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SPACECRAFT CABIN AIR QUALITY CONTROL AND ITS APPLICATION TO TIGHT BUILDINGS

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Abstract

Air quality is an important consideration not only for the external environment, but also for the indoor environment. Most people spend a majority of their lives indoors and the air that they breathe is important to their physical and emotional well being. Since most modern building designs have focused on energy efficiency, less fresh air is brought from the outside. As a result, pollutants from building materials, furniture, cleaning, and cooking have no place to go. To make matters worse, most ventilation systems do not include any means for removing pollutants from the recycled air. Unfortunately, pollution at even a small level can result in eye, throat, and lung irritation in addition to chronic headaches, nausea, and fatigue. A spacecraft cabin, which represents the worst case in tight building design, requires special consideration of air quality since any effects pollutants may have on a crewmember can potentially place a mission or other crewmembers at risk. A detailed approach has been developed by the National Aeronautics and Space Administration (NASA) to minimize cabin atmosphere pollution and provide the crew with an environment which is as free of pollutants as possible. This approach is a combination of passive and active contamination control concepts involving the evaluation and selection of materials to be used onboard the spacecraft, the establishment of air quality standards to ensure crew health, and the use of active control means onboard the spacecraft to further ensure an acceptable atmosphere. This approach has allowed NASA to prevent illness by providing crewmembers with a cabin atmosphere which contains pollutant concentrations up to 100 times lower than those specified for terrestrial indoor environments. Standard building construction, however, does not take into account the potentially harmful effects of materials used in the construction process on the health of future occupants and relies primarily on remedial rather than preventative techniques when addressing contamination. This approach results in a building that theoretically has low operating costs, but may actually have high costs associated with lost work days, increased medical claims, decreased productivity, and problem remediation. A similar approach to NASA's may be adopted by the building construction community which can tap the extensive database of material offgassing properties that has been collected to support the space program. Many materials used by NASA are commercially available and are frequently used in building construction. In addition, computer models which have been developed for assessing various methods of active contamination control can be applied to building ventilation system design and the analysis of their economics. Through using NASA's experience, the expense associated with the current remedial approach can be avoided.

Introduction

Air quality is an important consideration not only for the outdoor environment, but also for the indoor environment. Most people spend a majority of their lives indoors and the air that they breathe is important to their physical and emotional well being. Pollution at even a small level can result in eye, throat, and lung irritation in addition to causing chronic headaches, nausea, and fatigue. As the trend in modern building design continues toward more energy efficient buildings with minimal air exchange with the outdoors, the similarities between them and spacecraft cabins have become more striking.

A spacecraft cabin, which has been recognized as the ultimate in tight building design, requires special attention to air quality since any effects pollutants may have on a crewmember can potentially place a mission or fellow crewmembers at risk.[1] Characteristics of a spacecraft which contribute to the tight building analogy by exacerbating the problem of trace atmospheric contamination are the small amount of leakage from and atmosphere makeup to the cabin, the small volume combined with a relatively large number of people, and the multitude of materials of construction used. Since the spacecraft must utilize lightweight components, a high percentage of nonmetallic materials are used. While these materials provide economically viable design solutions, they present the unique problem of increased trace contaminant generation from offgassing. Combined with the small volume and large crew-to-volume ratios, a very small amount of contamination can cause problems which may threaten the physical and emotional well being of the crewmembers.

Since it is not practical to provide large amounts of makeup atmosphere, much of the atmosphere if circulated through an atmospheric revitalization system (ARS), which is part of the environmental control and life support system (ECLSS) of the spacecraft, to provide active control of trace chemical contaminants and carbon dioxide. In order to minimize the weight, power, and volume resources required by the ARS, a passive control approach employing strict material selection and control guidelines is used to achieve the most effective system from both the performance and life cycle economics standpoint.

Standard building construction has many similarities to spacecraft cabins. As energy efficiency and life cycle economics have become more important, buildings have been designed to minimize leakage and recycle a larger percentage of the indoor air. Likewise, an increased reliance on nonmetallic materials of construction has been experienced, especially in the use of carpeting and synthetic upholstery for furniture. Also, more people are being squeezed into much smaller buildings to help maximize company profits. The driving factors of energy efficiency, life cycle economics, and rate of return on investment are very similar to the factors driving the design of a spacecraft. However, one major exception is the small amount of attention given to the health and well being of the occupants.

Contributing Factors to Sick Building Syndrome

Sick building syndrome (SBS) is frequently associated with office buildings and it has been defined by the World Health Organization as frequent complaints by building occupants of specific symptoms. These symptoms may include one or more of the following:[2]

1. Nasal and eye irritation
2. Dry mucous membranes
3. Fever, joint and muscle pain
4. Lethargy
5. Nose bleeds
6. Dry skin, skin rash, and headache

Symptoms tend to subside after exposure to the irritants ends, such as during the weekend or overnight, but return rapidly and grow worse during subsequent exposures.[3]

The problem is not limited to office buildings and can actually be worse in residential buildings. An example is the case of a Limerick Nuclear Power Station worker who set off the radiation alarms at the plant even before the plant was activated. The worker's clothing was tested and the radiation source was determined to be from a source other than the plant. The worker's home was tested and a radon buildup producing a radiation level of 3,200 pCi/l was found. This level is 800 times higher than the 4 pCi/l set by the U.S. Environmental Protection Agency.[4] In this case, the home was found to have a higher health risk than the workplace.

Many contributing events since World War II have had a part in either contributing to or focusing attention on SBS. Five of the most important events are the following:

1. Use of synthetic building materials during the housing boom just after World War II
2. The energy crisis of the early 1970s which lead to changes in building insulation and ventilation practices
3. The addition of new office technologies such as computers, printers, and copying machines to the office and home environment without consideration for proper ventilation requirements
4. Advances in capabilities to detect increasingly lower levels of chemical and biological agents in the environment
5. The shift toward indoor jobs which has lead people to spend a majority of their time indoors.

All of these factors have lead to the increasing prevalence of SBS. By far, the shift toward more indoor activity over outdoor activity combined with less fresh makeup air from the outside has had a profound effect on the incidence of SBS. Furthermore, the most susceptible people, the very young and the elderly, tend to spend almost all of their time indoors.[5]

Numerous studies of SBS have resulted in just as many hypotheses for its causes. They range from poor ventilation to multiple chemical sensitization. In many cases, the exact source of the symptoms could be determined, such as formaldehyde from insulating materials or chemicals released by activities within a building that are incidental to work being conducted. A study of 4,373 workers in the United Kingdom investigated the correlation between SBS symptoms and the type of building ventilation. This study concluded that naturally and mechanically ventilated buildings had the least prevalence of reported SBS symptoms among workers. Workers in buildings in which the air was chilled in addition to heated were found to have a higher incidence of reported symptoms.[6] This study indicates that microbial and fungal sources of contamination in air conditioning systems may be a major contributing factor in SBS beyond chemical sensitization. This conclusion is further supported by recent findings that additional ventilation with fresh outside air does not reduce the incidence of SBS symptoms in air conditioned buildings.[7,8] Fresh air makeup in this study was still below 40 percent, however. It is most likely that SBS results from a combination of chemical-, microbial-, and fungal-induced sources. Specific attention will be given to chemical contamination control which tends to be more pervasive and difficult to track to any singe source.

Other factors which may contribute include the age and gender of an individual. Studies have found that women have typically shown more symptoms than men. Also, people under 21 and over 40 years of age are less likely to suffer from SBS symptoms.[9]

Air Quality Control Background

Spacecraft Experience

Careful consideration is given to contamination during all phases of the design, manufacturing, and operation of a spacecraft. Since the crewmembers are exposed continuously to chemical contaminants in the cabin atmosphere originating from sources ranging from the materials of construction to human metabolism, special consideration is given to minimizing the production rates of most sources. Since it is difficult to control contamination originating from human metabolism, special atmospheric revitalization hardware is used onboard the spacecraft to help control them. This hardware provides for physical adsorption, chemical adsorption, and catalytic oxidation trace chemical contaminants. Particulate contamination is also a concern. A majority of particulate contamination originates from the crewmembers. Their clothing, food, and body continuously produce particles. Efforts are made before flight to select clothing and food, in addition to screening onboard operations, to minimize or eliminate particulate production. Onboard filtration is provided to remove particulates.

Approaches to dealing the atmospheric chemical contamination onboard spacecraft have been developed since the early years of the space program. Not only were contaminants identified during Mercury spacecraft flights but the information served as the basis for identifying methods for dealing with the contamination to ensure that the crew were not adversely effected.[10] Although the Mercury spaceflights lasted from several minutes to hours or days, the need to address contamination for proposed longer duration space missions was identified and early attempts were made to develop integrated approaches to controlling contamination for spacecraft cabins.[11] These early approaches, although simple, included the areas of design; manufacturing; requirement and specification definition; and the identification of contaminants, their generation sources and rates, and control approaches. These early approaches developed for the Mercury, Gemini, Apollo, and nuclear submarine programs along with closed system tests conducted in the mid-1960s have been refined as the space program evolved. Now, specific requirements for material selection, spacecraft systems design, air quality standards, spacecraft hardware manufacturing, and ground processing have been developed for the Shuttle, Spacelab, and International Space Station programs.[12,13,14] Figure 1 illustrates the detail of the process for limiting and controlling trace chemical contaminants onboard spacecraft.[15]

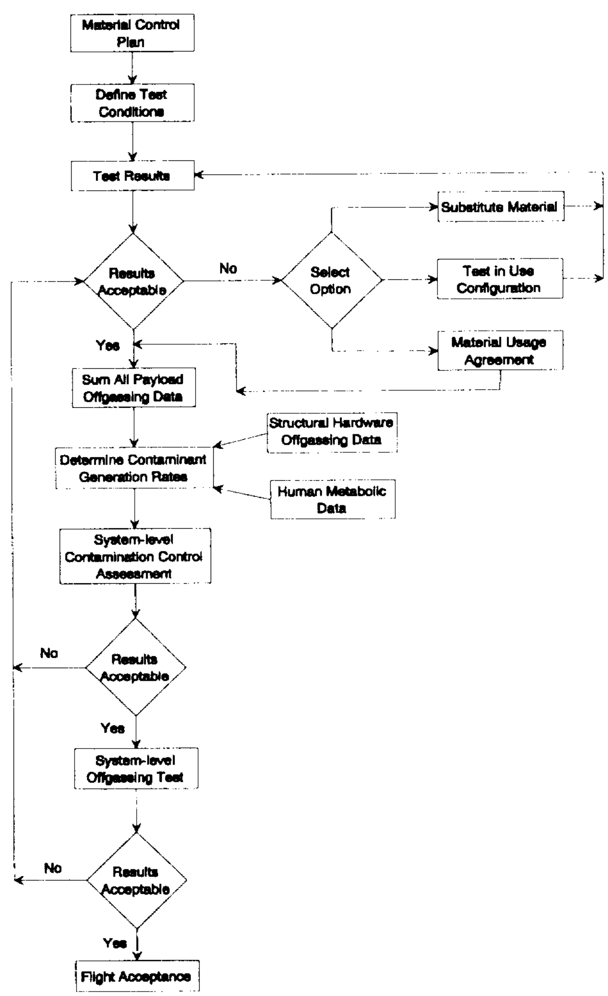

Figure 1. Spacecraft Contamination Control Procedure

The process illustrated by Figure 1 begins with a material control plan. This plan defines the specifications for both metallic and nonmetallic materials to be used onboard a spacecraft. The plan may also include a contamination control and implementation plan which defines the processes for controlling contamination during the development, manufacturing, and flight of the spacecraft. Many materials have already been approved for use onboard spacecraft and their test data are documented in a database. Materials which have not been approved are tested according to test conditions defined in the contamination control plan. If the materials test results are acceptable, the results are used to determine overall generation rates for each trace chemical contaminant. Unacceptable materials must be either replaced or accepted via a waiver of the requirements based upon its use. These rates include sources such as payloads, spacecraft structure, human metabolism, and other sources identified for the particular mission. These rates are used in an analysis of the ability of the onboard active contamination control systems to maintain trace chemical contaminant concentrations below the specified spacecraft maximum allowable concentrations (SMACs). A final system-level offgassing test is performed as a final verification of the overall process.

Building Experience

Terrestrial construction practice usually does not provide for the careful consideration of trace contaminant generation by the completed project nor is it concerned with the effects that these contaminants may have on the occupants. Most building materials are selected based upon their physical properties, durability, ease of manipulation and installation, and cost. In addition, many chemical treatments are used on building materials to increase their resistance to attack by insects, water, and other sources of wear. Beyond the pressures to produce a final product economically, the pressure to have a product which is economical to operate is high. Reduced utility costs are a primary driver in the life cycle economics of the structure regardless of its use. If a building is difficult to heat and cool, chances are no one will wish to purchase it. Not only does this trend toward energy efficiency lead to reduced leakage from a structure but also an increased use of insulating materials which can produce contamination. Also, lower ventilation rates have lead to exposure from contaminants, such as radon, from natural sources.

Approaches to controlling indoor air quality in buildings have not been as well developed as those for spacecraft. Although it is acknowledged that the terrestrial case can more readily benefit by diluting indoor contamination with fresh air, increasing ventilation rates has not been a common practice during the last 20 years. Even in other terrestrial applications, such as commercial aircraft, the trend toward lower fresh air makeup to achieve energy efficiency is quite strong. As recently reported, up to 25% of commercial airline flights experience carbon dioxide levels above the comfort threshold of 1000 ppm set by the American Society of Heating, Refrigerating, and Air-Conditioning Engineers. Older aircraft were less likely to have the problem because cabin air makeup is typically 100% from the outside. Newer aircraft, however, only have a 50% fresh air makeup.[16] Further, no means for removing trace contaminants is provided in the air circulation loop.

Typically, controlling SBS in buildings has been limited to remediation rather than prevention. Approaches to control chemical contamination include exclusion or removal of the source, changes in design, encapsulation of the source, spatial confinement of the source, time limitations on equipment use, dilution via ventilation, and removal by air filtration.[17,18] None of these approaches is concerned with selecting materials and processes which minimize chemical contamination in the first place. The penalty for not addressing these problems during the design and construction process is a higher risk that the occupants may develop symptoms of SBS. In extreme cases, remediation for the problem has taken years and millions of dollars.[19] In some instances, the building has been left empty since it could not be guaranteed that the occupants would not become sick again. Although extreme cases are rare, SBS has been reported in both the United States and Europe and up to 1,200,000 commercial buildings in the United States alone are estimated to have problems which contribute to SBS.[20]

Spacecraft Air Quality Control

Spacecraft cabin air quality control is a comprehensive process as illustrated by Figure 1. Much of it occurs during the design and manufacturing phases of the spacecraft. This passive control helps to minimize the contamination load that will be experienced onboard and thereby reduces the size of active contamination control hardware necessary in the cabin. Together, when combined with a rigorous on-orbit monitoring program, these phases of contamination control provide a crew with high quality air to breathe.

Passive Control

Passive contamination control is concerned with the type and amounts of materials used within the spacecraft cabin. During the design phase, materials are selected according criteria established by NASA to minimize contamination from offgassing and particulate production in addition to fire risk.[21] Based upon the data collected on an individual material, it is given a rating and in many cases a maximum weight limit for its use in the spacecraft cabin. NASA maintains these data in the Materials and Processes Technical Information System (MAPTIS) in an electronic database. While more than 300 users have access to the MAPTIS computer system, it is also available as a hard copy report.[22] Through MAPTIS, information on materials properties, oxygen environment compatibility, test results, and materials and processes verification and control can be accessed. Figure 2 shows the major elements of MAPTIS. For cabin, contamination control, the toxic offgassing data shown as part of the materials database of MAPTIS are the most important. Materials which generate large amounts of trace contaminants via the offgassing route can only be used onboard spacecraft in limited quantities. These data are used during the design, development, test, and verification of space hardware.

In some instances, the preferred material selected for a spacecraft application may not be included in MAPTIS or an off-the-shelf flight article has been selected for use in the cabin. To accommodate these cases, specially designed tests to determine the offgassing characteristics of the material or assembled component are conducted.[23] Upon completing the required tests, the offgassing test data are analyzed and a rating is assigned to the material. This rating may include a weight limitation for use for spacecraft cabins. Similarly, the number of assembled components allowed onboard may be limited. The data obtained from the tests are entered into MAPTIS for future reference.

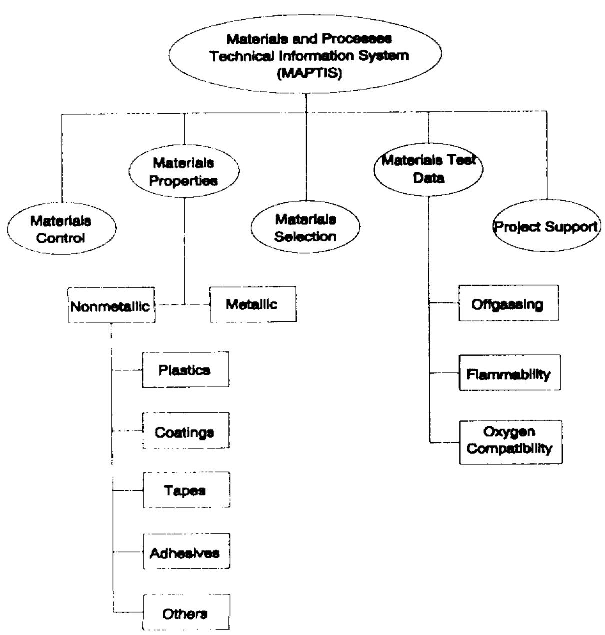

Figure 2. Materials and Processes Technical Information System

As part of the material selection and control program, the materials used for constructing any spacecraft must be reported as part of a materials identification and usage list (MIUL). This list allows NASA to assess whether a spacecraft design is acceptable from a materials standpoint and typically consists of both metallic and nonmetallic material lists. All materials listed in a MIUL must come from the list of materials approved for spacecraft applications. If any material has been selected which is not part of the list of approved materials, a material usage agreement (MUA) must be submitted. The MUA provides detailed descriptions of the material, its properties, and how it will be used onboard the spacecraft. Materials test results may also be included. A material which has been identified with a MUA must be approved by NASA. If it is not, an alternate material must be selected and approved. Both the MIUL and MUAs are included as part of the overall spacecraft design information package to provide material selection and control verification.

A second part of passive control involves the prelaunch assessment of the ability of active contamination control systems onboard the spacecraft to control chemical contaminants to levels well below the spacecraft maximum allowable concentrations (SMACs) set by the NASA Toxicology Group. This assessment involves collecting offgassing test data for the materials and components used onboard the spacecraft, estimating a generation rate for each contaminant, and then conducting a mass balance calculation on the cabin to determine whether the contaminants can be effectively removed.

<u>Active Control</u>

Although great care is taken to limit the offgassing rates within the spacecraft cabin, it is not possible to completely eliminate trace contaminant production. In addition, since people are present, trace chemical contaminants are also produced from a source which is not controlled by the passive means. To provide the final line of control for atmospheric contamination, the spacecraft is provided with active contamination control systems which remove trace chemical contaminants and particulates from the cabin air during normal operations. This control system consists of particulate filters, activated charcoal adsorbers, catalytic beds, and other means necessary for removing contaminants from the air. Hardware design is based upon past experience concerning the types and quantities of materials typically used onboard a spacecraft and MAPTIS offgassing test results. From these data, generation rates for each contaminant are estimated and a contamination control system is designed which most effectively controls contamination levels well below the spacecraft maximum allowable concentrations (SMACs) set by the NASA Toxicology Group.

Prelaunch Verification

Typically, the design of the trace contaminant control system (TCCS) precedes the overall spacecraft system design. For this reason, the TCCS design is an iterative process requiring verification at several points during the spacecraft design. The initial design is based upon generation rates derived from past spacecraft experience. Although this initial estimate of trace contaminant generation is based upon actual spacecraft data obtained by the NASA materials selection and control program, each spacecraft is unique and must ultimately be assessed independently. To accomplish this, the offgassing generation rate data used for the preliminary design is replaced with data from the actual flight vehicle as the material selection and offgassing data become available via the MIULs and MUAs. These data provide for a final estimate of contaminant generation in the spacecraft cabin and they are used to analytically project the concentrations for each contaminant and, therefore, the effectiveness of the TCCS.

Since the effectiveness of trace contaminant removal technologies can change over time, a transient mass balance is conducted on the cabin using the Trace Contaminant Control Simulation Computer Program (TCCS-CP). This program, or earlier versions of it, has been used successfully to evaluate the effectiveness of the Spacelab Transfer Tunnel Scrubber for controlling contaminants generated during Spacelab module missions and also to develop and verify the performance of the TCCS design for the International Space Station Alpha.

The TCCS-CP has the capability to run simulations of single contamination control technologies or combinations of those technologies. Contamination control methods which currently can be simulated include activated charcoal adsorption, high and low temperature catalytic oxidation, water absorption, and lithium hydroxide chemical adsorption. The activated charcoal simulation also includes options for phosphoric acid washed charcoal and chromate-treated charcoal to specifically target contaminants such as ammonia and formaldehyde.

The program, documented by references 24, 25, and 26, is written in FORTRAN and runs on a personal computer. Input and output data from the program are manipulated with commercially-available spreadsheet software. The program not only calculates the removal efficiency of selected trace contaminant removal technologies, but also estimates the cabin concentration at the projected generation rate. Computer code for each removal technology is based upon laboratory experimental results. Figure 3 shows an overall flow diagram of the calculations. Results of this prelaunch assessment is used during the final vehicle flight readiness reviews and are documented by references 27 through 32.

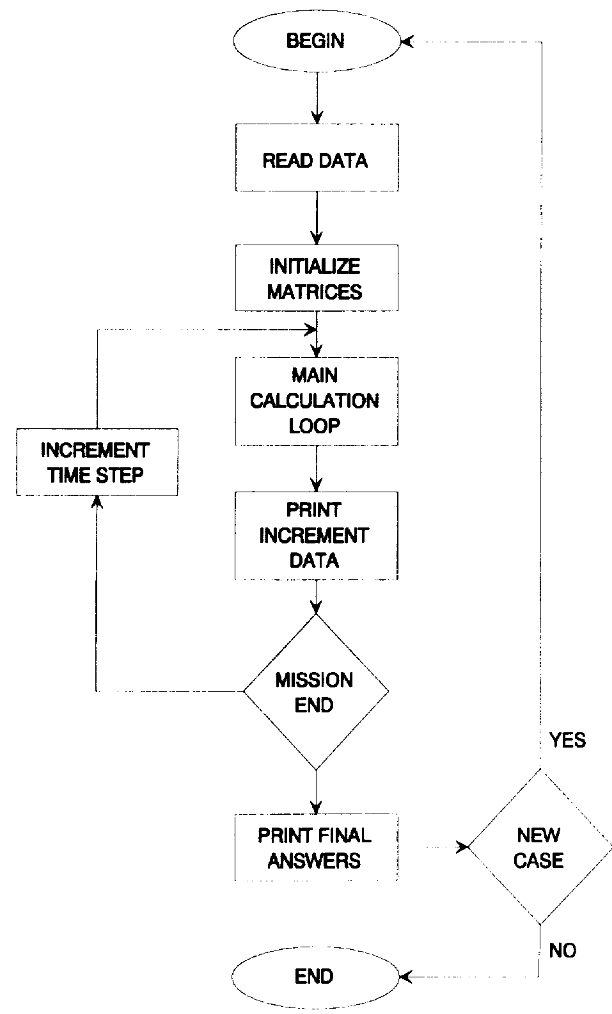

Figure 3. Simplified Computer Program Flow Diagram

On-orbit Verification

Final verification of the acceptability of the cabin atmosphere occurs during the mission. On Shuttle and Spacelab module mission, samples of the cabin atmosphere are taken periodically during the mission using evacuated sample bottles and adsorbent traps. These samples are returned to NASA for analysis at the conclusion of the mission. Specific trace contaminants in the samples are identified and their cabin concentration determined. NASA toxicologists then review the results with respect to the overall acceptability of the atmosphere.

Applications To Building Construction

Controlling contamination in spacecraft cabins, office buildings, and residential buildings is central to providing people with a safe, comfortable place to live and work. With this similar goal in mind, it is possible to apply the approach for controlling trace contaminants in spacecraft to office and residential buildings.

Passive Control

Selecting materials which meet the intended use, both structurally and environmentally, is fundamental to providing passive control. Materials which exhibit the proper physical properties for the intended use plus meet the economic constraints of the customer are necessary. However, the future environmental aspects of the selected materials cannot be overlooked.

Many of the materials documented in the MAPTIS database system are commercially available and do not represent severe departures from materials commonly used in construction. An example is silicone rubber sealant. Not only are data on the toxicity data included which provide the identity and amount of each trace chemical contaminant released, but also information on the manufacturer, flammability test data, fluid systems compatibility, oxygen compatibility, and an odor rating. Not all the data may be necessary for building construction purposes; however, the toxicity data can be most useful. Toxicity data are listed in micrograms of chemical contaminant per gram of material. For the silicone rubber example, the primary contaminants evolved are *t*-butanol, 1-butene, and carbon monoxide. The amounts evolved during the toxicity test, which is conducted over a 72 hour period, are 20.00, 0.10, and 0.20 micrograms per gram of sealant for *t*-butanol, 1-butene, and carbon monoxide, respectively.

The data in MAPTIS may be accessed remotely and offgassing characteristics of building materials obtained. From the MAPTIS data, contaminant generation rates which may be used for designing active control systems may be estimated for the building. These generation rates can be used as input data for the TCCS-CP. Although many of the fine details for material selection and control for a spacecraft may not apply to an office building, the overall approach can provide a designer with the necessary data to minimize the risk that the finished structure will develop SBS. Arrangements for accessing the MAPTIS database system can be made by contacting NASA field center technology utilization organizations.

Active Control

Active contamination control in office and residential buildings has mainly been limited to remediation rather than prevention and the addition of equipment for continuous active removal. While prevention through materials selection and active removal devices may add some cost to the overall construction process, it can eliminate the costs associated with the medical and productivity issues inherent in SBS. Through first implementing a passive control approach, the data necessary to adequately design the active control system are obtained. Optimization and verification of the active control approach can be accomplished by employing the TCCS-CP. As summarized earlier, technologies such as charcoal adsorption, high and low temperature catalytic oxidation, and absorption in water during dehumidifying processes can be studied using the TCCS-CP. This flexible program can be used to assist in studies to determine regulation compliance and the economics of active contamination control concepts. It may be obtained by contacting the NASA Marshall Space Flight Center technology utilization office.

Benefits

As is demonstrated by spacecraft experience, the overall benefits of initiating a passive contamination control program for building construction combined with the addition of continuously operating active contamination control systems is the possible elimination of SBS. Through careful consideration of the materials used in a building, the costs associated with chronic illness, loss of productivity, and building refurbishment can be avoided and means can be provided to economically control any residual contamination as it is generated.

Summary

Although seemingly different in their purpose, spacecraft and terrestrial buildings have very striking similarities in regard to contamination buildup and its effect on the occupants. Although spacecraft do not have the luxury of dilution with outside air, they have lower incidence of health-related problems associated with contamination by virtue of a rigorous material selection and control program combined with active control systems. This is in spite of the very small volume-to-crew ratios experienced onboard spacecraft. Both spacecraft and buildings must be economical to maintain and provide the occupants with a healthy environment in which to live. By adopting some of the approach and evaluation tools used for spacecraft design and verification, building construction can go a long way toward preventing SBS rather than having to employ expensive remediation techniques after the problem has already occurred. This application of systems and tools for space travel can effectively enhance our terrestrial environment.

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