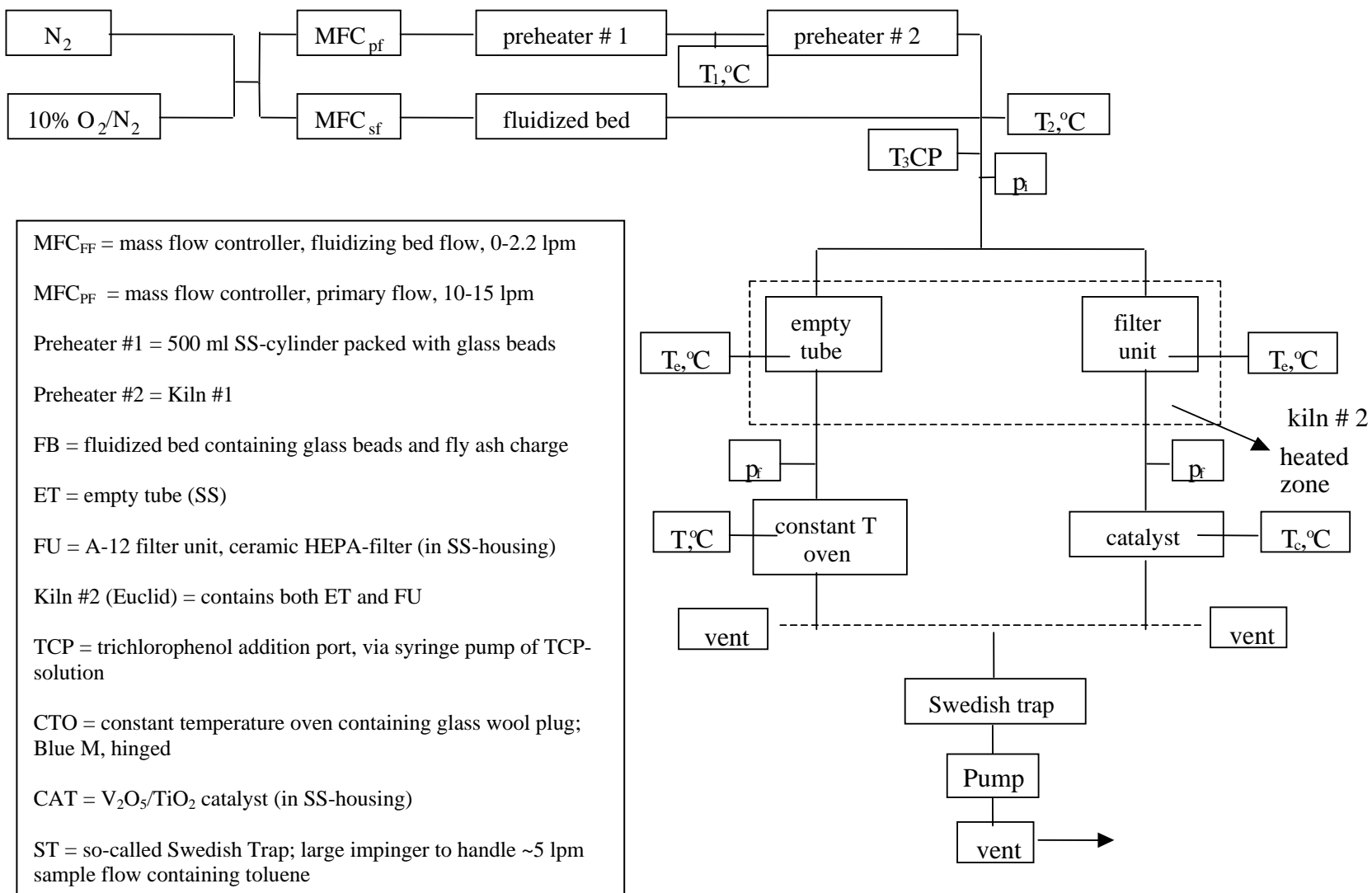
Fig. 3   Phase I bench scale test system flow sheet

Umea in Sweden [17]. Flow through this trap is about 5 lpm STP. The remainder was vented into a hood via a carbon bed. To get accurate D/F measurements, all surfaces potentially contaminated with D/F were rinsed with toluene after each run to get the total D/F mass. The solution volumes were reduced by vacuum and the samples were purified by column chromatograph prior to being quantitatively analyzed by GC/MS using a Hewlett-Packard 5890 series II gas chromatograph and 5971 mass spectrometer.

A summary of the run conditions and D/F analytical results is included in Table II. Three different feed types were used: (1) dioxin-contaminated ash (D-Ash), (2) ash that had dioxin cleaned from its surface using solvent (C-Ash), and (3) TCP plus C-Ash. The temperatures of the filter unit or empty tube reactor in the kiln are listed along with the temperature of the catalyst or glass wool plug in the constant temperature oven. The last column, percent conversion or reduction, refers to one of two comparisons. Percent conversion refers to the percentage of dioxin that was destroyed in the FU/CAT or ET/CTO systems as compared to that injected with the D-Ash. Percent reduction refers to the percent decrease in equivalent TCDD/F mass in the outlet of the FU/CAT system relative to that in the outlet of the ET/CTO system for comparable runs. In other words, the first comparison is the decrease in dioxin actually injected into the systems while the second is the relative amount prevented from forming.

Table II Summary of RPI phase I bench scale process experiments

System Type	Feed Type[a]	FU or ET Temp. (^{o}C)	CAT or CTO Temp. (^{o}C)	Outlet TCDD/F (ng)	Percent Conversion or Reduction
FU/CAT	D-Ash	564	210	2.1	99.2
FU/CAT	D-Ash	581	415	< 0.5	> 99.75
FU	D-Ash	588	---	798	58.1
ET/CTO	D-Ash	554	206	948	36.9
ET/CTO	D-Ash	550	300	2,537	< 0[b]
FU/CAT	C-Ash	585	204	0.4	99.9
ET/CTO	C-Ash	545	300	649	---
ET/CTO	C-Ash	600	70	373	---
FU/CAT	TCP	589	200	1.4	---
FU/CAT	TCP+D-Ash	587	207	25.5	98.1[c]
FU/CAT	TCP+C-Ash	587	204	0.4	> 99.9
ET/CTO	TCP+C-Ash	549	300	55,356	---

[a] D-Ash is ash contaminated with a known amount of dioxin; C-Ash is ash cleaned of dioxin.
[b] Formation of TCDD/F occurred while holding the ash at 300°C.
[c] Based on dioxin fed with ash. Does not include any dioxin formed from TCP.

The first set of runs with D-ash showed that the combination of the filter and catalyst was very effective at destroying D/F. Because 500-600°C is a temperature range where D/F-formation and adsorption on fly ash is expected to be small, using fly ash containing D/F was a convenient method of introducing these compounds into the experimental system. The filter by itself (row 3, Table II) reduced the TCDD/F by almost 60% indicating that the catalyst played an important role in D/F-destruction and that destruction (on the filter) competed with vaporization of D/F from the ash. The catalyst was effective at both 415°C and 210°C. After the high-temperature catalyst run, the ash was physically removed and was found to

have 19 ng of dioxin (OCDF)/g of ash. This is a reduction of 99% from the starting ash contamination level. This indicates that the proposed technology may be applicable to cleaning dioxin-contaminated ash prior to ash disposal.

In contrast, the runs using the ET/CTO system had much lower conversions of TCDD/F. In fact, if the ash was held in the CTO at 300°C, dioxin was formed. This is not surprising in that the ash did not have a long residence time at high temperature so much of the dioxin was still present on the ash and could have volatilized while held in the oven at modest temperature. Additional formation may have resulted from de novo synthesis.

The runs with clean ash also showed that the filter and catalyst system was very effective. In these runs, it was established that de novo synthesis was occurring using only clean ash and no chlorinated organic precursors. When the ET/CTO system was used, TCDD/F formation occurred with a greater amount being formed when the ash was held at the optimum de novo synthesis temperature of 300°C. It is expected that much less TCDD/F formed while the ash was held at 200°C indicating that at least some of the TCDD/F was formed in the duct. The reduction in TCDD/F formed was 99.9 percent when comparing the FU/CAT system and the ET/CTO run with the glass wool at 200°C. The amount of TCDD/F for the FU/CAT run could indicate a minor memory effect from previous D-ash runs.

The FU/CAT-experiments with TCP injection gave no evidence of formation of the characteristic tetradioxins of that compound, namely 1,3,6,8- and 1,3,7,9-T4CDD. TCP was chosen because these useful, diagnostic tetra isomers are formed under higher temperature (600°C) gas phase conditions [18] as well as over fly ash at ~300°C [19]. Also, the combination of the D-ash and TCP gave conversions comparable to those observed in the absence of TCP. However, in the empty tube run, the expected tetra-isomers were the dominant products, suggesting gas phase formation from TCP in spite of the short residence time. The addition rate of TCP resulted in a nominal gas phase concentration of ~10^5 µg/m^3 (STP). The percent reduction due to the FU/CAT system was in excess of 99.9% as compared to the ET/CTO system with ash held at 300°C. In addition, ash mechanically removed after the run with both TCP and D-ash had about 8 ng of dioxin/g ash. Based on the starting ash contamination, this is a 99.4% reduction in the dioxin concentration.

This work demonstrated that a high-temperature HEPA filter/oxidation catalyst sequence could achieve a >99% conversion of TCDD/F when TCDD/F was injected into the system and a >99% reduction in the amount of TCDD/F formed when CDD/F precursors were injected into the system. Also, decontamination of dioxin-contaminated ash was 99% or greater.

Use of Ceramic HEPA Filters in Simulated Radioactive Calcine Transfer

Calcine is a dry granular material resulting from the   alcinations of acidic, liquid, sodium-bearing radioactive waste which came from processing of DOE's spent nuclear fuel at the Idaho National Engineering and Environmental Laboratory (INEEL). While much of the liquid waste has been calcined, there are still 4 million liters of such liquid waste at the INEEL. DOE is still determining the final disposition for both calcine and liquid waste. However, it is possible that calcine will need to be transferred from the Calcined Solids Storage Facilities (CSSFs) where it is presently stored to another location for treatment to a final, disposable form.

Calcine will likely be transferred by a dilute phase pneumatic transport system. The transport system will consist of two stages. The first stage will be used to retrieve the calcine from the storage bins. The second stage will include the transfer line from the bins to the calcine treatment facility. Both stages will require removal of particulate from transport air streams prior to discharge to the atmosphere from the systems. Prior treatment of calciner off-gas was performed using a series of wet scrubbers and HEPA

filters; however, the use of scrubbers for each dust generating unit operation in the transfer system may not be feasible. In addition, wet scrubbers generate liquid waste that must be subsequently treated.

The use of cleanable prefilters followed by nuclear-grade HEPA filters is a more desirable approach to controlling particulate emissions from the pneumatic transfer system. First, the system is dry resulting in only a fine, particulate calcine that would have to be treated using essentially the same process as that for the coarser calcine (material that got disengaged from the air using a cyclone). Second, the cleanable prefilter will minimize the number of times the HEPA filter will have to be changed. This will minimize secondary waste generation, personnel exposure to radioactivity, and cost.

INEEL personnel selected CeraMem HEPA filters based on a number of requirements listed in Table III [20]. CeraMem filters were selected over metal filters based on a much higher filtration surface area to volume ratio. This allowed INEEL personnel to fit the filters into the filter vessel, which is part of their transport air filtration test system.

Table III Requirements for selecting HEPA prefilters for calcine transport air filtration

Requirement	Basis	CeraMem Filter Attribute
Filter materials to withstand 10^8 RAD of radiation	Ability to survive extended periods of time with radioactive char in prefilter	Filter and housing fabricated from ceramic and metal only. No polymers.
Prefilter to capture at least 99.9% of particles larger than 2 µm	Few particles less than 2 µm are expected so prefilter with this quality should be able to adequately protect downstream HEPA filters	Filters have HEPA type quality with more than 99.97% retention of 0.3 µm DOP aerosol
Prefilter to have original pressure drop less than 254 mm wc and cleaned filter pressure drop less than 305 mm wc	Transport air filtration system design and industry vendor data.	Acceptable performance (See below)
Capable of being tested with calcine surrogate	Demonstrate feasibility	See below

CeraMem fabricated and delivered three prototype filters to INEEL for their evaluation. Filter characteristics are included in Table IV. A photograph of one of the filters is shown in Fig. 4. These filters were installed in INEEL's Gravity and Pneumatic Test (GPT) system.

Table IV Characteristics of CeraMem filters delivered to INEEL

Component	Item	Value
Ceramic filter element	Length	305 mm
	Diameter	67 mm
	Active surface area	0.13 m^2
	Retention	Integrity checked by CeraMem[a]
	Pressure drop	140 to 165 mm wc @ 2.5 cm/s
Filter housing	Material	304 stainless steel
	Length	400 mm
	Diameter (max.)	89 mm
	Sealing	Expandable ceramic fiber mat
	Backpulse venturi	75 mm to 25 mm reducer

[a] Similar materials have passed DOP aerosol retention test standard for HEPA quality.

Fig. 4 Photograph of prototype CeraMem HEPA filter

The GPT system consisted of a particulate injection unit, a prefilter unit, and a downstream HEPA filter. The calcine surrogate was a ground limestone, which had an average particle size smaller than the actual calcine but still had over 90% of the particles greater than 1 µm in size. The limestone was dropped into the airflow through a partially opened valve. Airflow through the system was set at 566 to 850 lpm. The CeraMem filters installed in the prefilter unit had pressure drops of 254 mm wc and 330 mm wc at these two airflow rates, respectively. The backpulse system was designed to engage when the filters reached 508 mm wc pressure drop. Backpulse cleaning was performed using fast-acting solenoid valves for each filter connected to a 700-kPa compressed air source. Separate 12.7-mm tubes each with a 5-mm orifice at the end were used to deliver air pulses to the top of stainless steel venturis for each filter. The valves were opened in sequence each for 0.1 seconds with a 2-second interval between valve openings. Each filter was pulsed once per cleaning. The downstream HEPA filter had a pressure drop of 12 mm wc at 1,699 lpm at the start of the tests.

Over several separate tests during which 2.4 metric tons of limestone were transferred, the filters were operated for a total of 6.5 hours and backpulsed over 30 times. The filters proved to be completely regenerable during these tests. In addition, the pressure drop of the HEPA filter downstream of the CeraMem filter did not change. Based on these tests, INEEL has concluded that a full-size calcine retrieval system would require 30 such filters or a smaller number of larger filters so as to have 3.9 m^2 of filter area. In addition, if the CeraMem filters were DOP-tested prior to insertion into the system, operating such CeraMem filters could be used as to collect data to support development of codes and standards for nuclear-grade, cleanable filters.

CONCLUSIONS

CeraMem Corporation has developed membrane-based, ceramic honeycomb filters, which operate as HEPA filters. The clean filter pressure drop of these filters is about six times that of traditional pleated, fiberglass HEPA filters; however, the ceramic HEPA filter is cleanable both by water flushing and backpulsing with compressed gas whereas fiberglass HEPA filters are not. The ceramic HEPA filters have been tested on a limited number of applications but have been shown to work as either a primary filter or prefilter depending on the application.

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FOOTNOTES