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**CROSS-FLOW,
FILTER-SORBENT
CATALYST FOR
PARTICULATE,
SO₂ AND
NO_x CONTROL**

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1.0 Introduction

1.1 Background

Emission control systems for small-scale combustors must be designed to provide highly effective removal of three criteria pollutants (particulate matter, SO_2 and NO_x) under a set of operational constraints that are unique to the small-scale application. In residential homes, commercial buildings, and light industrial facilities, the availability of space is limited and there may be no trained, on-site technicians. In this environment, any piece of installed equipment must be safe, reliable, quiet, small, easy to access and maintain, and should produce no waste by-products that cannot be handled by local waste handling systems.

In addition to satisfying these operational requirements, the emission control systems must clean the flue gas down to emission levels that are comparable to those produced by existing (fuel-oil) combustors. Reduction or elimination of respirable particulates, odors, and acid mists will be critical because the stacks of these combustors will be low and located in densely populated areas. The deposition of acid-coated particulates will be particularly noticeable in residential areas because these acid smuts eat away the paint on cars and houses.

For high reliability, safety, compactness and cost effectiveness, the emission control system should have few moving parts, involve a minimum of extra flows or treatment process, have high area to volume ratios and produce no additional waste products. It would be desirable to have particulate matter, SO_2 and NO_x controlled by one device that could be easily serviced on a monthly, quarterly or seasonal basis.

These requirements make dry, regenerative clean-up processes particularly attractive. This report describes a new concept for integrated pollutant control: a cross-flow filter comprised of layered, gas permeable membranes that act as a particulate filter, an SO_2 sorbent, and a NO_x reduction catalyst.

1.2 Description of Single-Unit, Three Pollutant Control Device

The device described in this section will simultaneously remove particulates, SO_2 and NO_x from the combustion gases of coal combustors. The device is configured as a cross-flow filter, as shown in Figure 1.¹ The gas flows from the inlet passages to orthogonally oriented discharge channels via thin, multilayered porous walls. As shown in Figure 1, flue gas enters from both the front and back of the device. With the left wall of the filter sealed, gas discharges from the right side of the device. The key to combined physical (fly ash) and chemical (SO_2/NO_x) cleaning is to utilize chemically active sorbent-catalysts (e.g., metal oxides) in the layered walls of the filter. A cross-flow filter wall with layered construction is shown in Figure 2. (This concept is currently under evaluation at MIT; a patent application has been filed.)² This arrangement avoids use of pellet beds that plug in the presence of soot and fly ash and require larger reactor volumes because of low surface/volume ratios.

Figure 1. Schematic of a Ceramic Cross-Flow Filter-Sorbent Catalyst

Figure 2
Close-Up of Filter-Sorbent-Catalyst Wall and Gas Flow Scheme

The top (tight-pore) layer serves as a barrier filter blocking passage of fly ash particles. As the gas flows through the porous walls, particulate purities are trapped on the walls of the inlet passage. The layer is fabricated out of an active sorbent-catalyst material that can absorb and chemically bind SO_2 into the porous wall. The metal oxide sorbent is also a NO_x reduction catalyst before and after it is bound with sulfur-oxides (e.g., CuSO_4). Thus, with the addition of NH_3 into the flue gas stream, the sorbent layer also serves as a NO_x reduction catalyst.

This configuration offers a compact filter (10 times higher surface-to-volume ratio than a typical baghouse), a low-attrition sorbent-catalyst (no moving or fluidized solid bed), low pressure drop (through a few mm-thick macroporous membrane), and a very simple flow scheme.

We estimate that better than 90% removal efficiency of SO_2 and NO_x is achievable with the use of mixed metal oxides (CuO , CeO_2) in the device. Also, high sulfur capacity is possible by increasing the metal oxide content of the active SO_2 sorbent phase. Aluminum oxide, Al_2O_3 , is planned to be used as a dispersant and/or catalyst support in the active sorbent-catalyst layer(s). The composite is expected to keep its bifunctional characteristics throughout its operation and not deactivate or lose its structural integrity in the presence of fly ash and trace metals.

Fly ash particles trapped by the cross flow structure can be periodically removed by a back-flushing procedure. Pulse-jet backflushing is a well established technique for high pressure applications of the cross-flow filter.¹ This technique may have to be modified for small-scale applications. Modifications may include frequency of backflush, duration and pressure of each pulse, and pressure source for the pulsation. The modifications may be necessary to make the system as simple as possible for small-scale use. The active composition for SO_2 absorption can be renewed by a regeneration procedure that produces either elemental sulfur or concentrated gaseous sulfur species which can be converted to elemental sulfur by well established processes.

The single unit, particle filter, SO_2 sorbent, NO_x reduction catalyst is an ideal device for small-scale applications. It is modular in configuration, compact, without any moving parts, quiet, producing no toxic materials or new solid wastes to be disposed of and requiring little auxiliary power.

1.3 Research and Development Activity

In October 1989, the team of Arthur D. Little, Massachusetts Institute of Technology, and GTE began a three-year, USDOE/PETC (Pittsburgh Energy Technology Center) funded program to research and develop the filter-sorbent-catalyst. The research priorities of this effort are listed below:

- Sorbent-catalyst material development
 - Which metal oxide materials provide best combined performance for SO_2 removal, NO_x reduction, and sorbent regeneration?

- Under what regeneration conditions is the production of elemental sulfur maximized?
- Active Filter selection
 - What ceramic filter design (thickness, porosity, size, active-phase layering) leads to acceptable pressure drop, particulate matter capture, and structural integrity at expected operating conditions?
 - What backflushing scheme is required?
- System design
 - How will these systems be incorporated into furnaces?
 - What will be the device size, seals, cost, and operating constraints?

2.0 Task Description Summary

The objective of this program is to successfully carry out the experiment and design tasks described herein that will lead to the development a single-unit, cross flow filter-sorbent-catalyst. We plan to carryout this research and design work in two stages.

The first stage of the work will be fundamental in nature: we will investigate the SO_2 removal and NO_x reduction characteristics of different sorbent-catalyst compositions (in bulk, granular form), and we will conduct exploratory tests of cross-flow filters under conditions similar to those found in the combustion gases of small-scale combustors. After a year of these fundamental studies, we will conduct a preliminary evaluation of the component performance and will design two or three prototype configurations.

In the subsequent stage of the program, we will investigate the pollutant control characteristics of prototype filter-sorbent-catalyst devices. The SO_2 removal and NO_x reduction efficiency of a 'unit-element' prototype will be investigated. This 'unit element' will be a slot reactor comprised of two flat porous walls, or 'slabs' of filter-sorbent-catalyst material separated by a 0.5 centimeter gap. The particulate collection efficiency and back-flushing requirements of a multi-element version of this device will be tested.

Concurrent with these efforts will be the investigation of a sorbent regeneration scheme that has the potential to produce elemental sulfur in a one step process. Final evaluation of component performance and the design of these emissions control devices for residential, commercial, and small industrial applications will be conducted at the conclusion of the project.

Table 1 summarizes the tasks to be performed in this program. A milestone chart is shown in Table 2. A complete description of each task can be found in March Technical Progress report (First Quarterly Report).³

Table 1. Summary of Tasks

Task #	Description	Lead Contractor	Schedules
1	Test Plan	ADL	Oct. 1989 - Dec. 1989
2	Component Development		
	2.1 Preparation for SO ₂ /NO _x Studies	MIT	Oct. 1989 - Oct. 1990
	2.2 SO ₂ /NO _x Screening Tests	MIT	Oct. 1989 - Aug. 1991
	2.3 Particulate Tests	ADL	Jan. 1990 - Aug. 1991
	2.4 Regeneration Studies	MIT	Aug. 1990 - Aug. 1991
3	Prototype Tests		
	3.1 Filter Fabrication	GTE	Apr. 1991 - July 1991
	3.2 SO ₂ /NO _x Tests	MIT	May 1990 - Dec. 1991
	3.3 Particulate Tests	ADL	June 1991 - Sept. 1991
4	Evaluation and Design	ADL	Feb 1991 - July 1991 and Oct. 1991 - Jan. 1992
5	Management and Reports	ADL	Oct. 1989 - Feb. 1992

3.0 Objectives for Sixth Quarter Activity

The objective for the sixth quarter's activity was to conduct a performance evaluation and a preliminary system design of the filter-sorbent-catalyst emissions control device. This evaluation/design task included:

- A review of research results and an update of system performance assumptions;
- A preliminary conceptual design of emission control systems for residential, commercial and industrial applications;
- A plan for Phase II tests that will include the investigation of design issues exposed by this evaluation task.

4.0 Approach

The evaluation was conducted in a series of tasks, outlined below.

4.1 Develop Design Goals

In this task we developed design goals for key system parameters, such as: pollutants to be removed, pollutant removal efficiency, regeneration scenario, regeneration interval, and overall pressure drop. In addition, we reviewed the results of the Phase I filter and sorbent tests in order to develop realistic goals for system size, maintenance interval, and backflush requirements. The result of this task established the bases for preliminary system designs.

Table 2: Revised Program Schedule and Milestone Plan

4.2 Identify Critical Design Issues

We identified and reviewed the impact of critical design issues on overall system size and performance. These design issues included: sorbent/catalyst performance, maximum face velocity, maximum space velocity, system geometry, sorbent/catalyst bulk density, sorbent/catalyst thickness, and backflushing method. Each of these design variables impacts overall system size and configuration. We investigated the interrelationships of these variables as well as their individual effects on system design.

4.3 Determine the Limiting Factors In System Design

From the review of critical design issues, we determined the limiting factors in the system design for each of the three systems being evaluated: residential, commercial, industrial. These limiting design factors were either face velocity (impacting system pressure drop), space velocity (impacting sorbent utilization efficiency and system size), and total sorbent mass (determining regeneration interval).

4.4 Investigate Various Active Filter Geometries and System Configurations

Though our testing has been with the Westinghouse cross-flow filter design (as fabricated by GTE), we investigated alternative cross-flow geometries for the filter-sorbent-catalyst design. An example of another cross-flow system is the Corning 'honeycomb' design, in which the gas flows in and out of the cross-flow filter along the same axis. (Figures 3 and 4). (This honeycomb geometry is used by Ceramem in their DOE PETC filtration program.) We examined alternative geometries in order to find geometries that matched the often competing constraints of face velocity, space velocity and sorbent volume (mass). We also looked at the merits of using a small number of cross-flow filters in the system exclusively for filtration, and the other filters for combined SO_2/NO_x removal. It was anticipated that this configuration could simplify the backflushing system, especially for systems with off-site regeneration.

4.5 Develop Preliminary Designs

We prepared preliminary designs for three applications: residential, commercial and light industrial. These designs includes material selection, size, configuration, specification of regeneration scenario and interval, backflushing system, and calculation of face and space velocities.

4.6 Define Issues to be Explored In Phase II Experimental Work

We identified critical issues that need to be investigated in Phase II work.

5.0 Results

5.1 Design Background and Goals

There is limited data available on the performance of commercially available, small-scale, high performance coal combustion systems. High performance coal combustion systems are currently under development by contractors funded by DOE PETC. In order to establish baseline combustor and flue gas characteristics for the design of our emission control system, we assumed that high efficiency, small-scale

Figure 3. Honeycomb Ceramic Monolith Diesel Particulate Filter Configuration

Figure 4. Commercially Available Diesel Particulate Filters (Products of Corning Glass Works)

combustors will soon meet the performance goals set forth by DOE program guidelines. These assumptions of combustor and flue-gas conditions for residential, commercial and light industrial systems are summarized in Table 3. For all cases, it is assumed that the combustor is firing coal with 2% ash, 2% sulfur and a heating value of 14,000 Btu/lb. It is assumed that uncontrolled NO_x emissions are 600 ppm. Flue gas flow rates increase directly with firing rate. Face velocities and space velocities through the filter are based on flue gas flow rate calculations.

The cross-flow, filter-sorbent-catalyst system is a dry, regenerative, combined emissions control system. The active filter needs to be backflushed and regenerated periodically. For residential and commercial applications, we assume that there will be an off-site, central regeneration facility and that the flue gas control system will be comprised of modules that can be exchanged on a regular basis. For industrial applications, we assume that regeneration will occur on-site. There are two options for on-site regeneration. For industries that operate on a one or two shift per day schedule, the emission control unit can be regenerated during the third shift. In this scenario, only one emission control unit is used, and no duplicate system is needed. Regeneration intervals of 8 - 16 hours of operation will keep the single unit size small. If the industry needs a three shift per day production schedule, the emission control system would include two modules. With two modules, one would operate in clean-up mode while the other unit was regenerating. With two modules available, the system could be regenerated as frequently as space and face velocity constraints permit. The regeneration interval would, therefore, have no limiting effect on system design.

Residential and commercial applications pose a particularly stringent set of design goals for the emission control system. There are many issues, in addition to frequency and location of regeneration, that distinguish these system constraints from those of larger systems. For example, it is highly unlikely that SCR can be used in a residence or an apartment building, for example. This is due to problems associated with the safety of ammonia use in a household, and the cost of SCR controls. In addition, system size and cost constraints are much more severe for small installations. Because residential furnace or boiler costs are relatively low, the overall system cost is very sensitive to both added capital cost and added service cost.

For this design study, it was assumed that the emission control system was configured for SO_2 and particulate matter control for residential and commercial applications, and that the system was configured for SO_2 , NO_x and particulate matter control for industrial applications. The emissions control targets for each application are shown in Table 4.

5.2 Design Issues

5.2.1 Choice of Sorbent/Catalyst Material

One of the key design choices to be made is between the various sorbent/catalyst materials which have been tested to date. A summary of the sorbent/catalyst performance data obtained to date is given in Table 5. The following parameters must be considered in making a sorbent/catalyst choice: operating temperature; de- NO_x

Table 3. System Design Basis

Design Assumptions	Residential	Commercial	Lt. Industrial
Furnace firing rate (Btu/hr)	100,000	1,000,000	10,000,000
Coal ash content (%)	2	2	2
Coal sulfur content (%)	2	2	2
Coal heating value (Btu/lb)	14,000	14,000	14,000
Combustion efficiency (%)	98	99	99
Flue gas flow rate (ACFH @ 750°F)	2,800	28,000	280,000
SO ₂ flow rate (lb/hr)	0.3	3.0	30.0
NO _x emissions (ppm)	600	600	600
Maximum pressure drop available (includes H ₂ O)	5	5	5
On-site backflushing possible?	yes	yes	yes
Regeneration scenario	off-site	off-site	on-site
Regeneration interval (minimum)	1 month	1 month	8-16 hours (1 unit) 2-8 hours (2 units)

Table 4. Emission Control Targets

Performance Goal	99% Particle removal 90% SO ₂ removal 90% NO _x reduction	99% Particle removal 90% SO ₂ removal
Operating Temperature	400°C	400°C-600°C
Residential (0.1-0.3 MBtu/hr)		X
Commercial (0.3-10 MBtu/hr)		X
Lt. Industrial (10-50 MBtu/hr)	X	

Table 5. Sorbent Performance Summary

Material	Operating Temperature	t/t* 1st Cycle	SO ₂ Removal		NO _x Reduction	
			Total Material Utilization	Regen. Temp., Selectivity	Fresh	Partially Sulfated
Cu-7Al	400°C	1.3	18%	400°C SO ₂	90%*	100%
Cu-3Al	400°C	0.9	24%	500°C SO ₂	66%	100%
Cu-Ce(B2)	400°C	0.3	26%	400°C SO ₂	90%*	99%
Cu-Ce(B2)	500°C	1.0	100%	500-600°C SO ₂ , COS	21%	68%
Cu-7Al + 2.5% Ce	400°C	0.8	7%	400°C SO ₂	100%*	100%
CeO ₂ +Cu-7Al	500°C	0.9	50%	500°C SO ₂	90%*	90%

*deNO_x tests conducted with SO₂ in flue gas

performance; de-SO_x performance; sorbent activity; sorbent utilization; sorbent regeneration performance; and material structural properties. Two candidate materials were considered in the design analyses performed: Cu-7Al and Cu-Ce.

Cu-7Al operates at 400C and has demonstrated good de-NO_x performance when fresh and excellent de-NO_x performance when partially sulfated. De-SO_x performance has been very good, with 100% SO₂ removal efficiency prior to sorbent breakthrough. The material utilization (18 percent) is higher than available with supported copper oxide sorbents (approx. 10 percent). The Cu-7Al material utilization is slightly lower than our expectation for the performance for bulk materials because the copper loading in the sorbent (18% by weight) is lower than we had hoped to achieve. But the material will be structurally strong because of the high alumina content (only the copper in the sorbent/catalyst is sulfated).

This material has shown good performance in repeated sulfation cycles, indicating little or no material degradation due to repeated sulfation/regeneration. Cu-7Al is therefore expected to have superior mechanical strength and structural integrity when formed, either by extrusion or casting, and when utilized. It is expected that this material can be formed into a cross-flow filter without an additional backbone structure of cordierite or alumina. This eliminates a wide range of potential problems associated with thermal stresses, delamination, etc.

Cu-Ce operated at 400C has also shown excellent de-NO_x performance when partially sulfated. At this temperature only the copper sulfates, giving a total material utilization of 26 percent. Complete material utilization can be obtained by operating at 500C. At this temperature both the copper and the ceria are sulfated. However, the NO_x reductions at 500C are reduced to approximately 70 percent when the material is sulfated. Regeneration of the sulfated ceria at 600C can also lead to a decrease in sulfation performance in subsequent cycles. For the purpose of the design exercise it is assumed that the problems associated with cyclic performance of the material can be solved and that the resulting Cu-Ce sorbent/catalyst operates at 450°C and has a utilization of 50 percent. The Cu-Ce sorbent is expected to have a lower mechanical strength than Cu-7Al, as it consists of a higher proportion of active materials. It may therefore require support in practical configurations.

5.2.2 Sorbent Mass and Regeneration Interval

The greater the mass of sorbent contained in the filter-sorbent-catalyst, the longer the regeneration interval can be. The residential and commercial applications require removal of sulfated sorbents for regeneration off-site. Therefore the sorbent system mass must balance two opposing requirements: the regeneration interval needs to be as long as possible, to decrease service cost, and yet the mass of the system should not be so great so as to make module replacement a difficult or unwieldy task. Thus the residential and commercial applications require the highest possible sorbent utilization, in order to maximize active sorbent mass and minimize total module mass.

In larger installations it is more feasible to provide duplicate systems and regenerate on site. In this case, regeneration interval may be shorter, the total sorbent mass required per unit of firing rate may be smaller, and the required sorbent activity may be less critical than in the residential case.

5.2.3 Choice of Geometry

The sorbent material utilization and the required system regeneration interval lead to the determination of the total mass of sorbent in a given system. However the packaging of such a mass of the sorbent/catalyst must be done in a way that matches the design criteria of face velocity for particle filtration and space velocity for NO_x and SO_2 control. Thus the choice of sorbent material may influence the choice of system geometry. Particle filtration can be accomplished at a higher gas velocity than can NO_x or SO_2 reduction. Thus, there is a difference between these two requirements which can significantly affect design choices. These issues are discussed in the next section.

5.2.4 Face and Space Velocity

Filter face and space velocities are illustrated in Figure 5. The filter face velocity is calculated by dividing the total flue gas flow rate by the total available filter area. Our filter tests have shown that this face velocity must be kept below about 5 ft/min in order for maximum pressure drop to be kept below 5 inches of water. The filter space velocity is the inverse of the gas residence time in the active sorbent material. The units of space velocity are inverse hours (h^{-1}). The space velocity can be calculated, for any particular geometry, by dividing the filter face velocity by the filter thickness. Most of our testing with sorbent powders at MIT has been conducted at space velocities of 2000 h^{-1} . Limited tests have shown that no decrease in sorbent performance occurs at space velocities up to $10,000 \text{ h}^{-1}$.

5.3 Limiting Factors In Design

In order to examine the various design trade-offs, the following design assumptions were made:

- Cross-flow filter module size is 12" x 12" x 4" (before sorbent installation) with a filter area of 10 ft^2
- Sorbent material bulk density as extruded is 2 g/cc
- Sorbent layer thickness is 4 mm
- Coal is 2 percent sulfur, 2 percent ash
- Combustor operates at 10 percent excess air
- Combustor size is 1 million Btu/hr

The assumed density is at the high end of the projected range for bulk densities of the formed sorbent/catalyst. Lower densities would result in less sorbent mass per module, thus leading to the need for a larger number of modules.

$$\text{Face velocity} = \frac{Q}{A} \text{ (ft/min)}$$

$$\text{Space velocity} = \frac{Q \cdot 60}{A \cdot t} \text{ (1/hr)}$$

$$\text{Face velocity} \cdot \frac{60}{t} = \text{space velocity}$$

The results of this design analysis are shown in Figure 6 for the two sorbents chosen (Cu-7Al and Cu-Ce). Figure 6 clearly demonstrates the different constraints for particle filtration and NO_x/SO_2 chemistry. Given a sorbent thickness of 4 millimeters, a face velocity of 1 fpm corresponds to a space velocity of $4,500 \text{ h}^{-1}$. Therefore, face velocities will need to be less than about 2 fpm in order for space velocities to be under $10,000 \text{ h}^{-1}$ (the maximum level established (so far) for good sorbent performance). Space velocity and regeneration interval requirements are compatible: a low space velocity requires a larger sorbent mass, which leads to longer regeneration intervals. Given a wall thickness of 4 mm, an optimal operating condition would be to have a face velocity of about 1 -2 fpm. This leads to an acceptable space velocity under $9,000 \text{ h}^{-1}$, and a regeneration interval of 25 to 100 hours, depending on the sorbent selected.

It is clear from Figure 6, that face velocity (and therefore system pressure drop) is not a limiting constraint on system design. In fact, the filtration function of the cross-flow filters is somewhat under-utilized. We have therefore examined different cross-flow geometries in order to better match the filtration and sulfation requirements of the system. In general the Westinghouse-style cross-flow design leads to large systems because the ratio of sorbent mass to filter face area in a given module geometry is very low. If this ratio can be increased, then a smaller space velocity will be achieved for a given face velocity, and consequently a smaller number of modules will be required for a given duty. This improved face-space velocity relationship is found in the honeycomb style cross-flow filters. This different geometry is discussed in the next section.

Other issues also impact the amount of active material contained in a control module. The ratio of sorbent mass to filter face velocity will be higher for sorbent materials which are strong enough to provide the structural integrity of the filter module. Weaker sorbents may need to be supported on an inert base, thereby leading to lower sorbent masses per unit area.

Another way to better utilize the filters for filtration, is to separate the particle control duty from the NO_x/SO_2 control duty. That is, a small number of high surface area, high face velocity modules may be arranged in series with a larger number of high sorbent mass, low space velocity modules. This arrangement will also lead to much simpler backflushing arrangements, as the number of modules to be flushed will be considerably reduced. These options are described in the following section.

5.4 Filter Geometries and System Configurations

A Westinghouse style filter geometry was compared to a Corning style filter. The two arrangements have been illustrated previously in this report (Figures 1 and 3). In the Westinghouse arrangement, the sorbent/catalyst is extruded in the form of highly porous plates, one side of which has a thin layer of small pore size material, for efficient particle filtration. The plates are then stacked and one end is blocked off to give a series of dead-ended channels. The stacking is performed so as to give a series of inlet ducts which are coated with small pore size material, which serves to filter the fly ash. The inlet gas flow is then forced to pass through the plates, where the NO_x/SO_2 reactions take place. The Corning honeycomb arrangement is similar, except that the

Figure 6. Design Parameters for a Cross-Flow, Filter-Sorbent-Catalyst for a 10⁶ Blu/Hr Combustor

sorbent/catalyst is extruded as a honeycomb with hexagonal or square cells. One half of the cells are blocked at the inlet end and one half at the outlet end to provide dead-ended passages. Thus the flow is filtered before passing through the sorbent/catalyst material.

The following sections discuss the tradeoffs between the two designs for the case of a 1 MM Btu/hr furnace. It is assumed that the sorbent/catalyst material has sufficient structural integrity to allow it to be extruded as either plates or honeycomb monoliths. The actual sorbent used will affect the regeneration interval obtained. In this analysis the parameters of primary interest are face velocity, space velocity and system size (i.e. number of modules required) for a given cleanup duty.

5.4.1 Westinghouse Arrangement

The cross flow arrangement has already been discussed extensively. As mentioned above, this arrangement leads to relatively low sorbent masses per unit filter area. In addition, this arrangement may prove to be expensive, particularly at smaller scales, as the module fabrication is highly labor intensive. The maximum filter module size (currently) is 12" x 12" x 4". When a 4 mm layer of sorbent is inserted for each inlet passage, the length will increase to approximately 18". Each module can contain approximately 0.13 ft³ (16 lbs) of sorbent and has a filter area of approximately 10 ft².

5.4.2 Honeycomb Monolith Arrangement

Once again it was assumed that the sorbent/catalyst materials could be extruded into monolith designs. The module size was again assumed to be one cubic foot overall and the cells to be square. The cell size and the cell wall thickness were varied to examine the tradeoff between filter area and sorbent volume. The results of this analysis are shown in Figure 7. In this chart the space velocity and number of modules required for a 1 MM Btu/hr combustor are plotted as a function of wall and cell size for a fixed face velocity of 5 fpm. At small cell sizes and wall thicknesses a small number of modules are required, but space velocities are high. At large cell sizes and wall thicknesses the number of modules required is increased, both the space velocity is considerably reduced. A reasonable compromise may be achieved with this design. For example, with a 8 x 8 mm cell and a wall thickness of 6 mm, the space velocity is approximately 10,000 h⁻¹ and four modules are required. Compared to the cross flow design at the same face velocity, both the space velocity and the number of modules required have been more than halved. Figure 8 shows the effect of face velocity on the design for a monolith with 8 x 8 mm cells.

5.4.3 Separate Particle Filtration

Given that a major design constraint on the system is the difference between face velocity and space velocity, it may be desirable to separate these duties. Of the three designs considered above, the most compact particle filter would be a small cell size monolith. With 2 x 2 mm cells and a 2 mm cell wall thickness, only one module would be required to filter the flow from a 1 MM Btu/hr combustor at 5 fpm face velocity. Such a filter placed upstream of the sorbent/catalyst modules would allow for a much simpler backflushing system and would also allow the sorbent/catalyst modules to be optimized for NO_x/SO₂ reduction.

Monolith Design (5 fpm, Cu-7Al)

Figure 7. Design Parameters for a Monolith, Filter-Sorbent-Catalyst for a 10⁶ Btu/Hr Combustor
(Effect of Cell and Wall Sizes)

Monolith Design (8 mm cell, Cu-7Al)

Figure 8. Effect of Face Velocity on Design Parameters for a Monolith, Filter-Sorbent-Catalyst for a 10^6 Btu/Hr Combustor
(Effect of Cell and Wall Sizes)

5.5 Preliminary Designs

5.5.1 Residential System

Table 6 summarizes a preliminary design for a residential sized (100,000 Btu/hr) emission control system. For this design, the critical design constraint was regeneration interval. We needed to limit regeneration to once per month in order to keep service costs low. In this design, one 6"x6"x6" corning-type filter is used upstream for particle filtration. This filter is permanently attached and is not exchanged on a monthly basis.

The sorbent modules are 12"x12"x6" honeycomb modules with 8mm cells and 6mm thick cell walls. The total system size is roughly 2'x3'x3'. In order to keep effective thermal mass low, only one unit is sulfated at a time. The flue gas is valved to pass from one unit to the next every 30 hours of furnace operation.

Table 6. Residential System Design

Component	Design
Sorbent-Catalyst Material	Cu-Ce
Configuration	Particulate filtration first, followed by SO ₂ removal
Regeneration Location	Off-site
Regeneration Interval	One month
Backflush System	Yes - flush one filter only
Face Velocities	Particle filter: 5 fpm Sorbent filter: 3 fpm
Space Velocity	10,000 hr ⁻¹
No. and Type of Modules	12 honeycomb monolith filters, each 12"x12"x6", 8mm cells 6mm wall thickness
System Size	2'x3'x3'
Other design notes:	Only one filter is sulfating at any one time. Valving will route gas from one filter to the next.

5.5.2 Commercial System

Table 7 summarizes a preliminary design for a commercial sized (1,000,000 Btu/hr) emission control system. Again, the critical constraint was the one-month long regeneration interval. The system is configured similarly to the residential system: one filter is used for backflushing upstream of the sorbent filters. This filter is a 12"x12"x12" honeycomb monolith with 2mm cell size and 2mm cell wall thickness. Face velocities in this filter are 4 fpm. The sulfur control system has 90, 12"x12"x12" honeycomb shaped monoliths. These active filters are made of Cu-Ce and have 8mm cells with 4mm thick walls. Four modules are sulfated at any one time at a space velocity of 10,000 hr⁻¹. Total system size is 8'x4'x8'.

Table 7. Commercial System Design

Component	Design
Sorbent-Catalyst Material	Cu-Ce
Configuration	Particulate filtration first, followed by SO ₂ removal
Regeneration Location	Off-site
Regeneration Interval	One month
Backflush System	Yes - flush one filter only
Face Velocities	Particle filter: 5 fpm Sorbent filter: 1.2 fpm
Space Velocity	10,000 hr ⁻¹
No. and Type of Modules	90 modules 12"x12"x12" honeycomb monoliths 8mm cells by 6mm thick walls
System Size	8'x4'x8'
Other design notes:	Only four modules sulfated at any one time

5.5.3 Light Industrial Application

In this light industrial system (10,000,000 Btu/hr), we are including two emission control systems so that one regenerates while the other operates. If the production schedule allows for regeneration during the third shift, only one system is required. The system design includes Cu-7Al material extruded into Corning honeycomb filters. No upstream filter for backflushing system is used; SO₂, NO_x, and particle removal are all accomplished in each filter module.

As shown in Table 8, each filter is a 12"x12"x12" honeycomb monolith with 8mm cells with 6mm walls. The space velocity through the filters is 10,000 hr⁻¹ and the face velocity is 5 ft/min. Eighty filters are needed if three-shift operation is necessary. Forty filters sulfate as forty are regenerated. Only forty filters are required if the sorbent can be regenerated during the third shift of operation.

Table 8. Light Industrial System Design

Component	Design
Sorbent-Catalyst Material	Cu-7Al
Configuration	Integrated SO ₂ , NO _x , particle control Corning style honeycomb monoliths
Regeneration Location	On-site
Regeneration Interval	Every 17 hours
Backflush System	All filters backflushed
Face Velocities	5 fpm
Space Velocity	10,000 hr ⁻¹
No. and Type of Modules	1 or 2 sets of 40, depending on availability of 3rd shift to regenerate Each module is 8mm cells, 6mm thickness
System Size	4'x4'x6'

5.6 Issues for Phase II Study

The design study revealed the importance of space velocity and filter geometry to overall system design. We plan to explore the effect of space velocity on SO_2 and NO_x control in more detail. We also plan to investigate the use of honeycomb style filters as the basis of the cross-flow, filter-sorbent-catalyst design. Filter face velocities of 1 to 5 fpm appear to be appropriate for all the designs. Our Phase II filter tests will be run at this face range of velocities. We need to examine methods to produce thick-walled extrusions of our candidate materials. Wall thickness of 6mm appear highly desirable for compact system designs.

6.0 Plans for Next Quarter

6.1 Sorbent Studies

We will conduct parametric tests of cyclic sorbent performance as a function of space velocity, temperature and regeneration conditions.

6.2 Regeneration

We will continue to investigate the regeneration characteristics of the sorbents tested.

7.0 References

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