

SOME NOTES ON THE OPERATION OF THE XCAPER™ SMOKE FILTER AND HOW IT COMPARES TO OTHER AIR PURIFYING FILTERS OF DIFFERING CONSTRUCTION

The Xcaper™ Smoke Mask works by trapping gaseous and particulate contaminants (often referred to as aerosols by smoke researchers) within a filtering medium similar to the "packed bed" filters commonly used in the chemical processing industry. Many such so-called mechanical filters, which do not rely on chemically reactive or catalytic components, are in widespread use in hazardous chemical and industrial environments; their efficiencies can approach 100%. They are often used to purify air by filtering out not only dusts and mists but also organic and acid gases such as carbon monoxide, carbon dioxide, hydrogen chloride, and many others. Many varieties of mechanical filter type purifying masks are available through industrial and laboratory safety supply houses. Several have been tested and investigated by NIOSH and other organizations for both filtering efficiency and tightness of fit. Vendors who market such personal respiratory devices through established industrial safety supply outlets publish performance data that suggests that these masks can be very effective filtering devices, indeed, when used within their prescribed limits.

Claims have been made that higher filtering efficiencies can often be achieved with "chemical" filters, those that rely on transformation of harmful contaminants by involving them in a chemical reaction as they pass through the filter medium. The reaction changes the chemical nature of the contaminant to something harmless (usually a relatively inert solid which remains trapped within the filter). This type of filter, however, must be chosen for a specific toxic species or a very limited range of species, as the reaction mechanism is tailored to a particular type of substance.

Since smoke from fires is a complex mix of particles, liquid droplets, gases, and sticky agglomerated mixtures of all three, chemically reactive filtering media, regardless of sophistication, cannot be expected to provide sufficient protection for all of the products of combustion which may be a threat to life-safety. As reactive media fill up with trapped particulates and the residues of reacted products, they become markedly less efficient. Breathing through them also becomes more difficult as the partially blocked air passageways produce a large pressure drop, which the wearer must overcome by breathing through the filter with more force. Chemically reactive filters also generate considerable heat through the chemical reaction mechanism, causing the breathable air to become in many cases too hot. The purported advantages of high capture and retention efficiencies of such filters, therefore, would not be borne out in most real fire situations.

Unlike chemical filters, the Xcaper™ filter can act effectively on a wide range of substances and actually become more efficient with use, as the trapped contaminants act to further obstruct the path of newly entering contaminants. The air passageways remain relatively free of obstruction since the filter acts primarily by adsorbing contaminants onto electrochemically active surfaces of otherwise inert filter material. No additional reaction products are created, and the adsorbed material is effectively removed from further interference with the passing stream. Adsorption continues even with particulate build-up because the micro scale electrochemical activity continues unabated. The growing quantity of adsorbed material acts only to further slow the passage of the coagulation aerosols, providing more "residence" time for the capture to take place. The filter, thus, becomes more efficient over time. Saturation will be approached but only very slowly and, as field tests have shown, the time to saturation is much greater than the time of anticipated use.

EXAMINATION OF THE POSSIBLE MICROSCALE PHYSICAL/CHEMICAL MECHANISMS RESPONSIBLE FOR THE OBSERVED PERFORMANCE OF THE XCAPER™ SMOKE FILTER

The Xcaper™ filter is a new type of smoke filtering device claiming a very high level of efficiency in filtering out the toxins and particulate products of combustion from common fires. A professional fire protection device called WHIFFS™, Wilfire Hazardous Inhalation Firefighters' Filtration System, holds an Xcaper™ filter in a protective Nomex™ shroud that is worn over the nose and mouth and allows the wearer to breathe normally, maintain a clear line of vision, and keep both hands free.

The Xcaper™ filter has undergone rigorous laboratory testing through an independent laboratory and it has also been informally field tested under a variety of conditions. Since the filter eliminates a significant percentage of the gas phase products of combustion, a question arises as to how the observed effectiveness of the filter in preventing toxic substance build-up in the body for extended periods of up to 4 hours or more can be explained. The purpose of this paper is to identify several possible physical and chemical mechanisms by which the filter's performance may be explained and is the result of extensive discussions with individuals highly educated in fire science.

The functional aspects of the filtering process are complex. They are dependent on details of the filter's construction as well as on the physical and environmental conditions of use. Among the most readily identifiable mechanisms are the following:

(1) As a rather densely packed collection of small plastic beads in a contained natural gel bath, the filter behaves most fundamentally as a simple physical absorption device, utilizing a large enclosed volume for 'storage' of breath-entrained combustion particulate matter.

(2) The active thickness of the filter offers substantial interference with the path of smoke particulates drawn in through the normal breathing process. Given the internal packing structure of fine beads and relatively small void fraction it is clear, even without quantification of the effect, that the mean travel distance (mean path length) of a smoke particle from outer to inner surface of the filter would be several times the direct linear thickness of the filter. As interstitial spaces (between the beads) fill with trapped particulates, mean path lengths would increase far more, delaying arrival of particulates at the inner surface.

(3) Over the course of active travel of combustion particulates, well known "aging" effects alter both their character and behavior. This widely observed phenomenon, generally termed coagulation, describes the agglomeration and coalescing behavior of gaseous, liquid, small solid and aerosol products into much larger masses whose number and size vary in a complex manner with both time and ambient temperature. Coagulation traps large numbers of toxic gas molecules within the clotted mass, the effect being enhanced by longer residence times and cooler temperatures.

(4) The physical structure of a smoke particulate may be thought of as characterized by a large surface area and a variable surface electric charge resulting from the polar structures of its constituent molecules. Polar charges of the far smaller molecules of the remaining free gaseous combustion products will eventually cause electrochemical adsorption of the gases onto the surfaces of the particulates. Due to the very large-scale difference between a gas molecule and even the smallest of particulates, it is likely that thousands of gas molecules can adhere to the surface of a single particulate given sufficient residence time for adsorption to occur.

(5) Most common gases, especially those typically found as combustion by-products, are soluble in water and other solvents and natural gels. Free gases not yet trapped by aerosol formation or by adsorption/coagulation processes are subject to secondary entrapment through dissociation in a solvent gel.

Still other mechanisms may be of importance, particularly as they affect the movement of ionic or surface charged species through the filter. Among these are electrolytic solution tension effects (i.e., Helmholtz double layer effects), electrophoretic effects, and potential equilibrium altering gas-solvent reactions. Such "secondary" mechanisms could be considered insignificant, but the exceedingly long reaction residence times characteristic of this type of filter may lead to enhanced effects which would not normally be expected.

SUMMARY

In view of the major roles played by such processes as adsorption, aerosol formation and coagulation in typical fire and smoke aging processes, it is likely that these mechanisms, along with the added effects of absorption, interference and solvent-induced dissociation, are also important in accounting for the observed performance of the Xcaper™ filter. It is also possible that other mechanisms related to microscale details of the electrochemical environment within the filter can be identified as possible contributors.

DETAILED FILTER MECHANICS

1. The detailed testing environment of the 4 hour CO test and the 37 minute test against b Hydrogen Cyanide:

The test chamber used in the Xcaper smoke mask testing was designed to replicate human respiration. Laboratory gases were provided by a company that certified the concentration of the gases, and the gas concentrations were verified by the independent lab that performed the tests prior to testing. During the test, gas concentrations were measured continuously both before and after the air stream passed through the Xcaper filter. The carbon monoxide concentration used in the four hour test was 54.5 parts per million with a 95.1% filtration rate. In a 30 minute test at 1200 parts per million the filtration rate was 94.4%. The 30 minute test is a more accurate measure of Xcaper's performance as an escape mask. The hydrogen cyanide gas concentration used in each of the tests was 20 parts per million and the filter absorbed 100% in all tests.

The test chamber was a rectangular box in which a model of a human head was mounted. Inhalation and exhalation were accomplished through the mouth of the model head by separate tubes. The Xcaper smoke mask was placed on the model head and the challenge gas was passed through the mask at a volume of 1 liter per inhalation and a rate of 40 respirations per minute. The volumetric rate of inhalation was 40 liters per minute and the temperature of the inhalant was 20 to 25 degrees centigrade (room temperature). Between inhalations, air was exhaled back through the mask from a carbon dioxide incubator. The exhalant contained water vapor, carbon dioxide, and air in a ratio and volume equivalent to that found in actual human exhalant and were maintained at 37 degrees centigrade.

Here it is worth noting that the gel used in the mask has an increased pH (a small amount of base is added to the gel to provide the mask with a higher alkalinity to neutralize acidic gases such as hydrogen cyanide and hydrogen chloride). Both carbon dioxide and carbon monoxide are highly soluble in basic aqueous solutions (the gel is 98% water and is used in hospitals to rehydrate the lungs of burn victims). When absorbed by the mask, the human exhalant of the wearer actually works with the mask to provide two benefits. The moisture of the exhalant helps to keep the mask moist, extending it's useful life, and the carbon dioxide that is absorbed establishes a buffer solution in the gel that maintains the slightly basic pH, further enhancing its capacity to neutralize acidic gases such as hydrogen cyanide.

Nine hydrogen cyanide tests were performed. Each was scheduled to be 30 minutes in length. The last test was extended by seven minutes to exhaust the remaining hydrogen cyanide gas in the test cylinder. The Xcaper mask has not yet been tested for hydrogen cyanide beyond 37 minutes, but is believed to provide protection well beyond the current test limit. The amount of acidic hydrogen cyanide gas that can be neutralized by the basic gel should be quite high because one hydroxide ion neutralizes one molecule of hydrogen cyanide and the buffer solution created by the absorption of carbon dioxide provides additional capacity. The number of hydroxide ions in the gel is millions of times greater than the number of hydrogen cyanide molecules a wearer may expect to encounter. Despite this, the manufacturer has stated that they will not recommend that the mask be used beyond 30 minutes for escape applications because they do not want wearers to believe that they can risk remaining in a hazardous environment to gather non-essential items before escaping.

2. Does black smoke clog the filter?

No, the mask has never clogged from black smoke. Hundreds of firefighters fighting wildfires and forest fires have worn the mask for eight to twelve hours in heavy smoke without experiencing any degradation in performance. It should be noted here that the manufacturer recommends that

firefighters replace their filters every four hours because performance test data has only been collected for up to four hours. Firefighters, however, continue to push the mask beyond this recommended limit and testify that the mask continues to perform very well over extended periods of time. See the answer to question 4 to understand how the mechanism by which the mask works prevents clogging.

3. The detailed description of the usage of mask by the firefighters:

The professional version of the Xcaper mask worn by firemen is a filter that is inserted into an advanced Nomex shroud or a Carbon-X Bandana. The advanced Nomex shroud and Carbon-X Bandana, which are also produced by Xcaper, provide heat resistant protection against direct contact by flames and radiant heat. The filter inside these shrouds differs from the Civilian Smoke Mask only in that it does not have straps allowing it to be worn independently.

The Xcaper professional mask is not intended to replace a self-contained breathing apparatus. It is recommended for use by firefighters only in applications where a self-contained breathing apparatus is impractical. The Xcaper mask was originally produced exclusively for use by firemen fighting wildfires and forest fires. These fires often become raging infernos that burn millions of acres of land on a seasonal basis in the U.S. Firemen fighting these fires often work 8 to 12 hour shifts for several days at a time throughout the fire season. Self-contained breathing apparatus are impractical when fighting these fires because they only last for short periods of time, are cumbersome, and heavy. Firemen fighting a wildfire or forest fire often are required to run for their lives, because of sudden wind shifts that can carry a wall of flame toward them at speeds over 30 kilometers per hour. The Xcaper mask was designed to provide protection, be light-weight, easy to wear, and easy to carry.

Once they had acquired the mask, however, firemen began to use the mask in situations for which it was not originally recommended by the manufacturer. The first of these was during the overhaul phase after a structural fire had been extinguished. During structural overhaul firemen were able to perform physically demanding cleanup work in the burned building without having to carry a self-contained breathing apparatus on their backs and without having to stop every 30 minutes to obtain a full air tank. Firemen also began to carry Xcaper masks during structural fires to provide emergency protection in case their self-contained breathing apparatus failed. In one case in Indianapolis, a firefighter was trapped in a structural collapse during a warehouse fire. Pinned down by debris, and separated from other firemen, who could not immediately find him; his self-contained breathing apparatus ran out of air. Forty-five minutes later the fireman was located. He was still alive and had no respiratory injuries because he had used an Xcaper mask after his self-contained breathing apparatus failed. Over 45,000 firemen are now using the Xcaper mask and many of them carry it as backup protection. Some fire departments are also considering having each fireman carry five Xcaper Civilian Smoke masks for people they may encounter who are trying to escape the fire, or who require rescue assistance. In the six years that the Xcaper mask has been on the market, they have never received a complaint about its performance from a fireman who has used the mask, and many firemen have provided high approval of the product.

With regard to the Xcaper mask's performance in extreme heat, the following information is known. The advanced Nomex shroud provides protection from heat up to 565 degrees centigrade. The bag used for the filter can withstand direct flame for 36 seconds before catching on fire (this is without the gel in it, a filter with the water-based gel in it should last longer). The polymer beads used inside the bag do not emit any gases until they reach a temperature above 429 degrees centigrade. The professional mask has also been worn in fire training towers. During a two hour training exercise wearers of the Xcaper mask have been able to spend the full two hours in the smoke chamber while firemen were forced to leave the chamber to replenish their self-contained breathing apparatus every 30 minutes. The professional mask with advanced Nomex shroud has also been worn in the flame chamber at temperatures in excess of 138 degrees Centigrade for up to 15 minutes. After 15 minutes the wearer stated that he was forced

to leave because his body was becoming too hot underneath his protective clothing. The wearer was not forced to leave because of any difficulty or discomfort breathing through the mask. The civilian smoke mask has also been worn in the same chamber at temperatures above 138 degrees Centigrade with flames within 30.5 centimeters of the mask for up to five minutes. The assumption that the water in the mask would produce steam that would scald the wearer's lungs is incorrect. In both cases when the Xcaper was worn in 138 degree centigrade heat, wearers reported that the moist filter mask cooled the air they were breathing. They reported that the air they inhaled was warm and humid, but not uncomfortable. This is consistent with the specific heats of both air and water. For every degree centigrade that a gram of water increases in temperature, a gram of air is cooled by 4.186 degrees. Since a gram of water occupies one milliliter and a gram of air at 138 degrees centigrade occupies 4.285 liters, this means that one milliliter of water will increase in temperature by one degree as it cools 17.9 liters of air at 138 degrees centigrade by one degree. The Aloe Vera in the gel also increases the temperature required for the water in the gel to vaporize. The Xcaper mask does not have a limitless capacity to cool extremely hot air, but it will protect a wearer's lungs longer than clothing will protect the rest of the wearer's body and it is important to remember that the mask is to be used for escape purposes and not for people to linger in a hazardous environment. It is also worth restating here that the gel used in the Xcaper mask is the same gel that is used to treat the lungs of burn victims in hospitals. In this procedure, a steam is produced from the gel and inhaled by the patient. This therapeutic steam is the same humid air that an Xcaper mask user would inhale under circumstances involving extreme heat and would provide a benefit to the wearer. Finally, the mask has been worn by numerous firemen caught in flashover situations while fighting forest fires and wildfires. During a flashover, when a firefighter is forced to shelter while a fire burns over and past him, the temperatures exceed 150 degrees Centigrade.

4. Mechanism of the wet-type mask against the protection of human being's airway.

The Xcaper mask protects the wearer from particulates by one mechanism and from gases by a different mechanism.

In the case of particulates, the mask stopped 100% of 0.3 micron sized latex particles for four straight hours. The average number of particles during this test was 25,700 particles per cubic centimeter, and the volumetric flow rate was 40 liters per minute. The professional mask and the Civilian Smoke mask each stopped 246,720,000,000 particles over the course of the test. The mask does this by a very simple means. A particle entering the mask comes into contact with the water-based gel and is wetted, effectively increasing both its size and weight. The wet particle is immersed in the gel coating the polymer beads and cannot be lifted back into the air stream because of the surface tension between itself and the gel. Since biological particulates have a high affinity for water, the Xcaper mask will certainly be effective against them. Other particulates that are prone to wetting include smoke particulates, radiological fallout, and dust from debris that may be encountered during building collapse or earthquake. The Xcaper mask will be equally effective against these.

In the case of water soluble gases, the gases simply dissolve into the gel. The dissolution of acidic gases is enhanced by the gel's slightly basic pH, and gases such as hydrogen cyanide and hydrogen chloride ionize once dissolved.

One further advantage of the mask's design is that the beads and gel can easily move around within the filter. This prevents the formation of saturated channels through the mask along which air can pass without being filtered. Channels often form in activated charcoal and fiber filter masks where the charcoal or fibers have become saturated with contaminant. When an activated charcoal or fiber filter mask develops a saturated channel, it becomes useless. This does not happen with the Xcaper mask.

5. Xcaper Smoke Mask compared to other filter masks:

Comparing the Xcaper mask's capability to absorb hydrogen cyanide to that of activated charcoal masks, there is no doubt that the Xcaper mask is the better performer. Untreated, activated charcoal is highly susceptible to hydrogen cyanide. Older military masks are defeated by hydrogen cyanide in less than ten minutes. New types of activated charcoal that have reactive coatings or metal doping work better at absorbing hydrogen cyanide, but masks using them are generally more expensive.

Most masks perform well when tested under laboratory conditions. In a laboratory, tests can be conducted and maintained under ideal conditions. Often mask manufacturers design their masks specifically to pass the idealized test itself, with less regard for the actual conditions under which their product will be used in an emergency. In a real emergency, however, conditions are never ideal. The Xcaper mask is superior to masks such as the Guardee mask and the EVAC-U8 mask because it does not use an expendable catalyst such as hopcalite. Hopcalite catalysts are rapidly expended and produce heat as they convert carbon monoxide to carbon dioxide, forcing the wearer to inhale air heated by as much as an additional 10 degrees centigrade. By contrast, the gel in the Xcaper mask absorbs the carbon dioxide rather than being consumed by it. Air passed through the Xcaper mask is also cooled instead of being heated. Masks that rely on activated charcoal, fiber filters, and powdered catalysts such as hopcalite rapidly degrade in performance when they are subjected to moisture from humidity, building sprinklers, broken pipes, human exhalant, or the humid black smoke. It clumps together, reducing its effective surface area and capacity of the catalyst. The Xcaper Civilian Smoke Mask, however, is different. The Xcaper smoke mask is not susceptible to degradation by moisture or humid black smoke, but instead uses moisture as a filtration mechanism to great effect. It is the same filter that is currently in use by over 45,000 firefighters in the U.S. Not only has the Xcaper filter performed well in testing, but it already has over one million hours of successful use in wildfires, forest fires, structural overhaul, and other fire-related emergencies. Among the firefighters and others who have used the Xcaper filter, there has never been a single death or respiratory injury. No other escape filter or escape mask on the market can make this claim.