History of Air Filtration and Air Cleaning: A 100 Year Review of Significant Advances and Related Influences in the Advancement of the Art and Science of Filtration and Air Cleaning

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ABSTRACT

Filtration and Air Cleaning (FAC) emerged during the 20th century as a key and essential component of the art and science of the control and removal of harmful contaminants from controlled environments. Its development and application has paralleled the advancement of ventilation and temperature control in built environments. In that process, it has been influenced by a number of societal, technological, industrial, and political factors. This presentation will trace the evolution of the growth and maturity of the FAC industry as a response to identified external influences and needs. These influencing factors will include the development and maturing of the healthcare industry; the role of electronics and computerization in industrial process control; the needs of the military establishment; the development of nuclear capability; the proliferation and wide spread growth of air conditioning in the building environment; the challenge of dealing with increased contaminant burden in outdoor air; the emergence of large and high-rise building construction; the development of man-made construction components; the developing concern for ecological and environmental impacts upon and emitting from the built environment; the powerful concern for proper management of energy usage and cost; the role and development of more precise and applicable test standards for evaluating FAC performance; and the pervasive influence of criminal or terrorist driven attacks employing airborne weapons of mass destruction.

INTRODUCTION

The story of the role and ascent of the filtration and air cleaning industry (FAC) is best described as the "supporting actor" that is essential and critical in enabling the successful development and outcome of the overall primary storyline or plot, but is seldom on center stage. That stage is much of the 20th century triggered by the Great War (WWI) and the story follows the timeline of the most significant and influential factors that become important in influencing the development of the full story, which is really the role of "clean air" and the human destiny. Figure 1 is visually illustrative of the significant FAC product components along with their time span of bringing the FAC industry into the limelight of the 21st century. The selected highlighted events in the telling of this story represent a combination of the opinions and judgment, personal knowledge, and experiences of the authors regarding those developments and influences that have driven FAC onto the stage of 2020. Regretfully, this judgment process may leave behind many players of minor roles that do not make it onto the stage.

THE OPENING SCENE: WWI 1914–1918

The story starts 100 years ago amongst the noise...the mud… the chaos… and the gore of deaths in the trenches of the Battle of Ypres during the early days of The Great War in 1915 [1]. This was a war of military "firsts" that included the plane, the tank, the machine gun and then a primary player in our story—the first use of weaponized poison gas loosed by the Germans against the French at Ypres. Initially tear gas and chlorine were used, but as the war progressed, the development of other poisonous weaponized gases worsened to include phosgene and by 1918, mustard gas. The response to these new risks was met by the exploitation of earlier inventions of masks, helmets, and respirators from the fire fighting and mining industries used for smoke and gas control. This

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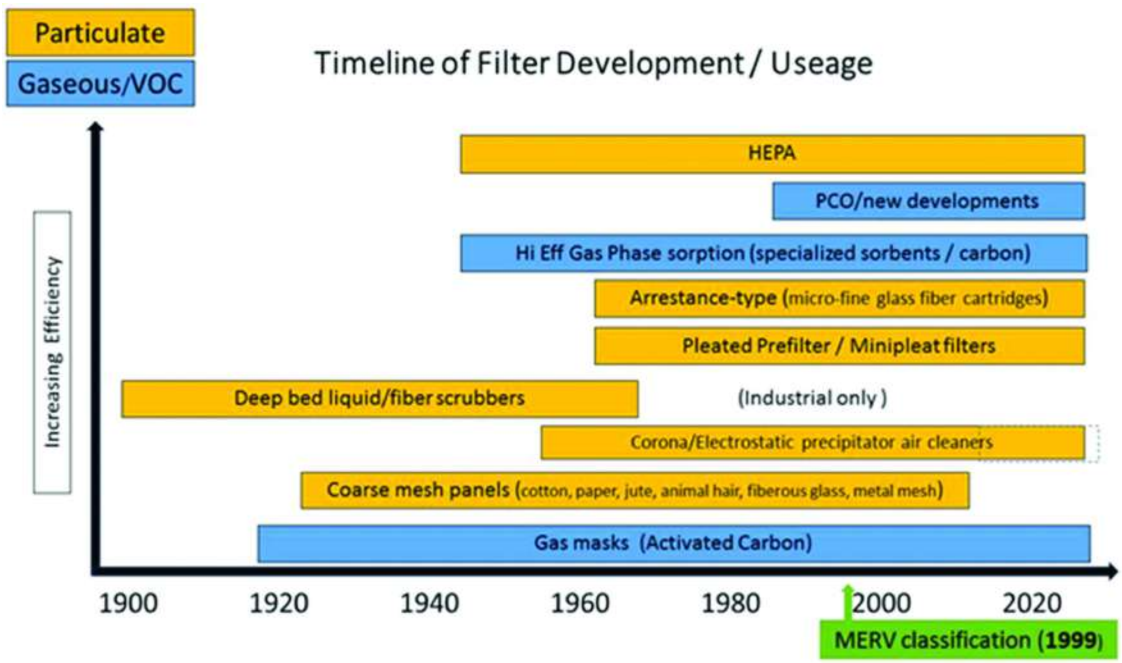

Figure 1 *Generic imeline of FAC technologies.*

Figure 2 *Soldiers in WWI wearing protective masks.*

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response included the additional use of cotton batts impregnated with activated carbon particles [2], and various chemical reagents, such as ammonia and sodium hyposulfite. This combination was incorporated into a compact cassette contained in a small box (called a "box filter") carried by the combatant like a "fanny pack" and attached by a breathing tube to a full head facemask or helmet. These early masks led the way for the development of modern gas masks that filter out both particulate matter and high dosage levels of harmful gases. These were refined in the 1920s and 30's and were widely employed in mining, fire-fighting, and emergency response teams, as well as serving the military in the early days of WWII when violation of the Geneva Protocol of 1925 [3] was feared.

From the FAC perspective, this gas mask development resulted in these significant historical platforms that prepared the way for further growth of FAC:

a. Establishing the usage of activated carbon and/or treated carbon impregnated with a variety of reagents to control airborne gases through sorption,
b. Establishing the usage of fibrous mattes as a method of filtering fine particles through straining and extraction,
c. Providing incentive for the development of commercial sources of carbon, such as bone, coconut shell, and coal, as well as their related product manufacturers, and
d. Establishing particulate and gas phase FAC control as an essential device for assuring health and safety of humans.

ENTER "HOT AND COOL" CONDITIONED AIR: THE ROARING 20s WITH A CAMEO APPEARANCE OF WILLIS CARRIER, A HERO OF THE STORY

The next player to whisk upon the stage is "moving air." As a legacy of the 19th Century, most new homes and commercial buildings were heated, as required by locale and season, with hot water/radiation or fireplaces and stoves. Cooling, ventilating and odor control as needed was provided with outdoor air, employing openable windows or engineered natural ventilation systems. The "Roaring 20s" changed that because of the notable commercial success of air conditioning to the credit of the "Father" of air conditioning, Willis Carrier [4]. He was an engineer and inventor working at Buffalo Forge Company where he applied the art and science of refrigeration to moving air and created the first successful air conditioning system in 1902* to treat a printing operation. This early unit employed a chilled water spray as a condensing medium which supplied both cooled and scrubbed air. Supported by his employer and marketed under the name Carrier Air Conditioning Company and claiming cool and healthy indoor environments, it gained rapid acceptance in the printing industry as well as other industries, such as textile and steel mills. The approaching war in Europe caused Carrier to lose his parent company support. Thus, he organized an independent Carrier Engineering Company that successfully survived the war by supporting the arms manufacturing industry's war effort and entered the '20s seeing his cool, clean air machine welcomed by theaters, hotels, industry, and high rise office buildings. In 1922, Carrier created the centrifugal compressor [5] which expanded the opportunity further, enabling air conditioning to flourish into the 30's in spite of the economic deterrent of the Great Depression. Concurrent to this air cooling advancement, hot air furnaces and blowers paralleled the acceptance and growth of air conditioning. Both air tempering techniques are dependent upon furnaces and air handlers for the mechanical acquisition, supply, and distribution of tempered air to the conditioned space.

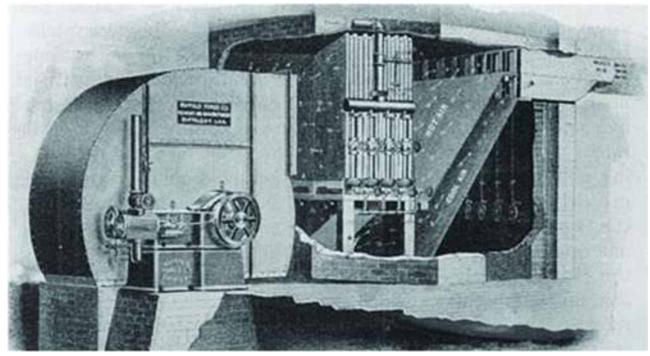

Figure 3 *Original Carrier air conditioner/scrubber (Source: Carrier).*

The FAC perspective from this successful development is:

a. Air cleaning became a significant component of the definition of conditioned air; i.e. control of heating, cooling, relative humidity, and cleanliness of delivered air;
b. The success of the earlier Carrier air cooling and scrubbing machine set the stage for the development of liquid scrubbers for the control of industrial pollutants using liquid phase chemistry; and
c. The requirements and opportunity for FAC growth and application paralleled and tracked the growth and application of HVAC systems in commercial and, later, residential buildings.

ENTER THE "FURNACE FILTER" AND WELCOME TO THE 30s

Creation of the early furnace filter was driven by the need to protect the furnace fire box from accumulation of household lint, fibers, and animal hair to avoid the risk of spontaneous ignition and fire spread outside the unit. Early approaches to filter media for such filters included an array of metal mesh, crepe/tissue paper, wood shavings, hemp, cotton/fabric mattes, or hog hair. These filtering media options were configured into 1" thick panels usually in a cardboard frame using a variety of options to contain and support the media including metal mesh, screening, or cardboard cross members. In 1936, the partnership of Owens-Illinois and Corning Glass patented the development of fibrous glass (#US 2233433A), trademarked "Fiberglas" enabling the manufacture of glass fibers into a matte suitable for furnace filters as in the earlier fibrous options [6]. It was available in both one inch and two inch thick versions, with the latter intended for commercial applications. At the time, this was determined to be the best balance of low cost, reasonably effective lint retention and capacity, low pressure drop, and ease of maintenance. Fibrous glass soon became the dominant type of general purpose air filter for use in residential and light commercial air streams for the next 50 years. Other versions of the media were applied such as cut pads in permanent frames; large rolls of media used in automatic advancing filtration machines; or in large "V" bank retention frames for industrial settings, such as textile mills. Further development of HVAC filters from this time to the present would wrestle with the same balancing act of issues involving: first cost; extraction performance, pressure drop; life cycle; dirt holding capacity; and maintenance cost.

The take away from this scene from the FAC perspective, is that the established generic fiberglass panel filter may have been effective for protecting the heating elements but was not effective for protecting the wet coils of the air conditioning cycle and did nothing to reduce the smaller contaminants, odors, and gases involved in occupant comfort, health, and well-being. The latter issue was not formally addressed until the last decades of the century.

THE FRAM AUTO OIL AND AIR FILTER

Every story needs a "love affair" and the love affair of early America with automobiles is an appropriate backdrop for FAC development because it parallels the development of HVAC. This is pertinent because Fredrich Franklin and Edward Aldham created the FRAM® oil filter* in 1932. It was developed to filter lubricating oil in automobile engines to reduce internal wear from fluid-borne combustion contaminants. Made of rigid moisture resistant filter paper that was tightly pleated, the cartridge delivered high levels of removal efficiency, low flow resistant, and long replacement maintenance cycles. Exploiting this technology, the oil-bath air filter was then developed for protecting the carburetor, the dry air filter was developed in 1951, and the pleated air filter cartridge in 1954.

The basis of the FRAM brand oil filter from the FAC perspective is the FRAM development of high performance resin-treated paper media that could be manufactured into a sustainable, self-supporting, and densely pleated matte cartridge.

THE QUEST BEGINS

The entry to the market stage by the American Air Filters Company development of the "Airmat PL 24" in 1936* started the adventure of improving on the concept of the generic 1" fiberglass panel filter. It was the first of the attempts to employ

Figure 4 *Early FRAM® filter cartridge (Source: FRAM).*

Figure 5 *Original AAF PL 24 (Source: AAF).*

media surface area extension in order to enhance efficiency and lower pressure drop, while extending life cycle and dirt holding capacity. It employed a heavy wire mesh that supported 12" deep pleats of multi-layered tissue or crepe filter paper. Since it was the first of its kind, the PL 24 received some limited acceptance, especially in the retail sector of large department stores that generated large amounts of lint from fabrics and occupant traffic. Its primary "Achilles Heel" was the need to employ a large and unwieldy frame to weave the delicate filter paper onto the mounting rack, which itself was heavy and hard to handle (over 40 pounds). Further, the filter was rated at half the approach velocity of most HVAC units (250 vs 500 FPM), which affected first cost and space constraints.

From the FAC standpoint, the PL 24 demonstrated the feasibility and effectiveness of extended media filtration, once

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the problems of weight, pressure drop, delicate media, and difficult change-out were overcome.

THE MILITARY DOES A REPRISE: WWII AND "THE BOMB"

They are back!!!! "Goose-stepping" across Europe, the Germans invaded their neighbors and conquered or coerced the entire Continent while threatening Russia and even Britain across the channel. This time, there is no poison gas, but early British intelligence revealed the possibility of something worse—the potential of splitting the atom and the production of a nuclear bomb. In 1939, at the urging of Albert Einstein through the "Einstein-Szilard letter"[7, 8], Pres. Roosevelt started an Atomic Research Program that became the Manhattan Project in 1942. Inherent within that project was the concern about radioactive exposures and the desire to protect the large number of engineers and specialists working on the project at a number of National Laboratories, as well as academic research facilities. The primary vector for the exposure was radioactive gas-phase Iodine, which had the innate ability to sublimate or "jump" physical phase states from gaseous into submicron particles as condensation-nuclei. This meant that the control technology must cover both gas phase molecular and submicron sized particulate matter, controlling to extremely high levels of removal efficiencies. This drove the establishment by the Army Engineering Corps of a classified research project to develop the appropriate control technologies resulting in the invention of the HEGA (high efficiency gas adsorber) and the HEPA (high efficiency particulate arrestor) using the current designations as they are now known. (See the "Story of the HEPA" as relayed by insider parties to one of the authors). Additionally the Research Project developed the DOP Test Method (Dioctyl-phthalate was the test challenge smoke) that enabled the verification of each filter as having the removal efficiency of 0.3 micron sized particles at not less than 99.97%. The DOP TM was administered as a Military Specification for several decades and merged late in the century as IEST RP-CCO34.1 [9](Institute of Environmental Sciences and Technologies, who also published guidance on the gaseous adsorber cells IEST RP-CC0084 [10]).

From the FAC perspective there are a number of significant and far reaching outcomes derived from this national security and military driven development:

a. The successful development of the HEGA and, especially the HEPA, again affirmed the role of FAC as an essential ingredient of health, well-being, and even survival of the human population.
b. The combination of HEGA and HEPA protection became the standardized protocol for personnel protection in the Nuclear Power generation industry.
c. The development of the HEPA enabled the later development of the entire cleanroom industry having an impact on electronics manufacturing; pharmaceutical manufacturing, space exploration; and the healthcare industry.
d. The development of the specially treated HEGA employed activated carbon treated with TEDA (Triethyl diamine), which led the way to other reagent impregnation for the control of specific molecular contaminants.

Figure 6 *Early ABSOLUTE® HEPAs (Source: CamFil).*

BEHIND THE SCENES: THE STORY OF THE "HEPA"

As orally relayed to the primary author by insiders to the process*, this is the "behind the scenes: story of the "HEPA" (subject to the flaws of "hear-say" and oral history). The Manhattan Project required a special device to protect the health and safety of staff involved in the laboratory development of "the bomb" from potential radiation exposure. Thus, the Army Engineering Corps contracted with a joint venture of the A. D. Little Company and the Carrier Corporation that resulted in the successful development of the radioactive particle control device. Subsequent to the end of the war and after its declassification in 1950, Carrier commercialized the fabrication process under the protection of a US patent that was granted because of the uniqueness of the invention. Manufacturing was performed by a new venture subsidiary firm called Cambridge Filter Company. They marketed the new device under the trade name and product label of "ABSOLUTE" as a reflection of its superior extraction efficiency. In 1954, Carrier came under scrutiny of the FTC because of its dominance of the air conditioning market; and, as a result, Cambridge was spun off to become an independent company. They exclusively marketed the product until the early 60's when the brand "ABSOLUTE" became synonymous with the device, making it vulnerable for becoming genericized, like the genericized trademarks "nylon" and "aspirin" had after WWII. At that same time period, the product itself was copied by Flanders Filter Company, challenging the validity of the patent protection on the basis that the invention was paid for with public money, thus making it part of public domain. During the ensuing protracted litigation and negotiations that lasted until the patent expired, the parties agreed to create a new generic description of the extraction device. This term enabled competitors to describe their copied products with a generic descriptive label while not violating the tradename "ABSOLUTE" and assured the validity of that brand on behalf of its owner, Cambridge Filter Company. Thus, "HEPA" was born in 1964! It was to serve as the generic noun that was descriptive of this new extraction device and was based on the acronym "High Efficiency Particulate Arrestor." As a descriptive noun, HEPA provided all other competitive marketers the opportunity to apply their own trade names to their brand of HEPAs and could do so without having to describe their device as a "filter," since this product class was generally known at the time to be an inexpensive, low efficiency, fiberglass lint/panel filter. An ironic twist to the story is that the original acronym has been forgotten over the decades. The term meaning has morphed and products are currently marketed as High Efficiency Particulate Air filters. A second irony is that the Farr Company acquired the Cambridge Filter Company in 1991, but refused to acquire their European subsidiary, CamFil. To complete this interesting twist, that subsidiary CamFil came back to acquire the Farr Company in 2001*. To further this irony, CamFil performed a thorough due-diligence intellectual property search at that time and found that the "ABSOLUTE" tradename had never been formally registered! CamFil was able to proceed to attain full formal trademark registration rights because the tradename had not been violated over the entire previous half century, simply because of the creation of the generic synonym term "HEPA."

This bit of history about the naming of the HEPA was an important milestone for the FAC industry that enabled competitive marketing to accelerate the growth and the maturing of the cleanroom industry and its significant role in nuclear energy, healthcare, pharmaceuticals, electronics, military, and space exploration.

ENTER THE US CONGRESS WITH THE HILL-BURTON ACT OF 1946

A new player to the stage is the US Congress that essentially legislated minimum filtration criteria in hospitals that was promulgated by the Hill-Burton Act in 1946 [11] a health bill titled The Free and Low Cost Healthcare Act. This bill provided grants and loans to healthcare facilities for new construction or renovation purposes in return for pledges from the facility to supply reduced cost or free healthcare to applicants meeting specific low income criteria. The funding activity continued throughout the balance of the century until 1997. As part of the compliance requirements by participating healthcare facilities, the usage of minimum efficiency particulate filtration in surgery, OB-GYN, and recovery suites was required. Surgery and OB-GYN were considered critical and were specified as 95% NBS and recovery was less critical at 85% NBS (National Bureau of Standards) Atmospheric Air Discoloration Test Method*. This TM was later incorporated into the first iteration of ASHRAE Standard 52-76 [12] and the same percentage categories prevailed until it was replaced by ASHRAE Standard 52.2 [13] at the end of the century. (See the discussion of test methods under the ASHRAE 52.2 heading).

From the FAC perspective, this act resulted in the following:

a. Hundreds of medical facilities across the country were motivated to renovate and to incorporate the usage of upgraded high efficiency filters. However, many were located in rural and low population counties; thus, many floundered financially because of initial low usage, a high percentage of qualified reduced cost or free patents, and higher operating costs of the larger under-utilized facility;
b. The required filtration criteria mandated by Hill-Burton quickly became the Standard of Care in other authoritative documents, such as the AIA Joint Commission guidance for all new healthcare construction; and
c. The requirements fueled the innovation and production of compliant high efficiency filtration devices such as those typified in the following discussions of extended media arrestance type filters and electrostatic air cleaners.

ELECTRONS HOOK-UP WITH CFMS

The Electronic Air Cleaner (EAC) or electrostatic precipitator, as it was called originally, was a new player coming into the Healthcare scene. Developed in 1908 [14], it represents an entirely new concept of contaminant capture and containment. It deserves some explanation as to its overall impact on the filtration industry. Rather than acting as a barrier or strainer like an arrestance filter, the EAC changes the behavior of capturing fine particles while in its air pathway and acts much like a fisherman throwing out "hooks" dragging captured fish from a river current onto the bank. The collection mechanism is based on the physical phenomenon that surfaces charged with high electrical voltage will create a halo called a "corona" that can alter or manipulate the charge of nearby particles. Thus, an applied corona from an electrified grid allows the airborne particles to be altered in charge. These particles then plate out on downstream collection surfaces. The first two-stage EAC that we know of today was developed in the 1950s.

The primary advantage of the EAC is that it will collect ultrafine particles very well meeting the required ASHRAE filtration efficiency, with little or no pressure drop and requiring no replacement cartridges. The disadvantage of the EAC is that there is an energy cost and the deposition plates require periodic cleaning, which is labor intensive. Also the system operates at its highest efficiency when the unit is clean and the efficiency drops over its loading cycle dependent upon the contaminant burden. Larger particles tend to foul the collection grid causing sparks or arcs and particle discharge. Further, the EAC does not fit well into any of established laboratory industry performance test standards because of end point determination for cleaning and the difficulty of carbon

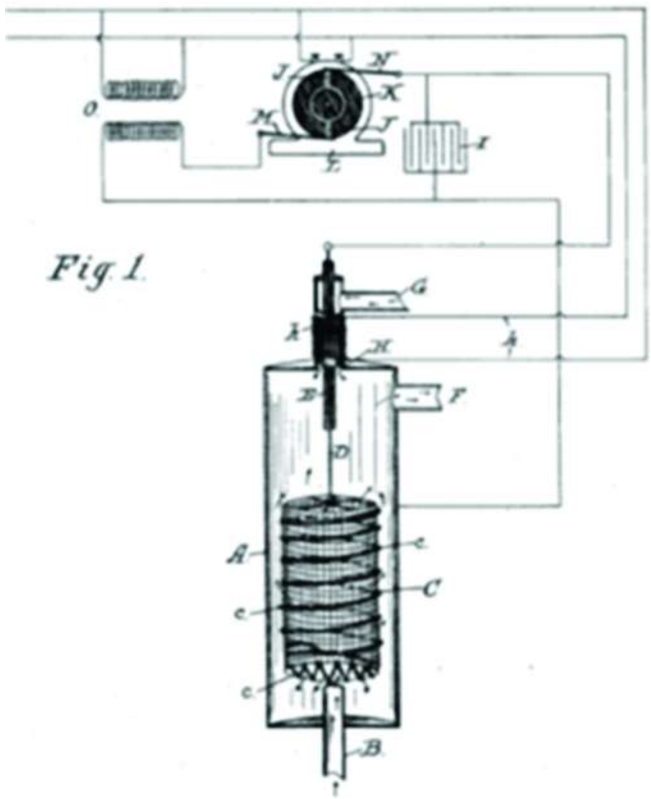

Figure 7 *EAC invention drawing.*

Figure 8 *Hi-flo extended media pocket filter (Source: CamFil).*

containing test aerosols which short-out the charging grid. Upstream/downstream particle count comparison would be useful to determine service life and cleaning schedules but was seldom, if ever, employed. Numerous EACs were installed in hospitals during the initial flurry of Hill-Burton grants because of the appeal of the low pressure drop. Most were abandoned after several cleaning cycles because of any or all of the above factors, but in most cases, it was simply the innate fear of the high voltage by hospital maintenance staff.

From a FAC perspective, the takeaways and impacts are:

a. EAC control, as this was applied, did not prove to be an effective or maintenance friendly device. As a result, it did not sustain further growth in the commercial and healthcare market. Miniaturized versions were introduced later in the century into the less sophisticated residential market without resolving most of the same obstacles observed in the initial healthcare market.
b. The electrostatic mechanism can be extremely effective against ultrafine particles, which sets up the platform for the exploitation of the electrostatic properties of polymeric fibers that will be introduced later in the century.
c. This early experience with the use of powered grids also laid the groundwork for alternate "energetic" approaches to be developed in the early 21st century, such as externally energized media and catalysis driven concepts.

NEW KIDS IN HEALTHCARE: STANDING IN THE STAGE WINGS

The driving force of the Hill-Burton Healthcare Act had provoked several innovations of particulate filtration products that typified new classes of filtration equipment introduced in the late 1950s and 60s as follows;

a. The fiberglass industry developed an ultra-fine microfiber matte of spun fiberglass capable of attaining high efficiency arrestance efficiencies. When backed with a non-woven fabric, the media was employed to construct deep pocket filters to provide the desired efficiency, long life cycles, and acceptable pressure drops. This product-type is still employed in selected brands of extended media filter cartridges.
b. Farr "HP"* was a similar concept to the original AAF PL 24 but with a lighter metal cage and deeper 24" pockets to allow 500 FPM airflow, and to enable easier cartridge installation. The collapsible filter cartridge was fabricated with pockets made of microfiber fiberglass matte that fitted into a wire cage for support and sealing. The advantage of this approach is that the replacement cartridge was compact, saving on freight and storage space and is held securely in place by the rigid metal cage. However, the cage increased first cost and required labor intensity in cartridge change-out. There are still installations of this model of filter that remain active in current service life though most installations have been converted to a later generations of the product line, a box-style self supported cartridge, trade-named "Riga-Flo."

c. Cambridge "Hi-Flo"*, introduced in 1963, was an entirely new extended media concept using tapered non-supported pockets of varied lengths up to 36" deep. The pockets were fabricated of microfiber matte backed with a nonwoven fabric and were held in a precise tapered profile using a patented progressive stitching process. The advantage of this invention was the varied pocket counts and varied pocket lengths enabling a full range of selection of face velocity and surface area, which translates into a variety of pressure drop, life cycle, and space options. The disadvantage of this approach was that the pockets of the cartridge deflate and sag during fan cycle; can become folded inhibiting airflow; and can flag during maximum air flow which erodes the delicate media around the stitch thread penetration. This version of extended media filter remained an active participant in the family of filters sold and serviced by the current owner of that technology and the concept was widely copied by other industry manufacturers later in the 20th Century.

From a FAC standpoint, the takeaway is twofold:

a. The Hill-Burton Healthcare Act triggered phenomenal innovation, opportunity, and growth for the FAC industry in the healthcare industry that lasted well into the end of the 20th century.
b. The established role of FAC as a proven component of the healthcare environment established a platform for the acceptance and employment of enhanced filtration in the prevention and remediation of Indoor Air Quality issues that emerged later in the 20th century.

THE "PLEAT" STEPS IN AND TAKES THE LIMELIGHT

The introduction of the Farr "30-30" in 1969* started a revolution that continues until now. An earlier version, called "J-12" created in 1963, was based upon the usage of a cotton-based matte supported on metal screen mesh that was densely pleated into a 2" depth. This enabled increased efficiency and greater life and dirt holding capacity without significant pressure drop, due to the extended media surface. It was focused toward the commercial prefilter market and experienced immediate inroads in market share. This was evidenced by the large number of product copies soon to appear in the market as the pleating manufacturing technology and equipment became more available.

The impact of this innovation from the FAC perspective was:

a. The 2" pleat was able to fulfill the minimum efficiency requirement of Standard 62 turning it into the workhorse of filtration in commercial HVAC.
b. As synthetic fiber based filter media became available later in the century, manufacturers were able to increase the applicability and performance of the pleat with higher pleat count, deeper pleats, varied media density and fiber count, and improved quality of framing. This enlarged the usage base of various pleat versions immensely.

Figure 9 *Farr J-12 earliest marketed pleated prefilter (Source: CamFil).*

c. Similar variations enabled the pleat to be manufactured in a 1"depths, enabling it to directly replace and upgrade previous fiberglass disposables in the residential and light commercial markets. By the early part of the 21st century, the "pleat" dominated the retail market making fiberglass or synthetic fiber disposable filters a matter of history.

CHEMISORPTION JOINS THE CAST OF CHARACTERS

Chemisorption and odoroxidant were new generic description terms created concurrent with the creation of Purafil Inc. in 1973, based on the 1962 patent of Borg-Warner Corp [15]. That invention consisted of a composition of matter, combining an array of active substrates, such as activated alumina, zeolite, or molecular sieve impregnated with a series of reactive reagents having oxidative properties, such as the permanganate salts. The marketed product was branded PURAFIL® which specifically combined activated alumina with potassium permanganate. Though originally developed for the control of occupancy generated odors, especially tobacco smoke, the product was most successfully initially applied to industrial applications involving acid gas pollutants, which was, and is, a strong performance characteristic of chemisorption. The uniqueness of the invention over simple sorbents was that the active oxidation potential of the reagent caused permanent control of the gaseous contaminants by chemically converting the absorbed molecule into benign byproducts. Since the patent expired after only 6 years, chemisorption technology was open to the FAC industry and because of the earlier demonstrated success in new markets for control, chemisorption products have been widely used by

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industry such as: the protection of electronics manufacturing; computerized process control in pulp and paper, chemical and petroleum refining, sewage treatment, steel and foundry manufacturing; protection of object d'art, rare book and archives, and precious artifacts and commodities. In commercial applications, the product was applied along with enhanced particulate filtration in critical spaces, such as airport control and data centers; and areas having high occupancy and diversity such as hotels, conference and convention centers, auditoriums, and theaters.

From a FAC standpoint, the takeaways are:

a. The successful application of chemisorption created the platform for broader application and usage of molecular gaseous filtration in general.
b. The usage of dual systems of both high end particulate and multiple molecular gaseous filtration products demonstrated the value of the total package of complete air cleansing and contaminant control.
c. Since a number of the noted areas of commercial applications of chemisorbent technology are multi-decade installations of the Indoor Air Quality Procedure (IAQP) of Standard 62 [16] (discussed later in this paper), the success of this procedure demonstrates to others the value and return on investment of exploiting the IAQP.
d. The successful usage of multiple sorbent products in series or as blends opened new opportunities for the control of specific contaminant challenges for the FAC industry.

FLANDERS REINVENTS THE HEPA

Reentering our stage from early FAC history is the HEPA, created in WWII, that was manually fabricated well into the 70's using the original techniques. The process was an extremely arduous and labor intensive process involving the manual folding of the filtration paper media over corrugated aluminum foil separators that formed and supported a 12" deep pleat. This process was repeated until the 24" pack was carefully sealed into a metal, wood or particle board frame. Then each and every filter was tested for compliance to the then prevailing DOP test to assure that there were no flaws in the media, penetrations due to the separator sharp edges, and had a fully integral seal of the pack to the frame. The manufacturing process also required a highly skilled and extremely manually dexterous workforce. All of these elements culminated in an expensive and time consuming process. To counter these issues, Flanders developed a proprietary method for making their own filter paper in-house, using the Fourdrinier paper making process (Early HEPA media contained a small percentage of asbestos fibers...but that, indeed, is another story). In the early 70's, this enabled incorporation of synthetic latex into the slurry adding thermal-forming properties to the paper when cured. This would enable a pleating process with built-in dimples that acted as the separator and support mechanism for the filter pack and would enable automation of the pack fabrication. Later in the decade, Flanders invented a sealing method that uniquely combined a knife-edge penetration into a non-Newtonian gel-filled trough to make a quick, foolproof seal that minimized leakage around the frame of the filter cartridge.

The importance of these inventions to the FAC are:

a. The use of polymer content and the exploitation of synthetic media forming properties were widely exploited by FAC suppliers as they entered the 21st century This facilitated filter pleating and retention, media dimension control, and self-supporting characteristics.
b. The liquid seal was more broadly applied beyond HEPA usage to resolve or minimize seal issues.
c. The advancement of a liquid seal brought focus to the industry's need to address a flaw of FAC products, which was the failure of fully attaining filter efficiency benefits because of seal failure and air leakage around the filter cartridge.

THE STAGE MANAGER MAKES AN APPEARANCE: ENTER NAFA

Early in the history of the HVAC industry, the Air Conditioning and Refrigeration Institute (ARI) had been formed to represent the trade interests of manufacturers of HVAC equipment. A small Section of that association focused on filtration and air cleaning but participation was minimal by the FAC industry because of the dominance of the large equipment manufactures in the affairs of the association, combined with the obsolescence of the original ARI 680 TM [17] caused by ASHRAE Standard 52.2 TM development. In response, the National Air Filtration Association (NAFA) was formed to focus on the small businesses involved in the distribution, application, and service of FAC systems; thus, its membership was based primarily upon the FAC sales and distribution function rather than manufacturing function of the industry.

The impact of this new player on the FAC industry was multi-fold:

a. NAFA developed and published educational. training, and "best practice" materials leading to the competency certification programs for its members resulting in improved benefits and value for FAC users.
b. NAFA members aided with the support and training that resulted in rapid acceptance and understanding of the then new ASHRAE Standard 52.2 TM by specifiers and users leading to the rapid modernization of the FAC industry by the end of the century.
c. NAFA supported and sponsored research specifically devoted to filter performance and application.
d. NAFA developed training and programming to assist members in improved management and marketing skills enabling sound member growth.
e. NAFA provided to members an industry voice in responding to and influencing technical and legislative issues impacting the FAC industry and their customers.

MODERN CHEMISTRY AND "ELECTRETS" TAKE CENTER STAGE

Although synthetic fibers were invented before WWII, the early Celanese patents for polyester; the DuPont development of the nylons; and the later creation of fibers from the olefins had been dormant from the perspective of the FAC industry. In 80's and early 90's, these fiber technologies awakened and expanded from the textile world, dancing onto the FAC suppliers' horizon, because new developments had made available fibers that could be varied in denier (even ultra-fine); could be fabricated into pads and matts of varying densities and thicknesses; and exhibited unique properties that translated into improved filtration extraction efficiencies, dirt-holding capacities, and pressure drop features. These new materials quickly overtook the dominance of fiberglass and became the filtration media of choice in most of the extended media filtration products marketed at that time, especially the shallow pleated filter prefilter. This market turnover brought an entirely new cast of manufacturing players into the FAC marketplace, names like, DuPont, 3M, and Kimberly-Clark. The physical property of these new synthetic media fibers that powered this rapid acceptance was the uniquely heightened electrostatic conditioning of their fiber surfaces. As a result, filters made with these new media exhibited heightened extraction efficiencies against ultra-fine particles because the ordinary impaction, straining, and diffusion capture methods were enhanced by an electrostatic effect of the fiber, similar to the EACs of earlier FAC history. This prompted the labeling of media having this property as "electret," to aid in marketing the media to the FAC industry as a superior product. To create electret fibers, synthetic polymers are heated to a melted liquid state and then extruded or blown through highly engineered nozzles and then spun into a non-woven matt. As the formed fiber cools and regains solidity, the surface of the plastic polymer fiber creates a molecular surface tension imbalance that results in an electronic charge. This charge can be controlled and enhanced by the manufacturing process.

The impact of this development on FAC was multiple:

a. The electret synthetic media quickly invaded the pleated filter suppliers, which enabled more versatility, higher performance, and lower pressure drop in this version of the filter.
b. The technology opened the FAC market to the chemical/plastics industry and led to the development of fiber technology designed specifically for the FAC industry and the technology of extraction of air/liquid-borne particles.
c. Application experience revealed that the effect of inherent charge of the media fibers could be diminished during the installed life-cycle of the filters due to exposure to atmospheric humidity, pollutants, and/or loading with ultrafine particles that tended to blind the fiber surface charge sites. This resulted in:
   1. Lower installed fractional efficiency performance than expected based on laboratory testing.
   2. Further research on the role of the electret enhancement balanced against the increase of efficiency due to the accumulated cake due to the loading of the filter
   3. Additions to the new ASHRAE 52.2 [13] test method (see following discussion on 52.2 TM and "MERV") to accommodate for conditioning tested filters to reveal the extent of reduced charge influence to establish a valid minimum efficiency to the assigned efficiency MERV classification.

IAQ STEPS FORWARD WITH A PLOT TWIST

The energy crisis of 1973-74 brought drama to the story in the form of "energy conservation" and to the attention of the American people like a 2 x 4 to the side of the head. Gas shortage and lines at the gas pumps were an obvious impact on the citizenry. The influence on the commercial building community was more subtle. The largest single usage of electricity in commercial buildings is HVAC and lighting, and the largest component of that HVAC expenditure is outdoor air treatment. The reaction… "shut down the outdoor air!" shouted the politicians and the building owners… and they did, with the result being that occupants were being negatively affected health-wise from inadequately ventilated buildings. These health-related symptoms were due to exposure over time to elevated internal contaminant concentrations that were no longer being controlled by dilution ventilation air. By the end of the decade, enter a new player to the scene "Tight Building Syndrome" soon replaced by "Sick Building Syndrome" both of which became the labels for unacceptable Indoor Air Quality. The issue was complicated further by the concurrent development of the ASHRAE 1981 version of Standard 62 [16], the ventilation design standard and the newly created Standard 90 draft, the energy management design standard. The Standard 62 draft had introduced an early version of the IAQP reducing outdoor ventilation air from 15 to 5 cfm per person in response to the energy crisis with the caveats that enhanced FAC be employed and there be no smoking in the space. The ASHRAE Standard 90 [18] energy standard draft was adopted by DOE and became Federal law virtually immediately, requiring the "use of the lowest number" (without regard for the cited caveats) for designing new buildings for maximum energy conservation. That created the perfect storm for creating a decade of commercial building construction, especially in office buildings and schools, to be designed and operated with inadequate ventilation. This developed into an outbreak of litigation and law-suits (ending up often in irrational and obscenely large awards) that lasted well into the 90's.

From a FAC standpoint the impact of this occurrence was:

a. To repair the damage of the prior decade, Standard 62 was reissued in 1989 [19] and included a defined Indoor Air Quality Procedure as an alternate compliance pathway that included the usage of enhanced FAC. This formally affirmed and sanctioned the usage of filtration as an effective and acceptable alternate to dilution for the control of indoor contaminants.

b. At the time, Standard 62 was accepted verbatim by the Southern Building Code (SBC) which had currently prevailed, and as a result, a number of buildings in Atlanta and the Southeast successfully employed the IAQ Procedure and many operate successfully to date several decades later. (The SBC became part of the Uniform Building Code of 1991)

c. Though Standard 62 has gone through a number of changes through continuous maintenance, the IAQP remains a valuable driver for FAC as an alternate method for controlling building and occupant generated contaminants and attaining acceptable IAQ, while saving energy over ventilation/dilution approaches.

d. Subsequent revisions of both Standard 62.1 (commercial) and 62.2 [20] (residential), prescribed minimum levels of filtration. Since both are code directed documents, these have been beneficial in driving the mandatory inclusion and improvement of filtration in all new construction sectors.

e. The IAQ focus and experience of the late 20th century provided the basis for the acceptance of FAC as an effective measure for both the prevention, but also the ongoing remediation of IAQ incidents.

THE SWISS BRING MECHANICAL GENIUS TO AMERICA AND TO THE FAC STAGE

Early in the last decade of the 20th century, The Filtration Group introduced a new particulate filtration concept that has quickly moved to center stage. It was called the "minipleat" and was based on Swiss manufacturing technology developed by, and licensed from, Luwa Air Engineering AG. The minipleat consists of tightly pleated paper-like media that is self-supporting using hot melt glues to seal and maintain the pleat shape integrity. The concept was developed for HEPA manufacturing initially since the technique enabled a much higher approach velocities than conventional products while still operating at acceptable pressure drops. This revolutionized the cleanroom industry in Europe before coming to America. The technology has grown rapidly throughout the commercial particulate product base including a range of MERV efficiencies as well as filter pleat depths from 1" to 12". The minipleat concept also lends itself to rigid thermoplastic frames that are dimensionally stable, which facilitates gasketing and reduced bypass.

The impact of minipleat technology on FAC was significant because:

a. The minipleat operates at lower pressure drop than conventional media that lowers operating energy cost, which is the actual operating cost of filtration;

b. The rigid thermoplastic frame is easily gasketed, tolerant of moist air streams, and retains its dimensions unlike paper based frames. This resolved leakage and air bypass around the frame in side-load filter installations.

Figure 10 *Typical minipleat cartridges (Source: IAQ Guide, Figure 7.5.D).*

c. The minipleat was the most expensive filter concept from a first cost standpoint; however the low pressure drop, high surface area, high dirt holding capacity, and long service life resulted in lower life-cycle costs than other filter versions.

THE VILLAIN AND THE NONREGULATORY REGULATION: NO SMOKING!

Every story needs a villain and, in this case, it was both Environmental Tobacco Smoke (ETS) and the "Fed" attempting to regulate IAQ by banning workplace smoking. In 1994, largely in response to the negative experience with the IAQ issues of the prior decade, OSHA (Federal Occupational Safety and Health Administration) announced an "Intent to Regulate" and the intent was to ban tobacco smoking in the workplace and most public buildings in the US. The intent also contained a plethora of related reporting requirements, prevention rules and measures, and violation remediation procedures that placed massive reporting burdens on most employers in the country (the villainous part of it). The agency was buried with tens of thousands of negative comments and the intent "went away" but… the shadow it left behind resulted in most public buildings voluntarily putting no smoking signs and rules in place within a matter of weeks. States and municipalities followed suit often on an emergency timetable and the local jurisdictions assumed the role and authority of imposing and policing the ban. It was the most effectively executed "non-regulation" ever promulgated by an agency of the US Government; thus resolving ETS, virtually overnight, as one of the most pervasive and complex contaminants from the environments of public and commercial buildings. One would think that the elimination of a significant contaminant of concern from the indoor environment would negatively affect the marketing opportunity of FAC suppliers. Surprisingly, the ban resulted in these positive outcomes affecting FAC:

a. ETS was such a difficult and pervasive contaminant because it was made up of a full "cafeteria" of contaminants of IAQ concern in an indoor environment. It had high concentrations of extremely small submicron particles along with a wide range of gas phase chemical compounds that ranged from highly odorous to potentially toxic with very low perception thresholds. Thus, it was virtually impossible to treat with conventional FAC equipment to the satisfaction of non-smokers. This left only dilution by ventilation as a feasible means of control, which was also unsatisfactory. This is because of the lingering effect of second-hand smoke that deposits on persons and porous surfaces of the interior space which become secondary outgassing sources.

b. The application of the no smoking policies generally allocated a "smoking zone" which provided a confined space where isolation; negative pressurization; high performance FAC; and controlled access were feasible and cost effective methods to accommodate the practice while protecting the surrounding area from ETS contamination.

c. With ETS eliminated from the workplace, many IAQ complaints went away. However, if Sick Building Syndrome still occurred, more accurate air testing and diagnostics by IAQ practitioners could prevail without the evaluation data being corrupted and overwhelmed with ETS, often revealing underlying causes that had been previously disguised by the more dominant ETS contaminant source.

ENTER THE POLICEMAN TO THE STAGE: ASHRAE 52.2 TAKES FILTRATION INTO THE 21ST CENTURY

Standardized Test Methods (TM) provide the yardstick by which products can "police" or control and validate their performance and benefit claims. The more reliable, applicable, current, reproducible, and pertinent a TM is, the better the quality assurance of the appropriately tested product. ASHRAE 52.2 was the TM for extended media enhanced efficiency filters and was published in 1999 ushering the Particulate Filtration portion of FAC into the 21st century. Unfortunately, previously employed TMs in place for much of the 20th century had lagged the industry in keeping current with advancing measuring technology; pertinent filtration application needs; and the growth of FAC into the air quality and health-related fields. The early pre-WWII history of low efficiency panel filters had relied on the Air Filter Institute (AFI) Arrestance TM, which basically evaluated the dirt holding aspects of the filter. Since the quality control test challenge dust was Arizona Road Dust (actual road dust from Arizona), paved roads both eliminated the source of test challenge and the applicability of the test and the test method "blew away". The National Bureau of Standards (NBS) developed their NBS Discoloration Test or Dust Spot Test 1938* with the emergence of higher efficiency extended media filters. The post-war acceptance of the NBS test was driven by the Hill-Burton Act related health facility regulated guidelines [21] and it soon became part of the AFI administered testing methodology. The TM employed ambient air as the test challenge to determine the degree of surface smudging or discoloration (ergo… Dust Spot Test/DST) averted with improved filtration. The NBS Atmospheric Dust Spot Discoloration TM was later adopted and incorporated into ASHRAE 52 in 1976. Its data product and rating system, such as ASHRAE 55%, 75%, 85%, and 95% classes of filter, was then incorporated into the ARI 680 [17] test and rating standard which prevailed for the balance of the century.

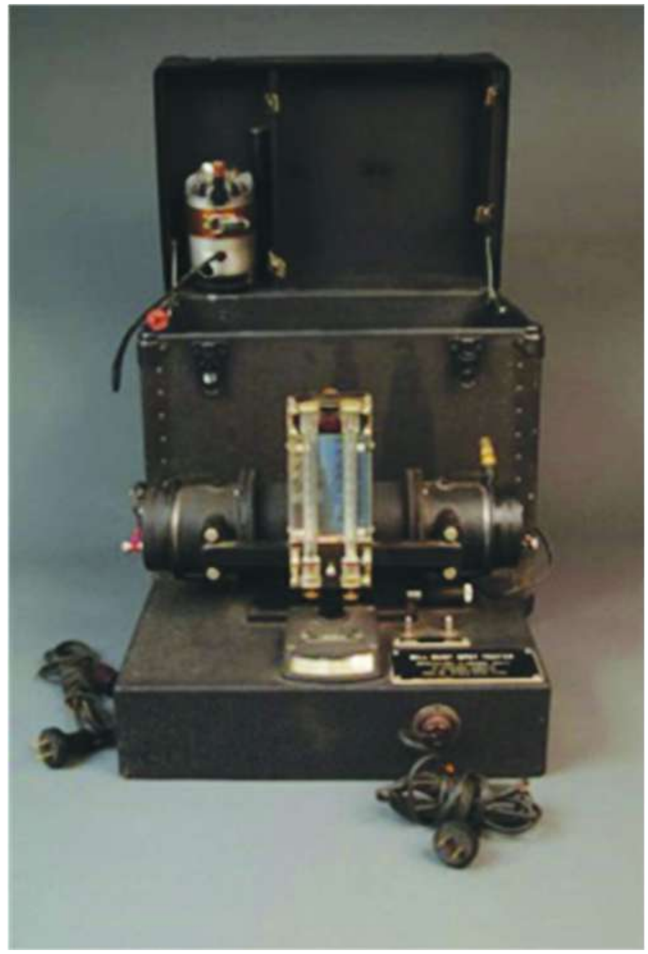

Figure 11 *NBS dust spot discoloration testing apparatus (Source: NIST archives).*

ASHRAE TC 2.4 (Technical Committee responsible for particulate filtration technology) recognized the obsolescence and measuring flaws of the NBS based ASHRAE 52 TM and an SPC (Standard Project Committee) was organized in 1987 to create an updated test method, 52.2. However, it disbanded because of the need for further research. Thus, an ASHRAE Research Project (RP-671 [22]) was authorized in 1991 for the development of recommendations and criterion for obtaining particle size efficiency data, which was fulfilled and accepted in 1993. TC 2.4 then reactivated the SSP 52.2 to incorporate the RP-671 recommendations into a new standard which was

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published in 1999. The new standard resolved a number of flaws in the previous standard and incorporated the newly developed recommendations of the RP including:

a. A new test duct design that resolved the issues of test challenge particle generation and dust loading; controls and criteria for test-air cleansing, humidity, and conditioning; concurrent upstream/downstream air testing protocol; exhaust effluent control; and staged construction for ease of cleaning and test filter installation and sealing;
b. Rigorous quality control measures;
c. A revised test challenge aerosol (KMnO4) with controlled particle size over 0.3 to 10 micron size fractions;
d. Usage of particle counters capable of data collection and reporting of multiple size bands, consisting of 0.3, 0.5, 1, 3, 5, and 10 microns;
e. Prescribed loading cycles for efficiency data over the entire loading/life cycle of the test filter;
f. Reporting methodology to report minimum efficiency for all the size fraction bands throughout the loading cycle; and
g. A classification system that enabled a short cut to the efficiency ranking of classes of tested filters on the basis of increased efficiency at smaller size bands, called Minimum Efficiency Reporting Value (MERV)

The impact of the development and publication of Standard 52.2 was significant and widespread on the Filtration portion of FAC, such as:

a. Although not published until 1999 the text was developed and committee consensus attained much earlier than final Society public review and consensus; thus the MERV classification was already incorporated into the Standard 62.1 and 62.2 versions concurrent to the 52.2-1999 publication timing;
b. Anticipating the successful publication, most filter manufacturers were developing test ducts; publishing early data results, revising product labeling, and performing product line revisions or additions to respond to the new MERV class designations.
c. The publication of 52.2 brought the Filtration industry into the new millennium with hard science and more reliable test performance data reinforcing the reliability of their product performance claims.
d. The design and building management community gained from the 52.2 fractional efficiency data more reliable information on the performance of filtration products for the control of contaminants of concern having known particle sizes, such as bacteria, pollen, and mold spores.

9/11! THE "MILESTONE" OR THE "TOMBSTONE" OF THE NEW MILLENNIUM

Where were you on 9/11/2001? If you were alive then (yes, it occurred almost two decades ago), you will remember where you were when you watched the Trade Towers collapse. Terrorism took the stage and spread fear, grief, and anger across the country. The scenes of the trenches of France filled with green gas and school children huddled under their school desks re-emerged to remind us of war gas and nuclear bombs. A new term emerged—"WMD" meaning weapons of mass destruction. Committees were formed; conferences were held; buildings were surveyed; mail was X-rayed, and safe zones were defined. CBR (chemical, biological, radiation) became the buzzword. ASHRAE responded with a high level Presidential Committees and special task groups to develop guidance for "hardening" HVAC systems. From an overall perspective however, the passion cooled after several years leaving little lasting impact on the general building population. A few high profile government buildings were hardened with special CBR filtration and air cleaning equipment. Further, Embassy facilities located outside the USA were retrofitted with FAC wherever possible and new standardized designs using FAC and clean room criteria were developed by the Dept. of State for new facility construction.

Figure 12 *Typical HEGA employed in CBR control (Source: IAQ Guide, Figure 7.5.F).*

The impact on the FAC industry followed this pattern:

a. The 9/11 event, and the frenzy that immediately followed, renewed the awareness of building owners and the business community of the essential role of high end filtration and air cleaning in the protection and even survivability of occupants from terrorist, criminal. or accident provoked events;
b. A sprinkling of high profile government buildings were retrofitted with high end FAC;

c. Likewise, a sprinkling of private sector buildings were hardened using FAC; and
d. FAC was included in ASHRAE response guidance documents, such as ASHRAE Guideline 29 [23] along with those of other related stakeholder associations and trade groups.

THE TM COMPANIONS MAKE THEIR STAGE DEBUT: ASHRAE TM 145.1 AND 145.2 ARE ACHIEVED!

The gas phase or "molecular" air cleaning (AC) and particulate filtration (F) are together in the Filtration and Air Cleaning duo for a number of reasons—they are applied to the same air flow; located in the same air handler/air stream to treat airborne "baddies"; generally are made by and/or marketed by the same supplier/distributor; serviced by the same maintenance personnel; and usually end up in the same dumpster at the end of their life cycle. But when it comes to the way they "capture" and control contaminants and the way they must be tested because of that… puts them in an entirely different category! Particles have one significant variable—size. Chemical compounds have dozens of variables but worse, each compound is unique. They can vary by molecular weights, polarity, pH, and even odor, as examples. These factors can affect whether they can even be controlled by adsorptive devices; they depend greatly on the properties of the sorbent; and are even dependent on the condition and constituents of the air stream, including other compounds, moisture, and temperature. This partially explains why the development of the TMs took decades. Their development was significantly powered by the requirements of Standard 62.1 and its IAQ Procedure, since the calculations for compliance of the molecular control segment of the procedure require the tested efficiency of the designated molecular filter module. The TM development was further supported by the industry need to employ controlled comparisons between sorbents and suppliers' products to aid in appropriate product selection. Recognizing this need for consistent testing protocols, ASHRAE TC 2.3 (the technical committee for gaseous air contaminant filtration) actively sponsored research projects that culminated in the development of the ASHRAE 145 series of test methods.

Since the performance of a molecular sorbent cartridge is dependent on both the selected sorbent as well as on the specific configuration and features of the cartridge container, the test method was developed in two stages. ASHRAE 145.1 [24] updated the previous ASTM laboratory scale evaluations of sorbents, and 145.2 [25] developed a full scale cartridge test as applied to an HVAC airstream. ASHRAE 145.1 was published in 2008 and addressed apparatus; test air conditions; selected challenge aerosols; and evaluation protocols. TM 145.2 was published in 2011 and exploits the use of the ASHRAE 52.2 test duct which has already been established as to airflow parameters, test conditions, and quality control. The TMs evaluate the single pass efficiency and related dwell time, as well as performance features of air cleaning products against selected test gas control challenges under prescribed laboratory conditions to enable comparative evaluation of both sorbents and their containment devices.

The impact of these TMs on FAC is important because:

a. 145.1 provides a third party industry consensus TM that has been needed for decades to evaluate, compare, and develop effective sorbents for molecular air treatment.
b. 145.2 provides data on filter cartridge removal/control performance under controlled conditions that fulfills and supports the requirements of the Standard 62 1 IAQP to enable wider application of this compliance pathway to assist building owners to apply energy management and sustainability to their buildings.
c. These TMs assist the FAC suppliers to apply quality control to their products and to also assist in product improvement and development through comparative performance testing.

THE FINALE! ALL PLAYERS ON STAGE FOR THEIR BOW AND THE NEXT SEQUEL

The key events and creativity of the last century have matured the FAC industry and the stage is set for the next sequel. This will be the launch into the balance of the 21st Century, which will bring on-stage new challenges and new opportunities. The FAC industry has the products, the players, and the technologies to face these challenges that include:

a. Sustainability, as the construction industry responds to the impact of buildings on the environment as well as the impact of the environment on buildings;
b. Net Zero energy demands that require designers and owners to deal with advanced techniques for treating buildings with cost/effective environmental conditioning tactics, including the full exploitation of Standard 62.1 and the Indoor Air Quality Procedure to reduce the energy load of treating outdoor ventilation air;
c. Occupant health and safety and the challenge of renewed focus in the areas of protection from environmental pollutants, criminal or accidental exposures to toxic contaminants, and airborne microbial and/or pandemic exposures;
d. Emerging or new technologies that pose the challenges of testing and appropriate application for contaminant control, and includes products involving energetics, UVGI, ionization, and photo-catalysis;
e. The space adventure that will require new levels of contaminant control in the artificially sustained environments;
f. Existing inventory of millions of buildings and homes present the opportunity of upgrades to bring their built environment forward into the 21st Century. There are many buildings across the USA, as well as in both the developed and undeveloped nations of the world, that due to circumstances of age, economics, or technical feasibility have not taken full advantage of the advances of FAC technologies. This opportunity awaits because the role of

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clean air and the related technologies for sustaining cleanliness can positively impact the human destiny wherever in the world, regardless of the status and realities of location and economic development

(Music up and out: curtain closes on the first hundred years of FAC history)

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