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Air Quality Criteria for Storage of Paper-Based Archival Records

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Public Buildings Service
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National Capitol Region
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National Archives and Records Service
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AIR QUALITY CRITERIA FOR STORAGE OF PAPER-BASED ARCHIVAL RECORDS

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ABSTRACT

Criteria for temperature, relative humidity, and gaseous and particulate contaminant concentrations are proposed for spaces used for storage and preservation of paper-based archival records. The criteria are based on available information from the literature, and recommendations of the January 19-20, 1983, National Bureau of Standards Workshop on Environmental Conditions for Archival Storage. Methods are discussed for meeting these criteria. Air quality criteria are proposed for different categories of archival storage. Factors to consider in the design of archival storage facilities are addressed and recommendations made to aid in the design of environmental conditioning systems for these facilities. A review of literature describes the damage that may be caused by high temperature, high and low relative humidity, and air pollutants to paper-based records.

Results of measurements of temperature, relative humidity, air exchange rate, and gaseous contaminant concentrations (sulfur dioxide, nitrogen oxides, and ozone) in the National Archives Building in Washington, D.C., are presented. These measurements are compared with those made in other buildings having controlled environments.

Key words: air quality, archival storage, criteria, design parameters, environmental conditioning systems, environmental conditions, environmental control, preservation.

PREFACE AND ACKNOWLEDGMENTS

This study on air quality criteria for storage of paper-based archival records was conducted by the Building Materials Division and the Building Equipment Division of the Center for Building Technology, National Engineering Laboratory, National Bureau of Standards (NBS). The work was sponsored by the Public Buildings Service (PBS) of the General Services Administration (GSA) and the National Archives and Records Service (NARS) because of the need to upgrade the performance of the heating, ventilating, and air-conditioning systems at the National Archives Building. This document provides criteria and documentation for temperature, relative humidity, and air pollutant concentrations in spaces used for storage of paper-based archival records. It is based on available information on the preservation of paper-based materials and the capabilities of commercially available environmental conditioning systems.

Information used in the preparation of this report was obtained from several sources: (a) a report entitled, "Final Report on January 19-20, 1983 NBS Workshop: Environmental Control for Archival Record Storage", NBS-GCR-83-438, August 1983, by Warren B. Johnson, William P. Lull, Charles A. Madson, Amos Turk, Karl L. Westlin, James E. Woods, and Paul N. Banks; (b) a report entitled, "Measurement of the Concentration of Sulfur Dioxide, Nitrogen Oxides, and Ozone in the National Archives Building," by E. E. Hughes and R. Myers, NBSIR 83-2767, November 1983 (appendix B); (c) a report entitled, "Air Exchange Rate Measurements in the National Archives Building," by Samuel Silberstein, Richard A. Grot, Douglas O. Pruitt, Philip Engers, Patrick J. Lane, and Steven E. Schweinfurth, NBSIR 83-2770, August 1983 (appendix C); (d) a letter report entitled, "Factors Affecting the Deterioration of Paper-Based Archival Records--A Literature Search," by Samuel Silberstein, May 1983; (e) measurements of temperature and relative humidity taken by GSA and NARS; and (f) other information from the literature.

The contributions of the Workshop participants who reviewed the Workshop Report, Alan R. Calmes, Tim Padfield, Carl J. Wessel, and William K. Wilson, are appreciated. The Word Processing Center of the Center for Building Technology is gratefully acknowledged for typing this report.

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1. INTRODUCTION

1.1 BACKGROUND

The National Archives Building in Washington, D.C., which houses many of the Nation's records intended for permanent preservation, was constructed in the early 1930's. It was one of the first buildings in Washington, D.C., to provide all season environmental control. The controlled environment was prescribed in order to protect the Nation's valuable records from the effects of extreme temperature, high and low relative humidity excursions, and attack from acid gases such as those resulting from sulfur dioxide. The original heating, ventilating, and air conditioning system was designed to meet these objectives, but has since been modified a number of times and has had a history of less than satisfactory performance [1][1/].

A recent report [1] from the General Services Administration, Office of the Inspector General recommended the following actions to improve environmental conditions at the National Archives Building:

a. Performance testing should be conducted to determine if environmental conditions (temperature and relative humidity fluctuations, and gaseous and particulate pollutant levels) exist in the building which would subject valuable records and documents to immediate irreparable damage.

b. Standards for environmental conditions should be adopted which would protect the records from accelerated deterioration.

c. The Public Buildings Service should develop cost estimates for bringing the control of the environmental conditions (temperature, relative humidity, gaseous and particulate pollutant concentrations) into compliance with the adopted standards.

d. These actions should be carried out as part of a time-phased plan to upgrade the performance of the heating, ventilating, and air-conditoning systems.

1.2 OBJECTIVES

To aid in carrying out the recommendations (section 1.1), to improve the performance of the heating, ventilating, and air-conditioning systems at the National Archives Building, the Public Buildings Service of the General Services Administration requested the National Bureau of Standards' Center for Building Technology to provide criteria for environmental conditions for the storage and preservation of paper-based archival records. This study may also be useful in the design and modification of other archival storage facilities.

[1/] Figures in brackets refer to literature references given in section 8.

The objectives of the report are to provide criteria which establish limits for control of environmental conditions in spaces used for storage of paper-based archival records; to consider factors affecting the degradation of paper and books which can be used to document the rationale for selecting specific criteria; to include information to assist in the design of environmental conditioning systems with regard to preservation of stored paper-based materials; to review up-to-date standards and operating procedures used in the design and maintenance of records storage facilities; and to present the results of measurements of pollutants, air exchange rates due to infiltration, temperatures and relative humidities in the stack areas of the National Archives Building which were used to determine baseline performance of the existing environmental control system. Gaseous pollutant levels in this building were compared to the pollutant levels in other buildings with similar functions having rigid environmental limits.

1.3 SCOPE OF THE PROJECT

This report is concerned only with the control of environmental conditions in storage facilities for paper-based archival records, and not with other areas of buildings. Excluded from consideration are general reading rooms, exhibition areas, offices, and work areas except as they influence storage areas. Also excluded from consideration are photographic materials (photographs, microfilms, and negatives, for example), parchments, and vellums. These may comprise significant parts of many collections and must be considered in designing air-conditioning systems. Light is not addressed in this report, although it may be as important in causing deterioration as other factors.

Much of the information and data presented in this report were obtained from existing sources including the literature, and opinions of those knowledgeable in preservation and conservation of paper-based materials and in the capabilities of environmental conditioning components and systems. No laboratory research on the preservation of paper-based materials was performed during the course of the study. Measurements were made of temperature, relative humidity, air infiltration rate, and gaseous pollutants (sulfur dioxide, nitrogen oxides, and ozone) in several locations in the storage areas of the National Archives Building to determine baseline performance of the existing environmental control system (appendices B and C). For comparison, measurements (except for air infiltration rate) were also made in the Madison Building of the Library of Congress and the East Wing of the National Gallery of Art. These buildings have modern environmental conditioning systems designed to maintain rigid environmental limits.

Criteria were provided in two ways: 1) through a literature search, and 2) by a Workshop on Environmental Conditions for Archival Records Storage held at the National Bureau of Standards on January 19-20, 1983 [2]. In addition to providing criteria, the Workshop participants reviewed equipment and other means for meeting these criteria. Workshop participants are listed in appendix A.

2. NATURE OF THE PROBLEM

The National Archives contains some 3,000,000,000 paper-based records in the form of loose documents, bound volumes, maps, manuscripts, and many other forms. As a general rule, it is assumed that once an item has been accessioned into the Archives (on the basis of legal requirements or historical value) it is to be retained indefinitely.

However, the assumption of "permanent retention" has caused at least two major problems: preservation of the records and space for housing them. For an estimated 17 percent of the records which have unquestioned "intrinsic value," preservation of the original records for as long as possible (in other words, indefinitely) is the single goal [2].

For the other 83 percent, however, it has recently been decided that they can probably be preserved by microfilming or converting them to some other secondary medium and discarding the originals. This has obvious benefits for space conservation, and significant cost advantages over preservation of the original documents. However, it is estimated that at present rates of mircofilm production, it would take about 435 years to convert just those documents that are most in need of conversion [2]. In other words, even with the most efficient technology now available, it will not be possible to capture the intellectural content of the documents before they have deteriorated to the point that they can no longer be handled.

Optimum storage conditions for paper-based records are essential. Important factors in designing these conditions include storage location, storage duration, frequency of access, contaminants, thermal loads, system constraints, and economics.

2.1 PAPER-BASED RECORDS

Although there are many exceptions and variations, the types of records under consideration usually consist of writing, typewriting, copying, or printing ink (of one or more colors) on paper. Additionally, some documents are bound, which implies composite structures; that is, objects of some degree of structural complexity composed of a variety of different materials; for example, thread, adhesives, cardboard, cloth, leather. Books are composed not only of different types of papers, but also of inks, glues, and bindings. All these materials must be protected simultaneously. Care of books and documents, their composition, the factors damaging to them, and recommendations for their storage and preservation have been described by Wilson and Gear [3].

Paper itself is a highly variable material containing cellulose fibers of natural origin. While some early (and incidentally highly stable) papers consist almost wholly of highly pure cellulose fibers, modern papers may contain lignin from wood, and additives such as alum-rosin sizing. Thus, different papers have different degrees of inherent stability, and different rates of deterioration.

2.2 FACTORS AFFECTING THE DETERIORATION OF PAPER-BASED ARCHIVAL RECORDS

The factors considered as those affecting the deterioration of paper-based archival records include temperature, relative humidity, gaseous and particulate contaminants, ventilation, biological agents, and lighting. The effects of lighting on paper-based records have not been covered in this report. Lighting systems can be designed and used to satisfy both preservation and visibility requirements [4]. The four environmental conditions generally accepted as those that primarily affect paper-based archival records are temperature, relative humidity, gaseous and particulate contaminants [5].

This section of the report is concerned with factors that affect deterioration of certain paper-based archival records, mainly books, that can be controlled by air conditioning systems. A compilation of descriptions of current practice and recommendations from several sources are given which provides information on factors to be considered in the design of spaces for storage and use of paper-based archival records. The information presented in this section is not meant to be an exhaustive listing of all references dealing with paper preservation, but it is intended to cite and summarize several representative sources that describe current practice in paper-record preservation. Examples are given of guidelines on temperature, relative humidity, pollutant concentrations, and protection against biological agents.

2.2.1 Separate Storage Areas

A general point in paper preservation is that optimal conditions, especially temperature, are not the same as conditions whose primary purpose is human comfort [6]. For this and other general protective and security reasons, archival materials should be stored in special storage areas and removed to other areas for use [7]. One of the reasons is that people can bring dust, insects, spores and food particles containing nutrients for insects and vermin into storage areas [8].

Storage areas may be maintained at slightly positive pressure with respect to surrounding areas to prevent infiltration of untreated air [2].

2.2.2 Ventilation

Ventilation must be adequate to prevent stagnant air and the formation of microclimates around books that are at variance with standards for air pollutants, temperature, and humidity [7]. Adequate ventilation around all storage materials is also required to remove any pollutants that are emitted by the materials themselves or fixtures near them [9].

The Royal Ontario Museum is an example of a building that was recently expanded and refurbished with preservation of its collections as a main objective. Separate air conditioning systems were installed so that different conditions could be maintained for different collections. Minimum airflow rates were established, depending on the size of the space served, from 60 L/h (2.1 ft^3/h) for spaces having a volume of 0.3 m^3 (11 ft^3) (display cases), to 1300 L/h (46 ft^3/h) for spaces having a volume of 30 m^3 (1060 ft^3). Each gallery was fitted with a system so that it could be separately fumigated. The fumigant is exhausted through pipes separate from the air-handling system [10].

2.2.3 Temperature (Dry-Bulb)[1]

2.2.3.1 Damage Caused by High Temperature

Heat, either by itself or in combination with light and/or insufficent or excessive moisture, damages paper and other materials used in records. The deterioration of paper becomes more rapid as the temperature is increased [11]. With an increase and decrease in temperature, paper-based materials alternately expand and contract, and may ultimately crack. Expansion and contraction of paper-based materials is, in general, more pronounced with increases and decreases in relative humidity. Heat causes water, solvents, and plasticizers to be driven off. Heat also increases the reaction rate of pollutants with books, changes acidity, and promotes mildew growth. As a result, paper is embrittled, yellowed, and weakened as measured in tear, burst and tensile tests [8,12]. Barrow's measurements [13] showed that for each temperature drop of 20°C (36°F), it takes 7.5 times as long to reduce to the same extent the folding endurance of paper, a measure of its ability to withstand use. It should be noted that exposure of some types of paper to heat even for short periods causes yellowing and embrittlement. Other types of paper, those compounded for stability, can be heated for a long time without observable change.

In general, low temperatures preserve paper, provided that relative humidity is maintained at proper levels. Moisture content in equilibrium with 30 percent relative humidity is as low as is safe for paper [8]. A sudden drop in temperature increases relative humidity, and may result in condensation and consequent damage [8].

It has been assumed, although not demonstrated, that materials for which maximum longevity is required, freezing would dramatically prolong their life [2]. The effects of freezing temperatures on paper-based materials have not been fully studied.

Paper is not uniformly sensitive to heat and other deteriorative factors. Rag papers were not affected by heat in tests performed by Shaw and O'Leary [14]. Purified wood pulp was fairly stable, and a mixture of sulfite and soda pulp was less stable than purer fibers. There is a close relationship between the purity of cellulosic fibers and stability of unsized papers made from them, when only a small amount of alum and no rosin size is used. In other tests, acidity of paper affected the ability to withstand heat [8].

Smith [15] used Browning and Wink's [16] Arrhenius equation approach to calculate relative lifetimes of papers at various temperatures. This approach is based on the fact that the rate of chemical reactions, including hydrolysis

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[1] Dry-bulb temperature is defined as the temperature of the air as measured by an accurate thermometer. Exposures to mean radiant temperatures or other infra-red radiation are not addressed in this report.

of cellulose, increases with increased temperature according to the Arrhenius equation. Luner [17] pointed out difficulties with this approach, including its dependence on the characteristics of papers. Smith [15] also predicted the combined effects of temperature and acidity. The interested reader is referred to the original references for more details.

2.2.3.2 Examples of Suggested Temperature Limits

Banks recommends the lowest possible temperature for book storage [7]. However, he allows for limitations to low temperature. People can not be entirely separated from books. Even if separation were possible, there is a lower temperature limit that would be tolerated by employees. Too great a temperature difference between storage and use areas could result in condensation damage when books are brought from the former to the latter. If reading rooms were maintained at a maximum temperature of 24.5°C (76°F) and a maximum relative humidity of 50 percent, then no condensation would result if the temperature were lowered to 14°C (57°F). Storage and use of materials should ideally be kept at as nearly the same temperature as possible. However, in libraries in which most materials are used infrequently, if at all, it is advantageous, in practice, to keep storage areas cooler than use areas [7]. Thus, in this case, the design criterion for temperature should be as low as consistent with such other considerations as the need for human access to storage areas [2].

The Library of Congress maintained use areas at 24°C (75°F) and storage areas at 20°C (68°F) in 1974. Storage temperatures are not lower than 20°C (68°F) because they must accommodate both books and people [7]. The British Museum Library maintains closed access rooms at 13-18°C (55-65°F) and other rooms at 18-21°C (65-70°F) [7]. The Royal Ontario Museum maintains different sets of conditions for different parts of its collections. Its rare books and leather bookbindings are stored at 21-23.5°C (74°F) [10]. Banks [7] recommends book storage at 15.5°C (60°F) plus or minus 3°C (5°F). Darling and Webster [18] recommend that temperatures should be kept at 18°C (65°F) plus or minus 3°C (5°F) year-round in collections subject to regular use. Storage collections should be maintained at lower temperatures. The Canadian Conservation Institute [19] recommends an optimum temperature of 21°C (70°F) with a daily fluctuation of no more than 1.5°C (3°F). The maximum acceptable temperature is between 20°C (68°F) and 25°C (77°F) with a monthly permissible changeover of 5°C (9°F). This is based on human comfort; to prevent deterioration, even lower temperatures would be tolerable.

2.2.4 Relative Humidity

2.2.4.1 Damage Caused by High Relative Humidity

Relative humidity is another important factor in deterioration of paper in libraries. Paper and virtually all other materials used in records absorb moisture and their moisture content has profound effects of them. Water content of materials such as paper varies directly with the relative humidity of the surrounding atmosphere because there is an equilibrium between water in these materials and in air. Since paper-based materials expand with increasing moisture content, it is important that relative humidity be controlled within narrow limits. In an accelerated aging study it was clearly demonstrated that moisture has a profound effect on the degradation rate of paper, particularly at high temperatures [20]. Relative humidity is the ratio of the actual amount of water vapor present in air to the amount of water vapor present at saturation for the same temperature and pressure. As temperature increases, so does the water vapor capacity of air. Both excessive and insufficient moisture contents, and hence high and low relative humidities at temperatures normally encountered in libraries, can damage books [7]. (The reader is referred to [21] for a thorough treatment of the relationship between water content and relative humidity.) This is why there is currently no agreement in the literature on an optimum relative humidity level for storage of paper-based materials [7].

High relative humidity increases the rate of deteriorative chemical reactions [7]. Movement of moisture in books in response to fluctuations in relative humidity may carry deteriorative contaminants such as acids and helps to distribute them throughout the book. At high levels of relative humidity some dyes and adhesives may dissolve out of books and other paper-based materials. Accumulation of moisture and hydration may turn paper to pulp and cause pages to stick together. Excessive moisture also leads to biological attack by fungi, resulting in staining of paper and leather, and weakening of materials [8]. This can occur at relative humidities above about 65 percent [22-24]. While low relative humidity by no means eliminates or eradicates insect infestations, high levels encourage them. Bacteria are not of concern unless the relative humidity is greater than about 70 percent and the temperature is above about 24°C (75°F).

Leather at 40°C (104°F) and 100 percent relative humidity loses all its strength [25]. Water in paper in equilibrium with 50 percent relative humidity hastens the rate of deterioration during laboratory tests in which accelerated aging is artifically induced [16]. On the other hand, insufficient moisture leads to drying, brittleness and disintegration [7,20]. Natural adhesives are especially subject to desiccation and embrittlement [7,26].

Folding endurance has been shown to be dependent on control of relative humidity [8,27]. Up to a point in some cases, each 10 percent rise in relative humidity results in doubling of folding strength of paper [28]. Flexibility of paper can increase two or three times with a change in relative humidity from 30 to 50 percent [29]. Thus, relative humidity can have a considerable effect on the use of books and documents which consists of weak or embrittled paper. Other materials such as leather and animal glues show similar effects.

2.2.4.2 Examples of Suggested Relative Humidity Limits

Unlike other factors, there is no agreement on what constitutes an optimum relative humidity level for preservation of books. At temperatures normally found in libraries, relative humidities are generally recommended to be, and are generally maintained at some point in the range of 30 to 65 percent, most often near 50 percent [7,8,10,18,19,30,31]. Fluctuations in relative humidity may be damaging [7]. Diurnal excursions from the set point are recommended to be within 2 to 6 percent by different sources, some of whom are willing to permit greater variations over longer periods [7,10,17,19]. For example, Banks [7] states that cycling at infrequent intervals is less damaging if the total range is less than 12 percent. The Canadian Conservation Institute [19] standard permits a minimum acceptable relative humidity of 38 percent for winter and 55 percent for summer with a maximum set-point changeover rate of 5 percent per month. The Royal Ontario Museum points out that the changeover to a new relative humidity after a new air-conditioning system has been installed should be very slow [10]. To maintain high relative humidity during winter, the Canadian Conservation Institute recommends that the building be maintained at slightly negative pressure relative to outdoors whenever pollution levels permit. Condensation damage has been reported to occur in air-cooled buildings [8,30].

As stated above, there is insufficient information to recommend an optimum relative humidity. Recommendations for relative humidities of less than 50 percent are based on laboratory studies of paper aging, not on studies of actual use of books in libraries [7]. On the other hand, according to Smith [15] recommendations for relative humidity of 50 percent emphasize current physical properties at the expense of future properties. In this vein, Banks [32] recommends that air-handling systems be capable of being modified to achieve lower relative humidities as further research might suggest this to be desirable.

2.2.5 Gaseous Air Pollutants

2.2.5.1 Damage Caused by Gaseous Air Pollutants

Gaseous air pollutants damage books by making them acidic, which promotes degradation by hydrolysis, and by oxidation, which causes discoloration and disintegration, and by providing essential nutrients for fungal growth, which itself is damaging to books [8,33]. Paradoxically, both oxidants such as ozone and reducing agents such as sulfur dioxide, can coexist in the atmosphere because of their extreme dilution [34]. The chemical pollutants of greatest concern are sulfur dioxide, the oxides of nitrogen, and ozone.

Acidity, an indisputable cause of book deterioration [8,15], results mostly from the processes used to manufacture paper and from leather tanning, in the case of leather-bound books. Inks may make paper acidic. Acids are produced from oxides of sulfur and nitrogen, which are universally found air pollutants [8,15,35-38]. Wood has been reported to emit carboxylic acids, especially acetic acid, and also aldehydes and alcohols [9]; this may or may not be true of paper as well. Library materials, for example shelves, may be made of wood.

At concentrations found in normal city atmospheres, sulfur dioxide is readily absorbed at the edges and by exposed pages and areas of a book [8,37,39-41]. Extensive studies have demonstrated that both paper and leather avidly absorb SO_2 [29,39,42]. These studies have included comparisons of identical books that have been stored in areas having different atmospheric SO_2 levels, and studies of the difference of pH levels between the edges and the centers of books. By itself, SO_2 is not damaging to books. However, once absorbed, its oxidation to sulfur trioxide is catalyzed by metallic impurities in paper [8, 35,43,44] and by leather surfaces. Oxidation may result from reaction with nitrogen dioxide, ozone, peroxides, and peroxy free radicals. Some of these reactions may possibly be catalyzed by inorganic constituents in the paper. Upon combination with water, sulfur trioxide yields sulfuric acid. Similarily, nitric acid is produced from oxides of nitrogen. Sulfuric and nitric acids then hydrolyze cellulose, causing decreased tear resistance and flexibility (folding endurance) and ultimately disintegration of paper [8,15].

Hydrolysis induced by sulfuric acid is also the prime cause of leather deterioration [8,37,45,46]. Below pH 3, leather becomes dry, reddish-brown and porous. It peels or powders, is easily scratched, its corners wear easily and cracks appear. This syndrome is known as "red rot." The ideal protection for leather bookbindings is isolation from contamination by sulfuric acid and storage in air-conditioned areas [37].

Oxidants, another class of damaging gaseous pollutants, include ozone and nitrogen dioxide. These pollutants, as mentioned above, help oxidize sulfur dioxide to sulfur trioxide. Oxidation discolors paper. Nitrogen dioxide reacts with polymeric materials such as rubber, synthetic elastomers used as fabrics, threads, and adhesives [8]. Little information was found in the literature on the effects of NO_x and O_3 on paper-based archival records, but they are also assumed to be harmful. The effect of ozone was studied by Bogoty, Campbell and Appel [47]. They reported that cotton textiles deteriorated somewhat when wet, but deterioration was slight in comparison with other elements of weathering, such as light, heat, and wetting and drying. No noticeable change occurred during dry exposure to ozone.

2.2.5.2 Examples of Suggested Gaseous Pollutant Concentration Limits

As an ideal, the British Museum Library recomends that sulfur dioxide, nitrogen oxides, ozone and dust be entirely removed [7,15,33]. The Royal Ontario Museum requires charcoal or equivalent filtration to remove sulfur dioxide, ozone and nitrogen oxides [10]. Banks suggests concentration limits of 4 ppb sulfur dioxide and 1 ppb ozone [32].

Both supply and return air should be monitored for pollutants by suitable instrumentation. This is especially true for sulfur dioxide, because books are excellent sinks for sulfur dioxide and a low concentration reading in the return air would not necessarily reflect low exposure levels [7,48,49].

2.2.6 Particulates

2.2.6.1 Damage Caused by Particulates

The effects of particulates on the deterioration of records have apparently not been well studied, but some effects are obvious and others can be hypothesized. There is abundant empirical evidence of the visible damage such as soiling of books and documents. Not only are exteriors disfigured by dust and soot, but perspiration and skin oils cause dust to become irremovably embedded, not only on the outside of items, but also on the pages themselves when dust or other soiling agents are carried on dirty hands.

Particles and aerosols exist in a wide size range, from particles large enough to settle on surfaces because of their weight, to smaller particles that may be deposited on surfaces electrostatically or thermally. The aerosol concentrations may be determined gravimetrically or by particle count. The weight methods are most generally used, and are applicable in all but the cleanest environments. The particle-count methods are applicable in clean-room-type environments, where the contaminants are usually sub-micron in size [50].

The concentration of large particulates, or dust, that many settle out can be measured by the weight arrestance test [32,51,52]. Fine, or respirable particulates (diameter roughly 1-10 μm), can carry adsorbed sulfur dioxide and nitrogen oxides, and can stain books; their concentration is measured by the dust spot test, a measure of filter efficiency. The smallest fine particulates are measured by the dioctyl phthalate test, a measure of ultra-high efficiency media [32,51,52]. In addition to carrying adsorbed acidic and oxidizing gases and staining books, particulates can also provide nutrients for mildew growth, are abrasive to paper and leather, and can change the acidity of paper [7,8]. Viable particulates such as fungal spores and mycelia, bacteria and mold can result in deterioration of books and documents, especially if the temperature and relative humidity in spaces containing these paper-based materials are not properly controlled.

2.2.6.2 Examples of Suggested Particulate Concentration Limits

The Canadian Conservation Institute recommends removal of 95 percent of particulates of diameter greater than or equal to 1 μm and 50 percent of diameter between 0.5 and 1 μm (which correspond, more or less, to the dust spot and dioctyl phthlate tests, respectively) [22]. The Royal Ontario Musuem requires 99 percent removal down to 10 μm and 95 percent removal down to 1 μm [10]. Banks [32] recommends as complete removal as feasible of these particulates. The Library of Congress and the Newberry Library require minimum filter efficiencies of about 95 percent [7,52]. Electrostatic precipitators are not generally recommended for removal of particulates as a stand alone system without some other conditioning component because they may emit ozone [7,19,53]. Oil and viscous impingement filters are excluded from use at the Library of Congress because they can produce aerosols of their own [7].

2.2.7 Biological Agents

Biological agents include fungi (molds), bacteria, actinomycetes, insects and rodents [8]. They do not cause great damage in United States urban libraries but are more damaging to museums [8]. The most important microbial agents in libraries are fungi, which cause staining, spotting and discoloration, especially, if they produce colored metabolic products [8]. Unlike bacteria, they do not need liquid water for growth, but do require high relative humidities [8]. Depending on the species, they grow optimally at 15°C (59°F) to 30°C (86°F) [8]. The average optimum temperature is 30°C (86°F) for 95 to 100 percent relative humidity. They do not tolerate cycling of temperature below and above freezing. High temperature, especially in combination with high relative humidity, will kill most fungi and spores. There is little growth below 70 percent relative humidity; they grow well above 80 percent relative humidity. The optimal temperature near 100 percent relative humidity is about 40°C (104°F) and lower for lower relative humidities. They grow either in light or dark. Some of their nutrient requirements can be met by air pollutants, as mentioned above.

Insects are not a major problem in United States urban libraries [8]. They can be brought in by people and are attracted by discarded nutrient refuse such as food and candy wrappers, in books and stacks. They are discouraged by low temperatures [8]. It has been reported that increasing relative humidity increases the number of insects [10].

2.2.8 Examples of Design Criteria

Design criteria for archival storage facilities for paper-based materials are reported from several literature sources. Some examples of criteria for temperature, relative humidity, and pollutant concentrations were given in sections 2.2.3.2, 2.2.4.2, 2.2.5.2, and 2.2.6.2. Some additional examples are given here. It can be seen that there are in some cases differences in opinion concerning air quality criteria for archival storage of paper-based materials.

a. ASHRAE [53] recommends that air in archival libraries and museums be filtered at a particle removal efficiency of 85 percent by the dust spot method. Relative humidity should be kept at 35 percent for books, and temperature at 13 to 18°C (55 to 65°F) in book stacks and 20°C (68°F) in reading rooms. Canister-type filters or spray washers should be provided if chemical pollutants are present in the outdoor air. ASHRAE [53] prefers all-air systems in library areas where steam or water damage may ruin rare books and manuscripts.

b. A suggested specification by Thomson [54] for museums with regard to gaseous pollutants is:

   Sulfur dioxide not more than 10 $\mu g/m^3$

   Nitrogen dioxide not more than 10 $\mu g/m^3$

   Ozone reduce to trace levels (0-2 $\mu g/m^3$)

   Thomson notes that these levels are readily attainable by present technology in air conditioning with recirculation. These methods will also keep concentrations of other acidic gases and oxidants low.

c. A report on the proceedings of a workshop on micro-climates held at the Royal Ontario Museum in February 1978 [10] gave guidelines for temperature of 21 to 23.5°C (70-76°F) and relative humidity of 50 percent ± 2 percent for storage of materials such as manuscripts (paper and parchment) requiring extremely stable conditions. The recommended performance specification for micro-climate units requires that the air be filtered for particulate matter to 99 percent removal down to 10 μm and 90 to 95 percent removal down to 1 μm. Further, the recommended performance specification states that the air should also be passed through a charcoal or equivalent filter to remove SO_2, O_3, and NO_x.

d. Federal Archives and Records Center Facility Standards [55] for long-term storage require that temperature be kept at 19-23° C (66-74° F) and that relative humidity be kept at 35-45 percent on a continuous basis.

2.3 SOURCES OF CONTAMINANTS

In addition to the factors that affect paper-based materials discussed in section 2.2, other sources of contaminants which affect these materials within archival storage areas include:

- building materials
- books and other paper-based material within the storage area
- human activity within the storage area
- airborne contaminants in the HVAC System (outside air and recirculated air)
- interactions among contaminants.

2.3.1 Building Materials

The surface areas of the storage facility may be a primary source of contaminants. Most unsealed masonry emits fine particles due to convection effects [56]. New concrete has been reported to emit small alkaline particles for periods up to two years [57]. Settling of these particles may cause degradation of materials containing animal or vegetable matter which are of an archival nature, and should be considered a threat to valuable leather bindings [32]. The extent of damage to paper-based materials caused by masonry, concrete and other building materials is not known.

Treated wood products can emit acetic acid, formaldehyde, hydrocarbons, and fine particles into the storage area [9,58,59]. In addition, untreated wood products can be a source of microbial contaminants.

Some thermal and acoustic insulation may outgas formaldehyde and hydrocarbons, and may be the source of particulates such as glass fibers, cellulose, and asbestos [58,59]. Jarke [60] has identified over 200 odorous compounds from building materials.

Fabrics, including carpeting, drapes and upholstery can be the sources of several gaseous contaminants such as formaldehyde, hydrocarbons, nitrogen compounds, and sulfur compounds [58,59]. In addition, they may emit fine particles due to convection or re-entrainment effects, and these may also be sources of microbial contaminants.

Paints, wall coverings and adhesives can also be sources of gaseous and particulate contaminants including formaldehyde, hydrocarbons, mercury, and other metallic fumes [58].

Windows must also be considered as a source of contaminants as they provide a means for entry of contaminants into storage facilities. Unless they are tightly sealed, they may allow outdoor contaminants to enter by infiltration. If windows are openable, little control of contaminants from outdoor sources can be expected during long-term storage. Moreover, windows may also be the site of condensation during winter months. This latter effect is especially true in cold climates if high levels of relative humidity may be required to maintain paper flexibility.

2.3.2 Paper-Based Materials

Books and other paper-based materials stored within the facility may themselves, be sources of contaminants. Embrittled materials may discharge fine particles into the air when the materials are handled. Also, autocatalytic deterioration of book bindings may occur under some air quality control strategies (section 4). Products that consist of, or contain nitrocellulose, such as pyroxylin or celluloid, may release nitric acid which promotes decomposition of paper-based materials [61]. The deterioration of cellulose acetate is also autocatalytic.

2.3.3 Human Activity

When the storage facility is occupied, thermal, gaseous and particulate contaminants are generated by the occupants. At sedentary activity, a typical adult will dissipate energy at the rate of approximately 120 watts, about one-fourth of which is a latent component. Associated with this heat dissipation is the uptake of about 40 g/hr oxygen (O_2), and the dissipation of about 30 g/hr carbon dioxide (CO_2) and about 30 g/hr water vapor. As the human activity increases, the uptake of O_2 and dissipation of CO_2, water vapor, and heat may increase to values up to ten times sedendary for short periods of time [62].

Skin flaking from humans is also a source of particulate contamination. The average adult sheds approximately 7×10^6 particles/minute, and each particle may contain up to four bacteria [63]. In general, Wang [64] estimates that at least 15 bioeffluents can be identified with human occupancy. More than 2,000 compounds have been identified from tobacco smoke [58].

Other human activities in adjacent rooms that can contribute to thermal, gaseous, and particulate loads in archival storage areas include: laboratory and workroom activities; food preparation, disposal, and dishwashing; health care and personal grooming; office work; and housekeeping activities.

2.3.4 HVAC Systems

Heating, ventilating, and air conditioning systems can be sources of gaseous and particulate contamination if they have not been properly designed or are not properly operated and maintained. Contaminant sources in these systems include improperly maintained filters, heating and cooling coils, humidifiers, and ductwork. Particularly important are improperly pitched drain pans associated with cooling coils and some humidifiers. These can be environmental niches for the growth of viable contaminants. If HVAC systems do not function properly, they may introduce excessive concentrations of contaminants from the outdoor air, recirculate excessive concentrations within the system, or cause interactions to occur within the system. Amines or other organic volatiles used in steam humidification systems may be sources of contamination. Ductwork systems have been found in some instances to be contaminated with dust, bacteria, and fungi. If this is the case, they should be cleaned and sanitized depending on the type of contamination.

2.3.5 Interaction of Contaminants

When contaminants are present in various combinations, the possibility exists that reactions can occur that result in contaminants other than those originally emitted into the space. An example of the interactions that might be of concern in archival storage facilities include reactions between acidic gases, such as SO_2, and water vapor which results in dilute concentrations of H_2SO_4 in the presence of catalysts such as metal fumes [32]. Another example of an interaction is the rate of growth of microbial contaminants as influenced by the relative humidity in the space [65]. A third example is the affect on fading of dyed materials caused by the presence of certain wavelengths of light, relative humidity, and acidic gas concentrations [5,66].

2.4 WORKSHOP ON ENVIRONMENTAL CONDITIONS FOR ARCHIVAL RECORDS STORAGE

A Workshop on Environmental Conditions for Archival Records Storage was held at the National Bureau of Standards on January 19-20, 1983. The objectives of the Workshop were to explore the rationale for establishing levels of air quality for archival storage and to review equipment technology with regard to its capability to provide special or recommended environmental conditions for archival storage facilities. Among the Workshop participants were experts in the preservation and conservation of paper-based materials and artifacts, and experts in environmental conditioning technology. The environmental conditioning experts were selected by NBS because of their leadership activities in the American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE). Most of them were chairmen of subcommittees or task groups of ASHRAE which had interests that were applicable to environmental conditioning of archival storage facilities. Although the participants with environmental conditioning technology expertise were drawn from the ASHRAE membership, they served as individual professionals and not as ASHRAE representatives. A list of the Workshop participants is presented in appendix A.

The Workshop provided a forum to discuss the needs for air quality for records storage and the capabilities of environmental conditioning components and systems to satisfy those needs. The Workshop participants also assisted in providing references which were used to document the air quality criteria for archival storage presented in section 3. A report of the Workshop was prepared by the environmental conditioning experts with the assistance of some of the experts in conservation and preservation [2]. Much of the information from the Workshop report is contained in this report, and some of the participants are coauthors of this report.

3. DESIGN PARAMETERS

In the design of environmental conditioning systems to control the air quality in storage areas or facilities for paper-based archival records, the following actions are recommended:

a. Establish acceptable air quality criteria.
b. Determine appropriate methods to control air quality.
c. Establish methods of performance evaluation of environmental conditioning systems.
d. Design the environmental conditioning system.
e. Establish a maintenance program to ensure that required environmental conditions are maintained.

These recommended actions are presented to aid the designer and are addressed in sections 3, 4, and 5 of this report. This section deals with the parameters to be considered in the design of archival storage facilities.

The efforts to achieve acceptable air quality control in buildings in which archival records are stored should be limited to those storage areas which contain paper-based archival records, paper-based documents of intrinsic value, records that by law must be kept in their original form, and records that cannot be duplicated in time to prevent the loss of information. Other spaces in the same buildings should only be considered as they affect the storage areas. The archival conditioning system should be designed to isolate the archival storage spaces from other building spaces.

Air quality criteria for the design of archival storage facilities are given in table 3, section 3.6. Some of the environmental factors included in the criteria, dry-bulb temperature, relative humidity, gaseous contaminants concentrations (SO_2, NO_x, and O_3), and particulate contaminant concentrations, are considered in the following sections in terms of expected outdoor values and in terms of desired or required indoor values with regard to preservation and conservation factors, human factors, architectural factors, and economic factors.

3.1 EXPECTED OUTDOOR LEVEL OF CONTAMINANTS

The levels of concentrations of gaseous contaminants inside the National Archives Building, the Madison Building of the Library of Congress, and the East Wing of the National Gallery of Art were measured by NBS and compared to the outdoor levels of air concentrations of these contaminants. Outdoor air concentrations of SO_2, NO_x, and O_3 are monitored at 24th and L Streets by the Washington, D.C. government. These data, recorded on a daily basis and corresponding to the dates of NBS indoor measurements of concentrations of the gaseous contaminants (section 6.2.1) indicate that concentrations close to the upper limits of Environmental Protection Agency (EPA) Primary Standards must be expected. Airborne concentrations of particulate matter, both outdoors and indoors, were not monitored nor were data obtained by NBS during this study. Thus, macro-environmental measurements for the Washington, D.C. area obtained from the EPA must be relied upon. These data also indicate that the upper limits of the Primary Standards for particulates must be expected. In general, outdoor dry-bulb temperature and relative humidity data may be obtained for different areas of the United States from the National Oceanographic and Atmospheric Administration (NOAA) [67] in three-hour increments on a yearly basis. Design winter and summer conditions may also be found for most parts of the United States in the ASHRAE Fundamentals Handbook [68]. For purposes of this report, the outdoor conditions may be summarized from the information given in tables 1 and 2.

3.2 PRESERVATION AND CONSERVATION FACTORS

In addition to the recommended air quality criteria (section 3.6), several other factors should be considered. They include:

- Dry-bulb temperatures should be maintained at the lowest acceptable temperature in archival storage facilities to reduce the rates of deterioration of paper-based material.
- Relative humidity should be maintained within limits of 35 to 45 percent to control paper flexibility and microbial growth.
- Stability of temperature and relative humidity control within narrow limits is needed to reduce fatigue cycles and minimize deterioration rates of paper-based material.
- Concentrations of SO_2, NO_x and O_3 should be minimized to reduce deterioration of paper-based material.
- Gaseous and particulate contaminants emanating from building materials and furnishings in storage areas must be minimized.
- Use-areas and offices should be separated from storage areas and have separate environmental conditioning zones.
- Environmental control of adjacent areas may affect control of the storage areas.
- Access to archival records should be controlled. Information is required regarding the expected length of undisturbed storage of the material, where the stored material will be used upon access, how long the material will remain out of storage, and what controls of human activity will be exercised.

3.3 HUMAN FACTORS

Although the primary design parameters are for the archival records, conditions to be maintained in the storage areas must be compatible with human occupancy. Thus, air quality criteria must also be considered in terms of human health and comfort. With regard to human occupancy, a primary factor is the length of time the occupant will be exposed to the environment within the storage area. If the exposure time is short and infrequent, the thermal air quality control may be less defined by the human needs than by the requirements for minimizing

Table 1. Summary of Outdoor Air Contaminants and Concentrations Given in National Ambient Air Quality Standards[1,2]

	Long Term		Short Term	
Air Contaminant	Level	Time	Level	Time
Carbon Monoxide			40 mg/m^3 10 mg/m^3	1 hr 8 hrs
Lead	1.5 $\mu g/m^3$	3 mo		
Nitrogen Dioxide	100 $\mu g/m^3$	yr		
Oxidants (Ozone)			235 $\mu g/m^3$	1 hr
Particulates	75 $\mu g/m^3$	yr	260 $\mu g/m^3$	24 hrs
Sulfur Dioxide	80 $\mu g/m^3$	yr	365 $\mu g/m^3$	24 hrs

Notes: [1] From ASHRAE Standard 62-1981 [69].

[2] See Reference 11 in ASHRAE Standard 62-1981. Pertinent local regulations should also be checked. Some regulations may be more restrictive than those given here, and additional substances may be regulated. The values given are from U.S. Environmental Protection Agency National Ambient Air Quality Standards.

Table 2. Summary of Outdoor Air Thermal Design Conditions for the Washington, D.C. Area, (Washington National Airport) from 1981 ASHRAE Fundamentals Handbook [68].

	Winter	Summer
Dry-bulb temperature	-8.3° C (17° F)[1]	32.8° C (91° F)[2]
Mean daily range		10° C (18° F)
Wet-bulb temperature		23.3° C (74° F)[3] 24.4° C (76° F)[2]
Degree-days 18.3° C (65° F) base	2347 (4224)	828.3 (1491)

[1] Temperatures exceed this value 97.5 percent of the time during the winter. Conversely, temperatures are at or below this value 2.5 percent of the time or 54 hours during the months of December, January, and February.

[2] Temperatures equal or exceed this value 2.5 percent of the time or 73 hours during the months of June, July, August and September.

[3] Coincident with summer dry-bulb temperature.

the deterioration of the stored material. However, if the exposure times are relatively long or frequent, control values should be defined to a greater extent by the requirements of the occupants, or consideration should be given to alternatives of long exposure, such as removal of a document from the storage area to a separate workroom.

For the air contaminants shown in table 1, the recommendation in ASHRAE Standard 62-1981 [69] is that the indoor concentrations not be allowed to exceed the National Ambient Air Quality Standards for outdoors. Thus, the lower concentrations required for preservation and conservation control will be the more stringent and thus will be the limiting criteria.

Humidity control for human occupancy is recommended by ASHRAE Standard 55-1981 [6] to be within the range of 1.7-16.7°C (35-62°F) dew-point temperature. Generally, this range may be considered to be associated with 30-65 percent relative humidity. The range of 35-45 percent relative humidity for preservation and conservation control is more restrictive but acceptable for human occupancy, thus the narrow range will be the limiting criterion.

In addition to relative humidity and exposure time, five factors must be considered when defining the thermally acceptable conditions for human occupancy: dry-bulb temperature, mean radiant temperature, air movement, human activity level, and thermal insulation of the occupants' clothing [6]. For those conditions in which relative humidity is near 50 percent, the mean radiant temperature is approximately equal to the dry-bulb temperature, the required air movement in the occupied space is less than 0.2 m/s (40 fpm), and the activity level of the occupant is near sedentary. The value of the clothing insulation is expected to be at least 1.3 clo,1/ if the dry-bulb temperature is to be maintained at or below 18°C (65°F) for exposure periods of longer than 1 hour.

3.4 ARCHITECTURAL FACTORS

The design of the successful archival records storage facility is a joint function of the architect and engineer, and it is incumbent upon both the engineer and architect to identify and coordinate basic architectural considerations that must be incorporated in the final design. Some of these considerations are functional relationships between areas, selection of building materials, and selection of furnishings within the storage area. In addition to the architectural considerations listed in this section of the report, the reader is referred to Federal Archives and Records Center Facility Standards [55] which include many other factors to consider in the design of these facilities.

a. Separation of areas - The stack area should be isolated from general public use areas, and from reading rooms. Suitable security

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1/ Clo value is a numerical representation of a clothing ensemble's thermal resistance, 1 clo = 0.155 m^2 K/W (0.88 ft^2 h F/Btu)[6].

arrangements should be made in order to limit access to these spaces to authorized personnel.

b. Water problems - The avoidance of any potential water-related problem is important. All toilet areas, drinking fountains, and other sources of potential water leaks should be excluded from the stack area, and from any area above the stack area. Required fire protection systems such as automatic sprinklers, may present a problem, and special shutoff type heads may be desirable in order to limit water damage in case of a fire. Water control valves on the sprinkler system should be provided with tamper switches and be connected into the building fire alarm system [55]. The use of floor drains in the stack areas may also be indicated, if the plumbing system is designed to prevent reverse flow from sewer backup.

c. Mechanical equipment areas - All mechanical equipment components must be located in separate rooms outside of the stack area, and not located directly above stack areas. Where local devices such as reheat coils or humidifiers are required, they should be located in a space outside the stack areas. All mechanical components should have adequate space for proper maintenance.

d. Pressurization - Pressure relationships between different areas must be maintained. In general the stack areas will be designed to operate under a positive pressure as referenced to the outside, and to other areas in the building. All door openings should be controlled, and openings in walls and ceilings must be closed off to minimize exfiltration from the stack areas in order to maintain positive pressure.

e. Interior finishes and furnishings - All wall surfaces, ceilings, and floor coverings should be selected of suitable material to minimize the generation of particulates, and to minimize outgassing from the materials. This criterion is also applicable to any interior furnishings in the stack area.

f. Relative humidity - All exterior surfaces must be analyzed to ensure that condensation will not occur under the maximum indoor relative humidity during the coldest winter weather expected. With existing older buildings, this may prove to be a problem, and methods must be undertaken to modify the exterior walls by adding insulation and vapor retarders where it is predicted that condensation could occur. Attention must also be given to any exterior glazing, and if present, multiple glazing may be required.

3.5 ECONOMIC FACTORS

For any paper-based material to be classified as an archival document or as a document of intrinsic value, an implication exists that the benefit of storing it with minimal deterioration is worth a significant financial investment. Present methods of providing the required environmental control for these documents generally are based on minimizing both first and operating costs of the systems. That is, systems are usually designed and installed on low bid, and they are operated with minimum budgets. Both aspects of this procedure are usually unsatisfactory in maintaining the desired environmental control. More rational methods for considering the importance of economic factors in controlling the environments for archival records may be based on life-cycle costs, benefit-cost analysis, or risk assessment. These methods include consideration of the following economic factors:

- Initial costs - including planning, design, and installation.
- Operational costs - including labor costs and supplies for maintenance and normal repair.
- Energy costs - including fuel consumption and demand charges.
- Replacement costs - including salvage, relocation costs, and related factors.
- Cost of capital - including interest on both debt capital and equity capital.
- Inflation rates - including projected increased costs for materials, labor, maintenance, and repair.
- Life expectancy - including components, systems, and buildings; also the life expectancy of the stored documents.

The economic methods must be applied to three different problems relating to these storage facilities:

a. Alternatives available to provide acceptable control in existing facilities which presently contain inadequate systems (i.e., retrofit).

b. Alternatives available to provide acceptable control in existing buildings which presently have no control systems (i.e., remodel or rehabiliation).

c. Alternatives available to provide acceptable control while plans are being developed or implemented for a new facility.

Several economic models are available for each of these cases, and some are included in reference [70].

Application of these models will often provide alternatives which may appear to be more expensive than that usually determined from low bid first cost policy, but may in the long-term prove to be most cost-effective. For example, many cases exist in which present equivalent costs may be minimized or inflation-free rates-of-return may be maximized by allowing increases in first costs and preventative maintenance costs if the energy efficiency, reliability, and longevity of system operations can be increased.

3.6 RECOMMENDED AIR QUALITY CRITERIA FOR ARCHIVAL STORAGE

The recommended air quality criteria for archival storage of paper-based materials are given in table 3. The criteria are based on information taken from the literature and from the recommendations of the participants at the Workshop on Environmental Conditions for Archival Records Storage [2]. Three categories of storage conditions are given along with the air quality criteria for each category. The three categories of storage conditions are as follows:

Category 1. Storage facilities for unrestricted public access.

Category 2. Storage facilities with access restricted to authorized personnel only, but in which documents must be removed and replaced frequently.

Category 3. Storage facilities with highly restricted access, and in which documents will be removed and replaced infrequently. Documents in this storage facility would require 6 to 8 weeks of pre-conditioning before removal or replacement.

In addition to the air quality criteria given in table 3, the following design parameters and guidelines are recommended:

A minimum amount of air recirculation is desirable to provide proper air distribution in the records storage areas and to avoid stagnant areas. A value of six air changes per hour is recommended for the minimum air circulation rates, or an air diffusion performance index (ADPI)1/ of at least 80 percent, regardless of the load calculated from thermal requirements (see section 4.2.1).

Storage facilities should be separated from other areas of the building, and controlled by a separate system. Pressurization control should be applied so that the storage facility operates under a slight positive pressure with respect to adjacent indoor areas and to the outdoors.

All building materials and furnishings within the storage areas should be selected to minimize the emissions of gaseous and particulate contaminants. For existing facilities, these materials should be treated with appropriate sealers or be replaced.

All windows in the storage areas should be removed or blocked if possible, or if not, sealed to prevent opening and to minimize infiltration. Special attention should be given to the possible formation of condensation on windows and exterior surfaces.

1/ Air diffusion performance index (ADPI) can be defined as the percentage of locations throughout the occupied zone of an office, or in a storage area, where measurements were taken which meet the specifications on effective draft temperature and air velocity. If the ADPI is maximum (approaching 100 percent), the most desirable conditions have been achieved.

Table 3. Recommended Air Quality Criteria for Archival Storage

Category of Storage Conditions	1	2	3
Public Access	yes	no	no
Duration of Storage	short-long[4]	short-long[4]	long[5]
Frequency of Access	often	often	seldom
Dry-bulb temperature range	18-24°C (65-75°F)	10-13°C (50-55°F)	-29°C (-20°F)
Temperature Control[1]	± 1°C (± 2°F)	± 0.5°C (± 1°F)	± 1°C (± 2°F)
Relative Humidity	40 - 45%	35%	2%[6]
Range and Control[2]	± 5%	± 3%	
Gaseous Contaminants			
SO_2	$\leq 1\ \mu g/m^3$	$\leq 1\ \mu g/m^3$	$\leq 1\ \mu g/m^3$
NO_x	$\leq 5\ \mu g/m^3$	$\leq 5\ \mu g/m^3$	$\leq 5\ \mu g/m^3$
O_3	$\leq 25\ \mu g/m^3$	$\leq 25\ \mu g/m^3$	$\leq 25\ \mu g/m^3$
CO_2	$\leq 4.5\ g/m^3$	$\leq 4.5\ g/m^3$	$\leq 4.5\ g/m^3$
HCl Acetic Acid HCHO	use best control technology	use best control technology	use best control technology
Fine Particles			
TSP[3]	$\leq 75\ \mu g/m^3$	$\leq 75\ \mu g/m^3$	$\leq 75\ \mu g/m^3$
Metallic Fumes	use best control technology	use best control technology	use best control technology

[1] Temperature should be in the given range and should not vary more than these control values.

[2] Relative humidity should be in the given range and not vary more than these control values.

[3] Total suspended particulate: the weight of particulates suspended in a unit volume of air when collected by a high volume air sampler.

[4] Short-long term storage is defined in this table as a wide range of time of storage. Documents may be removed and replaced daily or stored for many years depending on requests for their use.

[5] Long-term storage is defined in this table as a time of storage intended to be 50-100 years or more. Documents designed for this type of storage would be those of "intrinsic value" and designated for preservation as long as possible.

[6] Two percent relative humidity at normal room temperature. At the temperature of storage, -29°C (-20°F), the water vapor in the sealed storage container is close to saturation (i.e., 100 percent relative humidity).

NOTE: It may be desirable to provide system capability to achieve lower levels of temperature and relative humidity than the levels given in this table. Some studies tend to indicate that for long term storage either or both lower temperature and lower relative humidity may be desirable.

4. AIR QUALITY CONTROL

4.1 STEADY-STATE MODEL FOR AIR QUALITY CONTROL

A simple, steady-state expression for a one-compartment model of the storage facility is helpful in identifying the three methods of control most commonly employed for thermal and air quality control: source control, removal control, and dilution control [62,71]. A mass-balance for the model shown in figure 1 may be expressed as:

$$\Delta C = \frac{\dot{N} - \dot{E}}{\dot{V}_o} \qquad (1)$$

where:

$\Delta C = C_r - C_o$ = the difference between the uniformly-mixed indoor air concentration, C_r, and the outdoor air concentration, C_o.

$\dot{N} = \dot{Q} - \dot{S}$ = the net generation rate of the contaminant where $\dot{Q}$ is the source strength (i.e., gross generation or emission rate), and $\dot{S}$ is the sink strength (i.e., settling or sorption rate within the controlled space).

$\dot{E} = \varepsilon \dot{V}_m C_u$ = the removal rate of a contaminant in the air cleaner;

ε = the efficiency of the air cleaner rate in terms of the contaminant removed; $\dot{V}_m$ = volumetric flow rate of recirculated air; C_u = concentration of the contaminant, upstream of the air cleaner, and; C_d = concentration of the contaminant, downstream of the air cleaner (see figure 1);

$\dot{V}_o$ = volumetric flow rate of outdoor air for dilution control.

In the model, the dilution rate, $\dot{V}_o$, represents infiltration, natural ventilation or mechanical ventilation with outdoor air. The removal rate, $\dot{E}$, represents fan-filter modules now available as consumer products, or filtered 100 percent recirculated air commonly used in residential forced air systems. In figure 1, $\dot{V}_r$ represents volumetric flow rate of indoor air for dilution control.

Although Eq. (1) was derived from a simple model, it serves to identify some control strategies and their limitations for indoor air quality control:

- If removal control is not employed, the indoor concentration will exceed the outdoor concentration unless the source is removed or an infinite dilution rate is provided.

- If the indoor contaminant concentration is to be less indoors than outdoors and the dilution rate is finite, the removal rate, $\dot{E}$, must exceed the net generation rate, $\dot{N}$.

- Outdoor air required for dilution control may be reduced, if alternative source control and removal control strategies are sufficient to provide the same quality of indoor air as would be achived by dilution control.

- To achieve an acceptable ΔC, economically, a combined strategy of source, removal, and dilution control may be required.

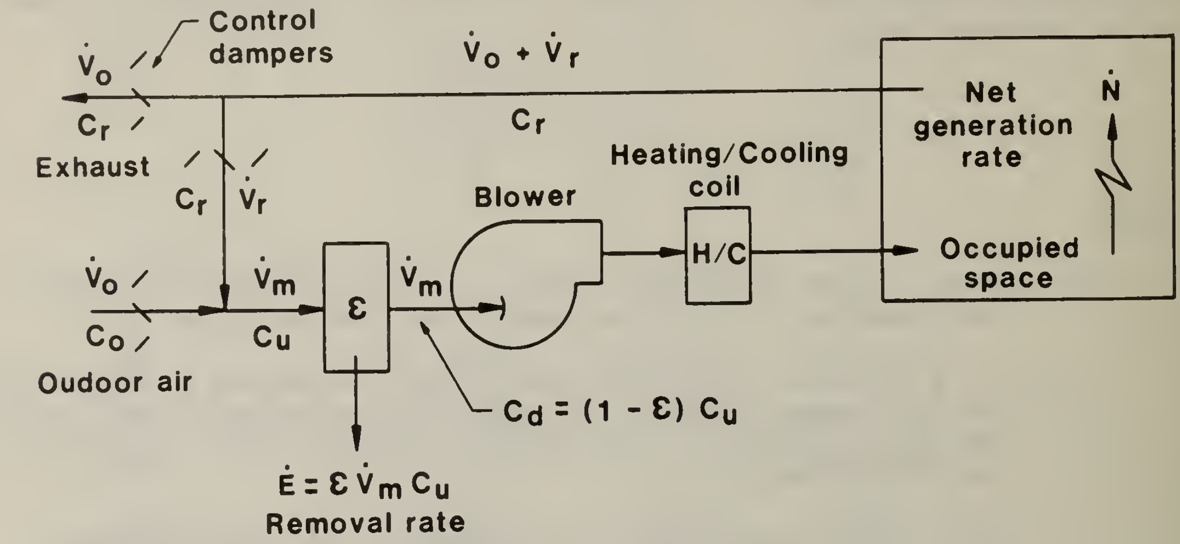


Figure 1. One-compartment, uniformly-mixed, steady-state model for indoor air quality control

Whether an indoor air quality control strategy employs an open-loop or closed-loop system, Eq. (1) indicates that the contaminant concentrations, C_r and C_o, must be known or specified and that the net generation rate, N, must be known or estimated if indoor air quality is to be controlled directly. In this regard, it should be noted that Eq. (1) is analogous to an energy balance in which N may be compared to the cooling load within an occupied space; ΔC to the change in enthalpy required to cool the supply air; and V_o to the volumetric rate of supply air.

4.2 COMPONENTS AND SYSTEMS

To achieve acceptable air quality control in archival record storage facilities, three types of control systems must be considered individually and collectively; temperature and relative humidity control, control of gaseous contaminants, and control of particulate contaminants.

4.2.1 Temperature and Relative Humidity Control

In general, it is expected that only air systems will be used in stack areas, as any steam or water system will present the possibility of water leaks. In a restricted stack area, the impact of people will be minimal upon the thermal and humidity loads from the space. Usually, lighting and transmission loads will be the major space consideration. These may be expected to remain fairly constant, although lights may be on during the day and off at night, and the required circulation air quantity, in terms of cfm per square foot, may be quite low. A minimum amount of air recirculation is desirable to provide proper air distribution in the space and to avoid any stagnant areas. A value of six air changes per hour, or an air diffusion performance index (ADPI) of at least 80 percent [72], is suggested for the minimum air circulation rates, regardless of the load calculated from thermal requirements (see section 3.6).

A constant volume, variable temperature system will probably most often be selected for stack areas. Little variation in temperature and humidity is usually expected within a stack area, so rather large control zones will probably be selected.

Reheat systems are commonly used, and with the proper selection of air temperature after leaving the coil, the amount of reheat can be minimized. Additionally, a hot refrigerant-reclaim circuit should be considered for this reheat energy during operation of refrigeration equipment.

Because the quantity of air that is circulated, based on filtration and distribution criteria, will usually be greater than that required for temperature and relative humidity control, a bypass or primary-secondary air handling arrangement may be used. It may be possible to provide cooling and dehumidification for only the outside air, or for a portion of the total recirculated air.

Winter humidification can be provided by several methods, however, the steam or evaporation type as opposed to atomizing type is preferred in order to minimize airborne particulates. Humidification may be added in the central air handler or individually as zone humidifiers.

A summer cooling coil should be provided for all systems. This will generally be a chilled-water system, as better control is obtainable, although with smaller systems direct expansion may be quite feasible.

Many systems have used a sprayed-coil system or an air washer. Air washing equipment provides a means of partial contaminant control, as well as a source of winter humidity. However, significant problems have been experienced in the long term operation of sprayed coil systems, generally consisting of extensive corrosion, scaling of the coil and fin surfaces, and bacterial growth in the water spray pans. In general, the use of a spray coil or air washer system should be used only when it can be assured that the materials of construction and owner commitment to maintenance will ensure long term operation.

For Category 2 Storage Conditions (table 3), the specified temperature of 10-13°C (50-55°F) and 35 percent relative humidity will be difficult to achieve with commercial equipment. Thus, low-temperature refrigeration and dehumidification equipment will probably be required. The economics of each project will dictate whether indoor design conditions must be modified so that commercial HVAC equipment can be used. Specially designed facilities and environmental conditioning systems will be required for Category 3 Storage Conditions (table 3). The design of these facilities is not addressed in this report.

Construction materials for the HVAC system should be those that would tend to have long life, and would lend themselves to convenient maintenance. The duct systems should generally be unlined galvanized sheet metal, insulated externally where required. For wetted coil casings and drain pans, the use of stainless steel should be investigated. Air handling systems should be arranged such that easy access is obtained between each component for servicing and cleaning.

In general, the traditional outdoor air economizer cycle is not recommended for these systems, as it would tend to introduce excessive amounts of outdoor pollutants. Thus, other energy efficient strategies should be implemented; e.g., heat reclaim chillers, using the recovered energy for reheat; or free cooling cycles; or using cooling tower circuits for reheat.

Economic considerations may govern whether standby equipment is specified for components of the refrigeration and air handling systems. Short term outages of the HVAC system may not cause excessive damage to the stored materials, thus complete redundancy in the HVAC system may not be necessary.

4.2.2 Control of Gaseous Contaminants

The two most common methods of cleaning air of gaseous contaminants are by application of granular beds and wet scrubbers. The state-of-the-art of these air cleaning methods along with other methods have been reported by an Interagency Research Group on Indoor Air Quality [73]. It can be seen from the following sections (4.2.2.1 and 4.2.2.2) that the control of gaseous contaminants using granular beds or wet scrubbers requires an intensive maintenance program to assure their performance over time.

4.2.2.1 Granular Beds

The typical compromise between the objectives of achieving effective gas/solid contact with a granular bed and of minimizing resistance to air flow is realized by selecting granule sizes in the range of 6 to 14 mesh. With such granulation, the half-life of a molecule in the gas phase (before it reaches the surface of a granule) is about 0.01 second [74,75]. Then, if an air stream that contains a concentration of contaminant, C_r, enters such a granular bed, the concentration of contaminants that have never reached the surface of a granule after n seconds of residence time, C_n, is:

$$C_n = C_r \left(2^{-100n}\right) \tag{2}$$

The ratio of C_n/C_r is the penetration, P, of the granular bed. Thus, the contact efficiency, ε, (fraction of molecules that have contacted a solid surface) is:

$$\varepsilon = 1 - \left(2^{-100n}\right) \tag{3}$$

This efficiency term is identical to that described in Eq. (1) and figure 1. Examples of the relationship between residence time, n, and contact efficiency of a granular bed are shown in table 4.

Table 4. Relationship between Residence Time, n, of a Gaseous Molecule in a Granular Bed and the Contact Efficiency, ε, of the Bed

Residence Time (sec.)	2^{-100n}	$\varepsilon = (1-2^{-100n}) \times 100\%$
0.01	0.500	50.0%
0.02	0.250	75.0
0.03	0.125	87.5
0.04	0.0625	93.75
0.05	0.03125	96.88
0.06	0.01562	98.44
0.07	0.00781	99.22

There are other factors to consider:

a. What fractions of the molecules that reach the solid surface are retained there?

b. Is the retention on the surface reversible?

c. What is the capacity of the granular medium for retention of the contaminant?

These questions should be answered in reference to the media commonly used in central HVAC systems. Only two substrates are in common use: activated carbon and activated alumina. Silica gel, synthetic zeolites, and other materials are sometimes used in small, room-type air purifiers sold in the consumer market. However, these latter materials are not generally available for use in central HVAC systems (either residential or commercial).

Activated alumina is used only with chemical impregnations; however, activated carbon may be used with or without impregnation, depending on the application. Tables 5 and 6 summarize the actions of these media.

4.2.2.2 Wet Scrubbers

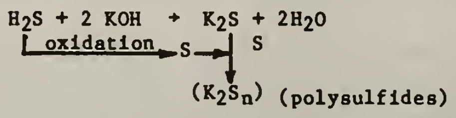
Acidic gases can be scrubbed by alkaline solutions. However, after all of the alkali is neutralized, the scrubber liquid will become acidic and corrosive. Thus, maintenace of a basic condition is important. The scrubber pH required for removal of acidic vapors depends on the strength of the acid. A strong acidic vapor, such as SO_3, is absorbed even by a strongly acidic solution. However, a weak acid, such as acetic acid, requires an alkaline solution.

Wet scrubbing for removal of acid vapors can be incorporated with thermal control strategies to improve energy efficiency and life-cycle costs. However, when these control strategies are combined, additional monitoring may be required or chemical imbalances can result in deterioration of the archival records, deterioration of the mechanical equipment and more expensive maintenance and repairs.

Table 5. Summary of Actions of Activated Alumina (Al_2O_3)

Impregnation	Mode of Action	Reversible?
None (substrate only)	Removes water in preference to other vapors. Not applicable to air cleaning.	Yes
Potassium permanganate $KMnO_4$	As oxidizing agent; it reduced to MnO_2 (brown). Effective for formaldehyde (HCHO) and sulfur dioxide (SO_2), but information on total capacity is not available from refereed journals. For reaction to occur, some moisture must be present, because the action is electrolytic. $KMnO_4$ is reduced to MnO_2 even by water, so its lifetime is limited, at best. However, MnO_2 is a catalyst for air oxidation, so some easily oxidizable contaminants continue to be oxidized, but reactions are slow.	No
Sodium carbonate (Na_2CO_3) or bicarbonate ($NaHCO_3$)	Reacts with SO_2 by acid-base neutralization $SO_2 + Na_2CO_3 \rightarrow Na_2SO_3 + CO_2$	No

Table 6. Summary of Actions of Activated Carbon

Impregnation	Mode of Action	Reversible?
None (substrate only)	Physical adsorption and capillary condensation. Applicable to a broad range of organic contaminants, generally with molecular weights larger than 50. Also adsorbs SO_2 Some catalytic oxidation ($H_2S \rightarrow$ sulfur)	Yes (except for the oxidation)
Sodium hydroxide (NaOH) or potassium hydroxide (KOH)	Neutralization of acidic gases, SO_2, H_2S, NO_2, HCl, acetic acid. Reaction is, for all practical purposes, instantaneous. Now used extensively for removal of H_2S from sewer gases. Capacity depends on amount of caustic used in impregnation, but can be enhanced by some catalytic oxidation on carbon surface.  $H_2S + 2\ KOH \rightarrow K_2S + 2H_2O$ $\xrightarrow{\text{oxidation}} S \rightarrow$ S (K_2S_n) (polysulfides) Some SO_2 oxidized to $SO_3 \rightarrow H_2SO_4$ (retained on carbon)	

4.2.3 Control of Particulate Contaminants

The particulate filtration system must be capable of continous operation with planned maintenance cycles of no less than three months. The system should be capable of removing at least 85 percent of 0.5 μm particles in each pass of the recirculating air stream through the filtration system when tested in accordance with ASHRAE Testing Standard 52-76 dust-spot method [51,76]. If special emphasis is put on the finer particulates (e.g., condensed acid aerosols), electrostatic filters, which offer a relatively "flat" collection efficiency vs. particle-size relationship can offer a real advantage. Upgrading the final filter to the high efficiency particulate air (HEPA) filter range of at least 99.97 percent collection efficiency of 0.3 μm DOP[1/] particles, will offer better protection from the smaller particles [77]. The combination of electrostatic charging of HEPA final filtration offers unique advantages in the lower submicron particle range [78].

To meet the design parameter of a three-month minimum planned maintenance schedule, it is important that a roughing filter be included in both the outdoor air supply system and in the recirculating air system, prior to the high-efficiency filter section. If the outdoor air is injected into the recirculation system downstream of the protected area and upstream to its roughing filter, that roughing filter can serve as protection from both the outdoor and recirculating air.

It is recommended that the roughing filters be roll-type filters using glass fiber media, and that an electrostatic filter be used next in the system, either as a collector or as an agglomerator ahead of high efficiency barrier filters. The reason for this recommendation as stated earlier lies in the added protection in the ultra-fine aerosol range, and in the extension of useful life of the barrier filters [79]. Note that the 85 percent discoloration efficiency target can be reached, or exceeded, with barrier filters alone. If first-cost is of primary importance, this alternative may be worthy of consideration. Extended barrier filter life, and improved ultra-fine aerosol removal will result from inclusion of electrostatic filter in the system. (Note: Typically, electrostatic filters result in less than 0.05 ppm increase of O_3 in the air stream, less than usually found in outdoor air. Further, it is expected that the carbon, or other gaseous filtration material will easily remove even this small amount. It may be further noted that the addition of O_3 in a gas-contaminant cleaning system can enhance retention of acid gases.)

The barrier filters should be extended-surface filters, either of envelope or pleated-paper configuration. They should be capable of attaining the 85 percent dust-spot efficiency target and should have a dust-holding capacity exceeding the targeted maintenance schedule with the dust load described earlier [79,80, 81]. Again, if special attention is to be given to the ultra-fine aerosols, consideration may be given to upgrading these barrier filters to the HEPA range

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[1/] Particle removal performance of high efficiency particulate air (HEPA) filters is normally established by the DOP Smoke Penetration Method, Reference MIL-STD-282 [51,52].

of efficiency, or to just adding the HEPA filters downstream of the regular high efficiency barrier filters to take advantage of still further extension of HEPA filter life [82,83].

Typical initial costs for the various kinds of filters described above, their operating resistance or electrical demand, and estimated service life for archival storage facilities are shown in table 7. This information should be used in comparing the order of magnitude, only, of owning and operating costs for alternative specific systems (system sizes greater than 25 m^3/s or 50,000 cfm).

A rigorous maintenance program, as with gaseous contaminant control systems, is vital to the continued desired performance of particulate removal systems.

4.2.4 Integrative Control

As indicated in the description of the one-compartment model, figure 1, three methods of control are available for thermal loads, gaseous contaminants, and particulate contaminants. These are source control, removal control, and dilution control. The suggestion was also made that, to achieve an acceptable level of concentration in the controlled space economically, a combined control strategy may be needed. As indicated in section 4.2.1, the supply air rate for thermal control may be greater or less than the removal rates needed for gaseous or particulate control. Also, if human occupancy is expected, a minimum amount of outdoor air will be required for ventilation (i.e., the supply of O_2 and dilution of CO_2) of the occupied space. Beyond these minimum conditions, the supply air rate and percent of outdoor air (dilution control) and air cleaner efficiencies (removal control) may be optimized economically within the constraints of acceptable environmental control for the paper-based materials. It is also noted that optimizing between dilution control and removal control presuppposes that source control is more cost-effective than either of the other alternatives, and therefore, that indoor generation rates have been minimized.

Table 7. Estimated 1983 Costs of Installing and Operating Various Particulate Control Devices[1]

Type of Particulate Air Cleaner	Initial Cost (installed)	Average filter Life or Maintenance Schedule	Renewal Cost	Average Operating Resistance	Electrical Usage
Roll-type filters	\$0.05-0.06/cfm	8 months	\$0.005/cfm	0.4 in. H_2O	---
Electronic air cleaners (used as agglomerator)	\$0.30-0.35/cfm	3 months	negligible (manual maintenance)	negligible	20 watts/ 1000 cfm
Barrier filter (85 percent dust spot efficiency)	\$0.05-0.10/cfm	10 months (behind roughing filter) 24 months (behind electronic air cleaner)	\$0.04/cfm	0.8 in. H_2O	---
Barrier filter (HEPA, >99% D.O.P.)	\$0.20/cfm	6 months (behind roughing filter) 15 months (behind roughing filter and electronic air cleaner) 5 - 10 years (behind roughing filter, electronic air cleaner and 85 percent barrier filter)	\$0.15/cfm	1.5 in. H_2O	---

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[1] Estimates based upon the January 19-20, 1983 Workshop on Environmental Conditions for Archival Records Storage, National Bureau of Standards. To convert from ft^3 to m^3 multiply by 2.832×10^{-2}.

5. PERFORMANCE EVALUATION OF ENVIRONMENTAL CONDITIONING SYSTEMS

Experience in museums and libraries has provided abundant evidence that environmental conditions are by no means necessarily what they are assumed to be on the basis of system capability or central control stations, particularly as HVAC systems age, personnel change, and buildings are altered. Thus the importance of a well-designed and carefully executed monitoring system cannot be overemphasized. Moreover, if the purpose of climate control is the preservation of valuable cultural property, it follows that the responsibility for monitoring environmental conditions should rest with those primarily responsible for the preservation of the collections.

For successful performance evaluation, two procedures are needed: monitoring procedures and assessment procedures. Monitoring procedures are needed for data acquisition, and assessment procedures are needed for data analysis. With these procedures, the performance data, obtained through monitoring the systems, may be compared to the specified performance criteria, and compliance with the criteria may be assessed. If compliance is achieved, no specific action is required, but the procedures should be repeated periodically. If compliance is not obtained, the system must be re-evaluated and the discrepancies must be adjusted until compliance is regained. The final two steps in this process may be considered to be the performance evaluation.

5.1 MONITORING PROCEDURES

The performance of the system may be monitored by obtaining data which can be compared to system performance criteria (i.e., thermal, gaseous, and particulate values), see table 3, or which can be compared to component performance criteria (i.e., heat transfer rate across heating and cooling coils; filter efficiencies, pressure drops, and loading capacities). For each factor to be compared, some instrumentation will be required to sense the values, and data acquisition methods will be needed to store the data.

5.1.1 System Performance

The overall system performance should be evaluated in terms of environmental and economic (including energy) factors. The environmental factors, including thermal, gaseous and particulate data, may be obtained with instruments such as discrete samplers or continuous recorders. These devices may have local or remote sensing. The economic factors must be obtained with instruments such as log books and utility records.

The basic instrument currently used for monitoring temperature and humidity conditions in archival storage facilities is the hygrothermograph. These are portable, continuous recording devices which require manual servicing and data transposition for analysis. To date, direct periodic monitoring of the gaseous or particulate concentrations within the facilities is seldom conducted. However, it was reported at the Workshop on Environmental Conditions for Archival Storage that instrumentation has been used for monitoring SO_2 at the Library of Congress.

Data for economic factors and energy consumption will probably be available in forms that will not be readily useful for performance assessment. Thus, these data will probably require transposition to formats that will be useful from an engineering aspect.

5.1.2 Component Performance

Within the overall system, component performance should be evaluated in terms of efficiencies, capacities, and component costs (i.e., maintenance, operational, replacement, etc.).

Performance of thermal control equipment is commonly monitored with portable type instrumentation, or central monitoring systems. The techniques for obtaining these data are well-known, and have been recently given visibility through the propagation of "energy auditor procedures." One such relatively thorough procedure is cited in reference [84].

Performance of gaseous control devices is not as well-known. There are two requirements for monitoring performance of either granular beds or wet-scrubbers.

1. Determination of the efficiency of the air cleaning unit (see figure 1):

$$\varepsilon = \frac{C_u - C_d}{C_u} \times 100\% \qquad (4)$$

2. Determination of the total capacity of the air cleaner in terms of quantity of contaminant that can be removed, or service life before replacement, reactivation, or regeneration is required.

Instrumentation for continuous, real-time monitoring of acidic gases and vapors is available, but somewhat expensive in the low ranges required for indoor air quality monitoring. This problem also exists when the instrumentation is to be used for "zero" effluent concentration or "100 percent" efficiency of the air cleaner. In the case of the granular bed, an alternative method of determining the efficiency may be based on the use of Eqs. (2) and (3). The sample probes are inserted at a bed depth where the efficiency is, say, 50 percent. The detention time to that bed depth is then the half-life of the contaminant vapor, and the efficiency at any other bed depth is:

$$\varepsilon = (1 - 2^{-N}) \times 100\% \qquad (5)$$

where N is the number of half-lives. Using the half-life of 0.01 second in the example cited earlier, the efficiency after 1 second detention time would be $(1 - 2^{-100}) \times 100\% = (100 - (8\times10^{-29}))$ percent, a value that is far too large to be measured. However, the value does mean that there is only a small chance for even one molecule to get through, so it is reasonable to call this value 100 percent efficiency.

Similar approaches for monitoring the efficiency of a wet-scrubber are theoretically applicable, but may be difficult in practice. One method might be to measure effluent concentrations as a function of air flow rate through a scrubber, and extrapolate from high to low rates as the detention time increases.

The problem of determining the total capacity is very different for granular beds and wet-scrubbers, because the concentrations in scrubber liquids are uniform, whereas in a granular bed, a mass transfer or reaction zone moves progressively through the bed in the direction of air flow.

If "capacity" is taken to mean the amount of contaminant that the air cleaner can remove, then the action of the air cleaner is of prime concern. If "capacity" means service life of the air cleaner, then the contaminant concentration must also be known.

In the first instance, the method of test is rather straightforward and can be carried out by procedures analogous to ASTM retentivity tests [75]. In such a test, the adsorbent is first saturated with the challenge gas at high inlet concentration (to accelerate the test), then subjected to a flow of clean air to constant weight. Other approaches to determining the total capacity are also commonly used in working with adsorbents.

For determination of service life, it is essential to establish the time-weighted average concentration of the challenge gas. This can be done by continous instrumental monitoring. Then the service-life may be determined as:

$$T_{SL} = \frac{C_{sat} \times V}{C_{ave} \times \dot{V}} \tag{6}$$

where

T_{SL} = service life (time)
C_{sat} = saturation concentration (mass/volume)
C_{ave} = average ambient concentration (mass/volume)
V = total volume of granular bed
$\dot{V}$ = volumetric air flow rate through the bed (volume/time)

Another approach to monitoring the capacity and service life is to use sequential adsorbent samplers. This approach has recently been described by Turk, et al. [85].

Performance of particulate filters should include the monitoring of the pressure drop across barrier filter (i.e., the operating resistance), and monitoring of the operating voltages of electronic air cleaners. Usually, such readings are adequate to ensure correct operation of filters.

5.2 ASSESSMENT PROCEDURES

The assessment of system performance is accomplished by analyzing the monitored data and comparing the results in terms of the specified criteria. This comparison may be done for system performance or component performance criteria.

5.2.1 System Performance

If comparisons between monitored and specified data are to be meaningful, sufficient data must be obtained so that representative or mean values, and standard deviations or ranges can be determined. It is also imperative that reasonable specifications be used. For example if precise control of relative humidity is required, then not only must the humidity control system be responsive, but the temperature control system must also be responsive and precise.

Also, for gaseous and particulate control, compatibility between the specified methods of control and sensitivity of the monitoring instrumentation must be assessed. It is possible to provide control conditions through open-loop systems that will maintain concentrations below the least-count sensitivity of the instrumentation [71].

5.2.2 Component Performance

As in the case for system performance assessment, care is required to assure that the conditions of specified performance of a component are compatible with those which existed during the period of monitoring. A need exists here for assurance of dynamic stability.

5.3 EVALUATION PROCEDURE

Results of the component performance or system performance assessment should be evaluated by a well-qualified person, with authority to rectify any "unacceptable" performances of the system as compared to its specified performance. Many cases exist to support the position that this type of performance evaluation can lead to environmentally acceptable and cost-effective operations.

6. BASELINE DATA FOR SELECTED FACILITIES USED FOR STORAGE OF PAPER-BASED MATERIALS

Measurements were made by NBS of gaseous contaminants, temperature, and relative humidity in the National Archives Building, the Madison Building of the Library of Congress, and the East Wing of the National Gallery of Art. Air exchange rate measurements indicating exchanges between the indoor air and outdoor air were also made by NBS at the National Archives Building. Temperature and relative humidity data from continuous recording hygrothermographs and printouts from selected locations in the storage areas of the National Archives Building were analyzed. The purpose of these measurements and analysis was to provide baseline data for the National Archives Building on the range of control of current air quality which could be useful in the upgrading of the environmental conditioning system. Further, the air quality in the National Archives Building could be compared with the air quality in newer facilities having more modern types of environmental conditioning systems.

6.1 FACILITY AND TYPE OF ENVIRONMENTAL CONDITIONING SYSTEM

6.1.1 National Archives Building

The environmental conditioning systems were installed in the National Archives Building in 1935 when the building was new. These systems have been modified several times. Currently, about 10 percent outside air mixes with return air. The mixed air passes through a prefilter and bag filter before passing a coil where the air is heated, or cooled, or dehumidified. After passing the coil, steam is used for humidification of the air before it reaches the supply fan. The return air is filtered (bag filters) before it is mixed with the outside air.

Nine air handling systems serve the National Archives Building (other than the garage). Seven of the systems have two supply fans and one return fan each, while each of the other two systems has one supply fan and one return fan. According to National Archives and Records Service personnel, most of the air handling systems serve both storage areas and offices. It was found by NBS from air exchange measurements that air mixes rapidly throughout the building (appendix C).

6.1.2 Madison Building of the Library of Congress

The Madison Building was completed and occupied in 1978. The HVAC system in this building has 48 environmental zones. The zones are provided for interior and building perimeter loads. All systems feeding the zones are high pressure, 1500 to 2000 Pa (6 to 8 in. H_2O) at fan discharge. All zones are provided with 20 percent make up air. Temperature is controlled at 20°C (68°F) and relative humidity at 50 percent in the storage areas. Occupied areas are controlled at comfort conditions.

Two diferent types of HVAC systems are used, one for storage areas and another for occupied areas. The systems are straight draw through with steam humidification. For the storage areas, 100 percent of the air passes through chilled water coils, whereas, for the occupied areas, the air is regulated so that only a portion of the air passes through chilled water coils depending on comfort conditions.

The only pollution control in the storage areas is for SO_2. Outside air is prefiltered before passing through packed beds, 0.5 m (19 in.) thick, of activated alumina (Al_2O_3) crystals coated with potassium permanganate. SO_2 in the air oxidizes to SO_3 which is trapped as potassium sulfate in the catalyst or purifier beds. After the air passes through the catalyst beds it is mixed with return air. The mixed air is then prefiltered before passing through bag filters and washer units. Tap water is used in the washer units. The design specifications limited SO_2 to a maximum value of 5 ppb. Measurement by Architect of the Capitol personnel indicate that SO_2 concentration is actually controlled to about 2 ppb. NBS measurements agree (appendix B). Architect of the Capitol personnel did not measure NO_x concentration. NBS found that NO_x concentrations tracked outdoor levels (figure 4, appendix B).

6.1.3 East Wing of the National Gallery of Art

The East Wing of the National Gallery was completed and occupied in 1978. Its HVAC system is not zoned with regard to gallery and occupied space. The system provides the building with 15 percent make up air. The outdoor air is passed through two sets of bag filters, over a preheat coil, and then through an air washer which is slightly alkaline. The air washer also humidifies the air. The air is then mixed with filtered return air. The mixed air is supplied at a temperature of 17-18°C (62-65°F). The gallery and occupied spaces are intended to be kept at 22°C (72°F) and 48 percent relative humidity. National Gallery personnel have not attempted to monitor the level of gaseous contaminants in the East Wing.

6.2 MEASUREMENTS AND DATA ANALYZED BY NBS

6.2.1 Sulfur Dioxide, Nitrogen Oxides, Ozone, Temperature, and Relative Humidity

Measurements of gaseous contaminant concentrations (SO_2, NO_x, and O_3), temperature, and humidity were made by NBS at the National Archives Building, Madison Building of the Library of Congress, and the East Wing of the National Gallery. The results of the measurements in the buildings and of the outdoor air are presented in appendix B. The outdoor measurements were taken 2.7-4.3 km (1.7-2.7 miles) from the three buildings by the Washington, D.C. government.

The nitrogen oxides concentration(s) in the three buildings and at the monitoring station show in general, two peaks each day corresponding to the morning and evening rush hours. The nitrogen oxides measured in the three buildings appeared to track the external atmospheric concentrations measured by the Washington, D.C. government. The concentration of nitrogen oxide in all three buildings, in general, greatly exceeded the criterion of 5 $\mu g/m^3$ (2.5 ppb for NO_2) given in section 3.6. It is difficult to determine how much or if any nitrogen oxides are removed by the HVAC systems in these buildings. The level of nitrogen oxides in general varied from day to day and was probably affected by the weather. The HVAC system in the National Archives Building essentially did not remove nitrogen oxides from the incoming air. While the HVAC systems in the two other buildings may have removed a small part of the atmospheric nitrogen oxides, the lower concentrations indoors than outdoors may be explained equally well by low air exchange rates (air exchange rates were not measured in these two buildings).

It appears that there is a correlation between the direction of the difference between the measurements made in the Archives Buildings and those made by the Washington, D.C. government, and the location of the air intake for the particular air handling system. The four air handling systems with penthouse or roof air intakes had lower nitrogen oxides concentration than the outdoor concentration. Air handling systems with air intakes at ground level showed, in general, higher concentration than the outdoor concentration. Nitrogen oxides concentration in the Madison Building and the East Wing of the National Gallery were, in general, less than the outdoor concentration. The air intakes for these two buildings were located at roof-top level.

Although the sulfur dioxide concentrations in eleven stack areas of the National Archives Building were less than the outdoor concentration, most of these concentrations exceeded the criterion of $\leq 1\ \mu g/m^3$ (0.4 ppb) given in section 3.6. The sulfur dioxide concentrations in the other two buildings (one site was monitored in each building) were less than 0.5 ppb in the Madison Building and 1 ppb in the East Wing of the National Gallery. Since these concentrations (0.5 and 1 ppb) were lower detectable limits of the instrumentation, it is not known if the concentrations of SO_2 in these two buildings were less than the criterion of $1\ \mu g/m^3$ (0.4 ppb) given in section 3.6. Outdoor concentrations ranged from 3 to 99 ppb.

No ozone was detected in any of the three buildings, while outdoor concentrations were up to 21 ppb. This may be explained by the high reactivity of ozone. These measurements were made during the winter. Outdoor ozone concentrations are higher in the summer. The criterion (section 3.6) limits ozone concentration to $25\ \mu g/m^3$ (13 ppb).

The temperature and relative humidity measurements made by NBS during the measurements of the gaseous pollutants indicate that the temperature in all three buildings was, in general, controlled to within narrow limits, and the relative humidity was controlled to within about 3.5 percent in the Madison Building and the East Wing of the National Gallery (table 9, appendix B). For twelve of the thirteen locations monitored, the temperature ranged from 20.4 to 23.7°C (68.7 to 72.7°F). The relative humidity in the National Archives Building varied from 31 to 58 percent in the stack areas. The average (median) temperature was 22.2°C (72.°F) in the National Archives Building, 21.1°C (70.0°F) in the Madison Building and 21.8°C (71.2°F) in the East Wing of the National Gallery. Storage area temperatures in the National Archives Building measured by NARS/GSA (section 6.2.3) were found to be similar to return air temperatures measured by NBS (appendix C).

6.2.2 Air Exchange Rate Measurements in the National Archives Building

Air exchange measurements were carried out at the National Archives Building under various combinations of temperature and wind speed. The purposes of the measurements (described in detail in appendix C) were to:

(1) Determine the air exchange rate (as defined below) of the building under normal operation of the heating, ventilating, and air conditioning (HVAC) system, and with the outdoor air dampers closed.

(2) Determine the extent of air movement between archival storage areas and other areas of the building.

(3) Assess the intrinsic air-tightness of the building envelope by means of a fan pressurization test.

Air exchange rate, the rate at which outdoor air enters the condition space, is defined as:

$$I = \dot{V}/V \tag{7}$$

where:

I is the air exchange rate (air changes/hour, or h^{-1})

$\dot{V}$ is the volumetric air flow rate into or out of the building (m^3/h)

V is the building volume (m^3).

The average air exchange rate under normal operation of the HVAC system was 0.9 h^{-1} for an average indoor-outdoor temperature difference of 11.3°C (20.3°F) and an average wind speed of 2.7 m/s (6.0 mph). No clear dependence of air exchange rate on temperature differences up to 17°C (31°F) or wind speeds up to 5 m/s (11 mph) was found.

With outdoor air dampers closed and fans operating, the average air exchange rate was 1.2 h^{-1} for an average indoor-outdoor temperature difference of 8.2°C (14.8°F) and an average wind speed of 1.7 m/s (3.8 mph). The air exchange rates for temperature differences between 11°C (20°F) and 17°C (31°F) with the dampers purposely closed, are similar to those under normal HVAC operation and similar temperature differences. This may be because under normal operation of the HVAC system, the dampers would be closed at these outdoor temperatures.

A test of interzone air movement showed that air migrates rapidly between non-stack and stack areas with fans operating normally.

The building could not be pressurized to an indoor-outdoor pressure difference beyond 14 Pa (0.06 in. H_2O). At this pressure difference the air exchange rate was 1.5 h^{-1}.

A similar study of eight new GSA buildings in various parts of the United States [86] shows that the National Archives Building is about twice as leaky as new office buildings, both under normal operation of the HVAC system and under pressurization. Their air exchange rates under normal operation of the HVAC systems vary from 0.2 to 0.6 h^{-1} for outdoor temperatures of 4-10°C (39-50°F) and wind speeds under 1.3 m/s (2.9 mph). Their air exchange rates at a pressure difference of 14 Pa (0.06 in. H_2O) were 0.5 to 0.9 h^{-1}.

6.2.3 Analysis of Temperature and Relative Humidity Data Recorded by the National Archives and Record Service and the General Services Administration

Stack temperature and relative humidity measurements, continuously recorded by hygrothermographs, were provided by the National Archives and Records Service. Printouts of stack temperature and relative humidity were provided by the General Services Administration. The data on the printouts were recorded automatically from instrumentation installed in the stack areas. These data were analyzed for their variation over time, and uniformity among stack areas.

Printout data were recorded at 10:00 a.m. and 2:00 p.m. on May 6, 1983. The continuously recorded data from the hygrothermographs began on May 3, 1983 and, in general, continued for 6 days.

Comparisons were made of the temperature and relative humidity data from the hygrothermograph charts and printouts for each of the 44 stack areas. The temperature and relative humidity data are presented in table 8 along with the number of days data were continuously recorded by hygrothermographs. There was one hygrothermograph and from one to three temperature and relative humidity sensors in each stack area. The locations of the instrumentation in the stack areas were not reported.

From table 8, the temperature and relative humidity data can be summarized as follows:

a. Temperatures were consistent for both hygrothermograph charts and printout data. The median temperature was 22°C (72°F) for the hygrothermograh readings and 23°F (73°F) for the printout data. The temperature range was 19 to 26°C (66 to 78°F).

b. For 21 of 27 stack locations for which comparisons could be made, relative humidity was consistent for hygrothermograph charts and printout data. The median relative humidity was 40 percent for the hygrothermograph charts, and 39 percent for the printout data. The range in relative humidity was 28 to 54 percent for the hygrothermograph charts and 21 to 50 percent for the printout data.

c. For the hygrothermograph data, there was a difference of 3°C (6°F) or less between the high and low readings for 39 of 41 stack areas.

d. For the hygrothermograph data, in 37 of 41 stack areas for which data were available there was a difference of 10 percent or more between

Table 8. Temperature and Relative Humidity Data

Area	Hygrothermograph Data[1]							Printout Data			
	Temperature May 6		Temperature Range	Relative Humidity May 6		Relative Humidity Range	Number of Days[2]	Temperature May 6		Relative Humidity May 6	
	10 a.m. °F	2 p.m. °F	May 3 - 9 °F	10 a.m. %	2 p.m. %	May 3 - 9 %		10 a.m. °F	2 p.m. °F	10 a.m. %	2 p.m. %
5E4	71	72	70 - 74	36	35	35 - 54	6	72	72	39	39
5E3	72	72	70 - 74	37	37	37 - 49	6	73	73	33	33
5E3	—	—	—	—	—	—	—	73	73	31	31
6E3	71	72	70 - 74	34	32	32 - 44	5	73	73	31	30
6E3	—	—	—	—	—	—	—	71	71	21	21
21E3	67	67	62 - 68	44	43	41 - 92	6	—	—	—	—
21E4	66	66	64 - 68	54	50	51 - 70	6	—	—	—	—
21W4	73	73	72 - 76	37	37	37 - 46	5	74	74	36	36
21W4	—	—	—	—	—	—	—	74	74	42	42
21W3	70	70	68 - 73	28	29	29 - 37	6	—	—	38	39
19E1	74	74	73 - 75	31	32	31 - 48	6	—	—	—	—
19E2	77	78	74 - 80	31	33	32 - 41	6	—	—	—	—
19E3	67	67	60 - 70	45	44	32 - 75	5	—	—	—	—
18E1	68	68	67 - 67	38	37	36 - 53	3	—	—	—	—
18E3	69	70	68 - 72	43	42	42 - 55	3	—	—	—	—
18E2A	67	67	66 - 70	37	37	36 - 48	5	—	—	—	—
18W2A	69	70	70 - 72	35	35	34 - 48	6	—	—	—	—
18E4	72	72	71 - 73	41	40	42 - 54	4	—	—	—	—
14E3	72	72	72 - 72	49	45	45 - 68	6	70	70	36	36
14E3	—	—	—	—	—	—	—	69	70	—	—
13E3	—	—	68 - 72	—	—	58 - 79	3	72	72	40	40
13E3	—	—	—	—	—	—	—	70	70	39	39
12E1	72	72	68 - 72	40	40	40 - 68	4	70	70	35	37
13E4	72	72	70 - 73	38	38	40 - 51	4	73	73	35	34
11E2	71	72	71 - 74	41	40	40 - 58	3	69	69	40	40
11E2	—	—	—	—	—	—	—	69	69	40	41
10E2	—	—	47 - 49	42	42	42 - 63	6	68	68	41	42
10E2	—	—	—	—	—	—	—	70	70	40	40
8E1	—	—	—	—	—	—	—	70	70	40	40
7E1	76	78	70 - 78	40	40	40 - 54	6	74	74	41	41
2E2	66	67	63 - 67	40	40	40 - 60	6	70	70	46	45
2E2	—	—	—	—	—	—	—	68	68	44	45
3E2	69	70	68 - 70	46	46	46 - 69	4	67	67	32	32
3E2	—	—	—	—	—	—	—	69	69	40	41
3E2B	72	72	69 - 72	—	—	52 - 66	4/1[3]	—	—	—	—
3E2A	73	73	72 - 78	38	39	36 - 50	4	74	74	—	—
3E2A	—	—	—	—	—	—	—	77	77	40	41
G13	75	76	71 - 77	32	38	32 - 58	4	75	77	38	46
2W1	74	75	70 - 75	40	40	32 - 50	6	75	76	37	39
2W1	—	—	—	—	—	—	—	75	75	39	41
19W3	72	73	72 - 78	30	30	30 - 50	5	72	72	32	33
19W3	—	—	—	—	—	—	—	74	74	-1	-1
18W1	—	—	—	—	—	—	—	75	76	44	41
18W1	—	—	—	—	—	—	—	75	77	38	35
18W2	74	—	72 - 75	37	—	32 - 47	3	74	75	41	43
15W3	76	76	75 - 80	34	34	34 - 49	4	73	73	30	31
15W3	—	—	—	—	—	—	—	74	74	33	34
13W3	74	75	70 - 76	26	28	25 - 46	6	74	74	29	30
13W3	—	—	—	—	—	—	—	75	75	30	33
11W1	—	—	—	—	—	—	—	73	73	41	41
11W4	74	74	73 - 76	45	42	40 - 54	7	73	73	36	37
11W2A	72	72	70 - 73	42	42	40 - 56	4	70	70	23	25
11W2	68	69	67 - 70	46	45	37 - 54	6	69	69	46	46
11W2	—	—	—	—	—	—	—	69	69	47	48
10W2	70	71	68 - 71	50	50	42 - 58	6	68	68	50	50
10W2	—	—	—	—	—	—	—	68	68	50	50
8W2	73	74	71 - 75	46	47	42 - 54	4	69	69	47	49
8W2	—	—	—	—	—	—	—	68	68	49	50
8W3	72	73	72 - 77	34	34	33 - 50	5	75	74	33	34
8W3	—	—	—	—	—	—	—	75	75	35	36
5W2	68	68	64 - 68	46	48	39 - 58	6	68	68	49	50
5W2	—	—	—	—	—	—	—	68	68	49	50
4W1	74	74	72 - 74	37	44	37 - 54	4	74	75	38	40
1W1	—	—	74 - 76	—	—	30 - 36	2	75	76	38	39
1W1	—	—	—	—	—	—	—	77	77	34	37
1W1	—	—	—	—	—	—	—	75	76	35	37

[1] Temperature and relative humidity data continuously recorded beginning about 10 a.m. on May 3.

[2] Number of days that temperature and relative humidity were continuously recorded on charts.

[3] Temperature recorded for 4 days and relative humidity recorded for 1 day.

the high and low values of relative humidity. In 29 stack areas this difference was 14 percent or greater. The maximum range of relative humidity was 29-92 percent.

e. The temperature in the stack areas was controlled within reasonable limits, however, there was little or no control of relative humidity.

7. SUMMARY

To aid the National Archives and Records Service and the General Administration in improving environmental conditions for storage of paper-based archival records at the National Archives Building, criteria are proposed for levels of environmental control and baseline data are provided on the present range of control of air quality in this building. The proposed criteria (table 3, section 3.6) are based on available information on the preservation of paper-based materials and the capabilities of environmental conditioning systems. Recommendations from the January 19-20, 1983, National Bureau of Standards Workshop on Environmental Conditions for Archival Storage are included in the proposed criteria. Other design parameters are addressed and recommendations made regarding factors to consider in the design of archival storage facilities.

Measurements were made by NBS of temperature, relative humidity, and gaseous air pollutant concentrations at the National Archives Building, and for comparison, at the Madison Building of the Library of Congress and the East Wing of the National Gallery of Art. These two buildings have modern (1978) environmental conditioning systems. Air exchange rate measurements under various conditions were taken at the National Archives Building to test the performance of the HVAC system, to measure air leakage into and out of the building, and to measure air mixing between storage and other areas of the building.

The January 19-20, 1983, National Bureau of Standards Workshop on Environmental Conditions for Archival Storage divided storage conditions into three categories on the basis of length of time of storage and accessibility of storage materials to the public. Storage temperature and relative humidity given in the proposed criteria (table 3, section 3.6) were recommended to be successively lowered as required accessibility decreased. In all three cases, temperature and relative humidity should be maintained nearly constant at their recommended levels. The recommended air pollutant limits were 1 μg/m^3 (0.4 ppb) for SO$_2$, 5 μg/m^3 (2.5 ppb for NO$_2$) for NO$_x$, 25 μg/m^3 (13 ppb) for O$_3$, 4.5 $\cancel{\mu}$g/m^3 for CO$_2$, and 75 μg/m^3 for total suspended particulates (table 3, section 3.6). ✓

A review of literature (section 2) describes the damage that may be caused by temperature, relative humidity, and air pollutants to paper-based records, and gives examples of air quality criteria used by various libraries and musuems.

Concentrations of SO$_2$ in the National Archives Building, where SO$_2$ is not controlled, were much greater than 1 μg/m^3, while concentrations in the other two buildings were about the same or possibly lower than this recommended limit. SO$_2$ concentrations in the Madison Building and East Wing of the National Gallery of Art did not exceed the lower detectable limits of the instrumentation of 1 μg/m^3 (0.5 ppb) and 2 μg/m^3 (1 ppb) respectively. Nitrogen oxides concentrations in these two buildings were lower than in the National Archives Building, but frequently exceeded 5 μg/m^3. Concentrations of NO$_x$ in all three buildings tracked outdoor concentrations. NO$_x$ concentrations in the National Archives Building for those air handling systems having roof air intakes, were lower than the measured outdoor concentrations at ground level reported by the Washington, D.C. Government. With air intakes at ground level, indoor NO$_x$

concentrations were higher than outdoor concentrations. Ozone was not detected in any of the three buildings (appendix B).

Temperature was well-controlled in all three buildings. The median temperature was 22-23° C (72-73° F) in the National Archives Buidling (section 6.2.3). Relative humidity was well-controlled in the Madison Building and the East Wing of the National Gallery. It was not controlled in most of the storage areas in the National Archives Building, where it ranged from 29 to 92 percent (section 6.2.3).

Air exchange rates between indoor and outdoor air in the National Archives Building were found to be about 0.9 air changes per hour at an average indoor-outdoor temperature difference of 11.3° C (52.3° F) and average wind speed of 2.7 m/s (6.0 mph) with the HVAC system operating. An air exchange rate of 1.5 changes per hour was found at an indoor-outdoor pressure difference of 14 Pa (0.06 in. H_2O). The air exchange rates under both natural and pressurized conditions were about twice the air exchange rate for newer General Services Administration office buildings. The tests showed that air in storage areas in the National Archives Building is immediately and thoroughly mixed with air in office and public use areas (appendix C).

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APPENDIX B.

NBSIR 83-2767

Measurement of the Concentration of Sulfur Dioxide, Nitrogen Oxides, and Ozone in the National Archives Building

November 1983

U.S. DEPARTMENT OF COMMERCE

NATIONAL BUREAU OF STANDARDS

NBSIR 83-2767

MEASUREMENT OF THE CONCENTRATION OF SULFUR DIOXIDE, NITROGEN OXIDES, AND OZONE IN THE NATIONAL ARCHIVES BUILDING

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FIGURES

The figures consist of five figures that are plots of the concentration of oxides of nitrogen measured at different locations. These begin on page 15.

Introduction

The ubiquitous nature of certain gaseous substances in the atmosphere assures us that if these substances exist in appreciable quantities outside of a building they will surely exist to an equal or lesser degree within the building unless some sort of barrier is interposed between the interior and exterior of the building. A brief study performed in 1977 at the National Archives indicated that both ozone and nitrogen oxides passed freely into the building through the ventilating system, but that sulfur dioxide was reduced in concentration compared to that expected from the outside air. The study described in this report was performed in a similar manner, but with several major differences in scope and with a somewhat different outcome. [The original report is appended.]

In the 1977 National Archives study, ozone, sulfur dioxide and nitrogen oxide were measured in only one area. In the present study, measurements were made at eleven locations, each supplied by a different supply fan.[1] The conclusion reached in 1977 regarding the reduction in sulfur dioxide could not be confirmed by the present study, although the finding regarding nitrogen oxide was essentially the same.

In addition, measurements were made at single sites in the Madison Building of the Library of Congress and in the library area of the East Wing of the National Gallery of Art. These measurements were intended to offer a comparison between an older ventilating system (circa 1932) and newer systems designed specifically for buildings intended for archival storage.

Experimental Approach

The measurements had a two-fold purpose: first, to determine whether or not the ventilating system modified the quality of atmospheric air during passage into the building, and second, to measure the concentration of each of the three species of interest in air passing into the stack (archival storage) areas of the building. The second purpose can be fulfilled by interior measurements using calibrated instruments. The first could be satisfied by simultaneous measurments of the air entering the ventilating system and air exiting the system into the stacks. However, such simultaneous measurements would require duplicate instrumentation, considerably more time at each location, and substantially increased costs. In any case, it was concluded in the 1977 National Archives study that this approach was not feasible because of the geometry of the building and the inaccessibility of the intakes of many of the systems. It was concluded, nonetheless, that observations of the pattern of concentration changes in the ambient atmosphere of Washington, D.C. and the pattern of changes within the building would yield sufficient information regarding the current capability of the system for removing portions of the pollutant gases of interest. Fortunately, the District of Columbia continuously monitors these gases, and the data from such measurements were made readily available for this study.

The supply air entering each sampling site was measured for a minimum of 24 hours, but in most cases for at least 48 hours. Nitrogen oxides as NOx (NO_2 + NO) and sulfur dioxide were measured continuously, while ozone was measured for several short periods of time during each day of sampling. Calibrations were performed at the beginning and end of each sampling period, and once every 24 hours during that period. Permeation tubes were used to calibrate the sulfur dioxide analyzer, while permeation tubes and an analyzed mixture of nitric oxide in nitrogen were used to calibrate the nitrogen oxide analyzer.

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[1] Nine consecutively numbered heating and air conditioning systems serve the National Archives Building. Each, with the exception of systems 2 and 4, is composed of two supply fans and one return fan. Systems 2 and 4 each have one supply fan and one return fan.

The ozone instrument was operated as an "absolute" instrument whose measurement characteristics were predetermined at NBS. It was only necessary to measure instrument temperature and barometric pressure to calculate the ozone content of the sampled air.

During each analytical period several measurements of barometric pressure, temperature, and relative humidity were made. These measurements were made near the analytical site, away from the direct flow of supply air, but close enough to be reasonably sure that the sampled air originated in the particular ventilating system. Temperature and humidity measurements are summarized in Table 9.

Sample Sites

The sample sites are listed in Table 2 in the order in which the measurements were made. The information regarding stack areas and the identification of the supply fans and ventilating system supplying each area was furnished by the National Archives. The sample probe was located directly in the path of the air entering the area from the ventilating system. In most cases, the probe was moved at least once during each sampling period to an area away from the inlet vent.

The sample site in the Madison Building was in the Manuscript Preparation Section adjacent to a doorway marked LM123. The sample inlet probe was located about 2.5 meters above floor level.

Table 1. Sampling Location and Dates at The National Archives.

Sequence	Sampling Site	Supply Fan	Sampling Period
1	3E3	9A	Dec. 1-3, 1982
2	1E2A	5B	Dec. 3-7, 1982
3	9E1	7A	Dec. 7-9, 1982
4	7E4	9B	Dec. 9-10, 1982
5	10E2	7B	Dec. 12-17, 1982
6	9W4	8B	Dec. 28-30, 1982
7	9W3	8A	Jan. 3-5, 1983
8	9W2	6A	Jan. 5-7, 1983
9	19W2	6B	Jan. 11-13, 1983
10	17W1A	1B	Jan. 13-14, 1983
11	3W2B	5A	Jan. 19-27, 1983

Sampling in the East Wing of the National Gallery of Art was done in stack level "B" in the library area. The probe was located at ceiling level adjacent to an air inlet duct.

Data Collection — Sulfur Dioxide and Nitrogen Oxides

The signals generated by the sulfur dioxide and the nitrogen oxides were continuously recorded on a strip chart recorder. The "zero" for each instrument was established during daily calibration periods by analyzing "zero air" produced by a clean air generator. The signal produced by the sampled air was adjusted for zero and converted to a concentration using one of the calibration factors determined during the daily calibration. Several points on each chart were read during each hourly period and the final concentrations are expressed as hourly averages. All of the hourly averages for sulfur dioxide and nitrogen oxide for each sample site are included in Tables 4 and 6. Tables 5, 7 and 8 include the hourly averages of nitrogen oxides, sulfur dioxide and ozone measured by the Air Monitoring Division of the Bureau of Air and Water Quality of the District of Columbia.

Data Collection — Ozone

Ozone measurements at the first few sites were made at approximately 30 second intervals for periods of up to 16 hours. As the study progressed, it became obvious that little or no ozone was present in the building and the sample periods were shortened in length. Initially, the data were averaged over the sampling period or for one-hour intervals (whichever was larger), and the averages were compared to the averages from "zero air".

Calibration

The accuracy required for a study such as the one described in this report is not great. An uncertainty in the measurements of 10% will still allow reasonable conclusions to be drawn. It was possible, therefore, to devise a calibration scheme that was adequate relative to the accuracy needed, and which also lay within the bounds set by the requirements for portability, availability, and economy. As previously mentioned, permeation tubes were used as calibrants for sulfur dioxide and nitrogen dioxide, while a gas mixture of nitric oxide in nitrogen was used to calibrate for nitric oxide. The uncertainty of the gas mixture was ±2 percent relative, and was established by analysis against primary gravimetric standards.

The uncertainty of composition of a calibration mixture generated by permeation tubes depends on the uncertainty of the permeation rate of the tube and the uncertainty in the flow of diluent air passing over the tube. The flow of air was measured with a calibrated rotameter. The permeation rate at the time of each calibration was estimated from the measured temperature dependence of the rate, and the temperature of storage just before calibration. It is difficult however to assign uncertainties to the various parameters affecting the concentration; therefore, the uncertainties of the concentrations of the calibration mixture generated with permeation tubes are estimated from measured instrument responses. This assumes that the instrument is stable and that the day-to-day variations are due to differences between the calculated and actual concentrations. The observed variation of the sensitivity (signal/concentration) for both sulfur dioxide and nitrogen oxides analyzers calibrated with permeation tubes was about ±10 percent relative over the more than two months course of the measurements. It should be noted that the ±10 percent variation affects the absolute measurement and not the relative measurements. That is, variations during an analysis can be defined with much greater certainty than can the absolute concentration at any time.

The calibration mixture uncertainty affects the measurement of sulfur dioxide much more than the oxides of nitrogen. This is because the primary calibration of the oxides of nitrogen depended on a stable gas mixture, with the permeation tubes used as an additional confirmation of instrument sensitivity (and to assure that the measured NOx reflected the true sum of NO + NO_2). Consequently, the maximum uncertainty of the measurement of oxide of nitrogen does not exceed ±5 percent relative.

The ozone instrument is essentially an absolute photometer. The absorption path length and the absorption coefficient for ozone are both known with a small uncertainty. It is only necessary to measure the temperature and pressure of the sample in the absorption cell to allow a calculation of the ozone concentration. However, because little or no ozone was measured at any of the sampling sites, it was really necessary only to be sure that the instrument was on and functioning during each sampling period.

Results — Oxides of Nitrogen

The principal source of oxides of nitrogen in Washington, D.C. is the internal combustion engine of motorized vehicles. Since these oxides are distributed over the entire urban area, it is expected that patterns of concentration would be similar in different parts of the city. This we found to be true when comparing the concentrations measured by the District of Columbia at 24th and L Streets, N.W., with concentrations measured at the National Archives, the Madison Building of the Library of Congress, and the East Wing of the National Gallery of Art (Tables 4 and 5). In general, the diurnal pattern of nitrogen oxide at any location shows two peaks corresponding to the morning and evening rush-hours. The minimum concentration occurs between 2:00 and 5:00 a.m. During daylight hours between the morning and evening rush there is another period of decreased concentration. However, this concentration is usually higher than the early morning minimum. Figure 1 represents measurements made over a 48-hour period at site 9W2 in the National Archives and measurements made during the same period at 24th and L, N.W. While the magnitude of the peaks are different, the peaks occur at the same times and, more importantly, the periods of reduced traffic (and presumably more diffuse sources) show surprisingly good coincidence. The differences in peak heights are most likely due to different physical locations of the sample probes and local variation in traffic density. The 24th and L probe is suspended at a height of about 8 meters above L Street. The sample probe at the Archives was located inside the building and was sampling air obtained from rooftop level.

Figure 2 represents similar measurements made at site 9W4, and Figure 3 represents measurements made at site 9E1. Site 9W4 gave results a little more typical than 9W2, only in that the coincidence of the two separate curves was somewhat less ideal. The measurements at 9E1 illustrate a situation which is not readily explained. Beginning around 1700 of Day 1 very unexpectedly high concentrations were recorded, and the signal exceeded the range of the recorder at the Archives' site early in the evening. The interesting point is that the concentration within the Archives is precisely tracking the external atmospheric concentration.

In several cases, the concentration of nitrogen oxides within the Archives exceeded that measured by the District of Columbia throughout the entire sampling interval or during a substantial part of the interval. The differences between the District of Columbia measurements and the measurements in the Archives can be correlated with the location of the intake for a particular system. If the results are examined carefully, the two systems with four attic or roof intakes have lower nitrogen oxide contents than the measurements made simultaneously by the District of Columbia. Those systems with intakes at ground level show higher values than the simultaneous District of Columbia measurements, with few exceptions. Even the exceptions, 9E1 and 10E2, show the correlation during part of the sampling period. This is summarized in Table 2.

The oxides of nitrogen measured at the Madison Building of the Library of Congress and at the East Wing of the National Gallery of Art track the concentration measured by the District of Columbia in a similar manner to the National Archives (Figs. 4 and 5). Perhaps because the ventilating system intakes for these two buildings are located at rooftop level, the measurements inside are generally less than the measurements at 24th and L, N.W.

Table 2. Relationship Between Air Inlet and Relative Concentration of Nitrogen Oxides.

Supply Fan	Stack	Intake Location	Archives Relative to D.C.
8A	9W3	Attic	Less
8B	9W4	"	"
9A	3E3	"	"
9B	7E4	"	"
1B	17W1A	Ground	Greater
5A	3W2B	"	"
5B	1E2A	"	"
6A	9W2	"	"
6B	19W2	"	"
7A	9E1	"	Inconclusive
7B	10E2	"	"

Results — Sulfur Dioxide

The bulk of the sulfur dioxide in the atmosphere arises from a small number of fixed sources unlike the oxides of nitrogen which arise from a large number of widely distributed sources. Consequently, sulfur dioxide measured at a particular location will vary according to source strength and wind direction. Because of this, it is difficult to relate the concentration observed by the District of Columbia to measurements made at the National Archives.

Sulfur dioxide was detected in the incoming air at all of the sample sites at the National Archives. The hourly average concentrations are shown in Table 6. The hourly average concentrations measured at 24th and L Streets, N.W. are shown in Table 7. The reason for the wide variation in concentrations at different locations and at different times in the Archives is not known at the present time and, as yet, no attempt has been made to correlate results at a particular location to wind direction, ambient temperature, or other meteorological parameters.

The significance of the sulfur dioxide measurements at the National Archives became obvious when compared to the results obtained at the Madison Building and the East Wing of the National Gallery. The sulfur dioxide concentration at these latter two sites did not exceed the lower detectable limit. At the time of the analyses, this limit was 0.0005 ppm at the Madison Building and 0.001 ppm at the East Wing of the National Gallery. (It should be noted that during a period of about one hour on February 8, 1983 the instrument noise level was such that a detectable limit of 0.005 ppm was observed at the East Wing.) During the sampling periods at the Madison Building and the National Gallery, the concentrations measured by the District Government were consistently above the lower detectable limits (Table 7).

The concentrations measured in the Archives are consistently larger than those measured at 24th and L Streets, N.W. If the averages of the two sets of measurements are compared, it is found that the ratio of the average of the Archives measurements to the average of the 24th and L Streets measurements is always less than 1.0.

However, the value ranges from 0.86 down to 0.16 with no obvious relationship between location of intake and the ratio.

Results — Ozone

No significant concentration of ozone was found at any of the locations sampled either in the National Archives, the Madison Building, or the East Wing of the National Gallery. The data supplied by the District of Columbia (Table 8) indicated a maximum of 21 ppb during any sampling period. Measurements made at the same time at all locations were indistinguishable from zero. The explanation is that, given a low ambient concentration to begin with and anticipating substantial losses in the air handling system, it is reasonable to expect that little ozone will reach the stack area. The situation may be quite different at times when the ambient ozone concentration is higher (such as during the summer or fall), but during the months of December, January, and February, the absence of ozone inside the buildings is not unexpected.

Other Measurements

The measurements at the National Archives summarized earlier in this report were all made with the sample probes positioned directly in the air stream issuing from an inlet vent. This was done in order to assess the quality of the incoming air without allowing the possibility of alteration of the composition by local materials or conditions. At several sample sites, the probes were removed from the inlet duct and were placed in the stack area in a position out of direct line with the inlet vent. While no change in the concentration of the oxides of nitrogen was observed, in several cases a reduction of up to 50 percent of the sulfur dioxide was seen. More often, the reduction was less, but it occurred often enough to be of some potential interest. Table 3 contains a qualitative summary of the effect observed at the various sites at the National Archives.

Table 3. Difference of Sulfur Dioxide in the Stack Areas Compared to Incoming Air.

Location	Observation
3E3	15% Reduction
1E2A	No difference
9E1	25% Reduction
7E4	Inconclusive
10E2	50% Reduction
9W4	Not measured in stack area
9W3	20% Reduction
9W2	50% Reduction
19W2	25% Reduction
17W1A	25% Reduction
3W2B	Not measured in stack area

Caution should be exercised in drawing conclusions from these results without further observations.

A series of ozone measurements were made in areas of the Archives at and near several high-use copying machines to determine whether ozone was being generated by the machines, and if so, whether it was being carried into document storage areas. No significant difference was observed between the instrument readings in the immediate vicinity of the copying machines (area 7E1), the stack area directly over the duplicating area (8E1), and measurements made at other locations throughout the Archives. The measurements indicate that the copying machines are not contributing a measurable amount of ozone to the atmosphere inside the National Archives.

Conclusions

The ventilating systems of the National Archives, the Madison Building of the Library of Congress and the East Wing of the National Gallery of Art do not appreciably reduce the concentration of nitrogen oxides in the air which passes through them. However, the ambient concentration of the oxides of nitrogen may decrease with increasing altitude, and a system drawing air from rooftop level may exhibit a lower concentration than a system with an inlet at ground level.

The measurements indicate that all sulfur dioxide is removed from the air entering the systems at the Madison Building and the East Wing, while the concentration entering the system at the National Archives appears to pass through the system with little or no change.

The effect of ventilating systems on the concentration of ozone could not be determined primarily because of the relative absence of ozone in the atmosphere.

Acknowledgment

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Table 4. Hourly Average Concentrations[a] of Nitrogen Oxides Measured at National Archives, Madison Building and East Wing.

		Sampling Location and Starting Date													
	Time	3E3 12/2/82	1E2A 12/6	9E1 12/7	7E4 12/9	1062 12/15	9W4 12/28	9W3 1/3/83	9W2 1/5	19W2 1/12	17W1A 1/13	3W2B 1/19	MAD. Bldg. 1/31	MAD. Bldg. 2/2	East Wing 2/7
	10	116	81											(Contd.)	
D	11	121	73			75	44	42		78		76			
	12	116	64	70		69	40	39		72	64	68	35	45	
A	13	126	59	66		69	31	36		71	64	65	32	33	36
	14	119	60	58	28	69	28	39	140	64	55	68	32	24	30
Y	15	134	67	60	35	70	34	41	150	65	55	62	28	20	31
	16	106	80	91	36	69	41	44	159	75	62	89	38	21	40
1	17	93	100	111	43	79	48	58	172	92	87	93	52	18	50
	18	80	99	104	44	80	40	80	160	77	90	85	57	14	47
	19	65	80	160	43	89	34	75	134	60	75	65	68	11	34
	20	55	65	--	51	101	32	63	113	46	78	42	92	9	24
	21	53	57	--	61	109	41	54	98	36	101	39	96	7	17
	22	51	41	--	58	109	36	41	100	32	111	37	78	4	14
	23	52	31	--	51	112	35	38	87	25	80	33	78	4	14
	24	49	27	--	46	116	40	34	75	30	79	35	78	5	12
	1	52	25	--	45	109	32	34	63	25	146	24	81	7	12
D	2	37	21	--	41	57	21	32	57	23	178	23	76	14	10
	3	22	18	--	39	29	15	29	46	21	136	19	64	23	8
A	4	19	16	--	38	15	12	24	38	20	97	15	67	31	7
	5	18	16	--	36	10	14	26	40	23	73	18	69	21	8
Y	6	32	24	--	39	13	22	36	66	32	70	23	88	15	14
	7	53	45	--	52	56	32	64	164	67	101	59	114	20	24
2	8	55	75	--	79	118	48	89	252	102	132	123	146	36	39
	9	57	88	298	90	139	49	84	223	107	120	98	154	43	37
	10	57		234	93	152	45	--	168		93	79	118	42	32
	11	52		155	84	136	44	--	133				89		26
	12	50		112	78	90	62	45	106				52		22

Table 4. Continued.

		Sampling Location and Starting Date													
	Time	3E3 12/2/82	1E2A 12/6	9E1 12/7	7E4 12/9	1062 12/15	9W4 12/28	9W3 1/3/83	9W2 1/5	19W2 1/12	17W1A 1/13	3W2B 1/19	MAD. Bldg. 1/31	MAD. Bldg. 2/2	East Wing 2/7
	13			59		72	62	42	89				45		21
D	14			65		64	58	36	78				43		22
	15			57		66	62	38	84				36		24
A	16			73		81	63	39	106				37		33
	17			90		99	70	53	130				37		44
Y	18			98		110	60	71	123				40		39
	19			82		96	44	72	138				41		29
3	20			68		83	36	78	174				48		23
	21			62		69	32	80	231				56		19
	22			75		47	36	90	198				63		18
	23			73		62	31	91	135				50		19
	24			66		59	29	107	90				31		18
	1			49		51	24	103	63				19		16
D	2			44		40	23	87	49				14		14
	3			45		32	22	76	35				10		12
A	4			43		24	19	65	38				8		11
	5			54		23	23	56	35				8		17
Y	6			86		33	29	59	39				14		23
	7			118		64	48	78	59				27		38
4	8			132		98	79	104	76				40		48
	9			128		102	75	122	80				55		46
	10			98		82		137	82				60		36
	11					69		131	71				57		
	12					66							45		

---

[a] Concentrations in parts per billion by mole (ppb).

Table 5. Hourly Average Concentrations[a] of Nitrogen Oxides Measured by D.C. Government at 24th and L Streets, N.W.

		Starting Date													
	Time	12/2/82	12/6	12/7	12/9	12/15	12/28	1/3/83	1/5	1/12	1/13	1/19	1/31	2/2	2/7
	10	195	61											(Cont.)	
D	11	168	33			158	66	65		44		--			
	12	179	31	31		161	--	34		37	43	31	61	129	
A	13	180	56	37		140	--	49		31	40	45	46	91	68
	14	196	39	55	64	157	84	57	114	31	32	40	53	88	65
Y	15	226	41	38	43	143	50	54	105	32	40	31	81	67	67
	16	120	49	51	49	145	64	36	124	38	66	36	73	72	76
1	17	155	86	104	58	174	67	67	147	34	86	38	109	76	77
	18	119	58	242	59	197	46	93	137	42	98	39	208	74	80
	19	92	44	419	62	153	36	86	94	40	115	35	173	77	73
	20	90	42	538	52	177	36	81	82	27	172	26	219	77	66
	21	80	25	466	59	148	30	50	99	22	178	29	161	72	53
	22	75	18	445	49	188	38	39	56	20	169	31	116	58	52
	23	73	18	418	40	179	51	33	50	22	219	26	115	66	53
	24	65	18	341	39	177	45	27	50	21	127	20	89	76	49
	1	61	15	316	46	94	34	30	44	22	114	17	90	58	49
D	2	57	14	316	47	63	13	35	42	24	106	18	86	53	45
	3	34	14	265	42	42	12	29	39	22	101	19	156	41	43
A	4	25	11	233	38	39	10	24	39	22	96	24	148	41	40
	5	28	12	238	33	44	12	27	43	22	98	27	154	46	40
Y	6	48	22	346	52	43	24	43	71	33	115	37	252	45	48
	7	93	61	516	80	47	60	108	156	62	110	69	318	83	71
2	8	137	84	507	109	97	78	210	192	79	92	83	247	72	78
	9	109	62	248	144	152	56	132	147	65	71	90	156	66	59
	10	83		125	87	89	88	--	88		71	82	94	55	
	11	77		114	81	31	98	--	61				76		51
	12	85		--	68	32	78	--	49				72		53

Table 5. Continued.

		Starting Date													
	Time	12/2/82	12/6	12/7	12/9	12/15	12/28	1/3/83	1/5	1/12	1/13	1/19	1/31	2/2	2/7
	13			--		26	73	--	51				74		54
D	14			--		21	60	46	64				88		54
	15			--		24	65	58	75				109		66
A	16			106		31	40	69	61				107		62
	17			160		39	41	87	125				107		69
Y	18			199		48	34	92	170				110		66
	19			190		41	28	87	307				110		62
3	20			165		36	28	86	527				116		56
	21			131		34	32	82	499				124		54
	22			110		39	33	137	339				113		54
	23			90		37	31	175	179				84		57
	24			63		34	31	126	79				68		55
	1			55		34	31	117	62				64		51
D	2			63		24	27	71	58				57		51
	3			48		15	23	62	65				54		50
A	4			43		17	26	70	43				51		49
	5			50		14	40	123	47				51		54
Y	6			--		21	73	114	72				69		65
	7			--		54	163	159	147				103		92
4	8			--		119	191	169	166				139		87
	9			--		134	124	192	141				134		71
	10			--		83		118	130				135		61
	11					70		149	78				145		
	12					36							129		

---

[a] Concentrations in parts per billion by mole (ppb).

Table 6. Hourly Average Concentrations[a] of Sulfur Dioxide Measured at the National Archives.

Sampling Location and Starting Date

	Time	3E3 12/2/82	1E2A 12/6	9E1 12/8	7E4 12/9	10E2 12/15	9W4 12/29	9W3 1/4/83	9W2 1/5	19W2 1/12	17W1A 1/13	3W2B 1/26
	10		1	5				5				
D	11		2	8		11	3	6			9	20
	12	8	3	9		--	4	5		9	9	16
A	13	12	2	9	2	--	2	5		9	9	16
	14	9		8	4	6	2	5	6	8	9	18
Y	15	28		9	8	--	2	5	7	8	9	20
	16	24		9	9	--	2	5	6	9	10	22
	17	19		9	10	6	2	4	6	9	12	25
1	18	18		9	9	6	2	6	6	9	12	28
	19	20		9	7	5	2	5	6	9	11	23
	20	26		8	7	4	3	4	6	10	12	32
	21	--		8	7	4	5	4	6	10	12	34
	22	--		9	6	3	7	4	6	10	16	30
	23	--		8	6	2	6	4	6	9	17	30
	24	--		8	5	2	4	4	6	10	15	33
	1	--		9	5	3	4	5	7	10	16	32
D	2	--		12	5	4	4	2	7	8	14	29
	3	--		12	4	4	4	3	7	7	13	26
A	4	--		12	4	4	4	4	8	7	11	25
	5	--		12	4	4	3	5	7	6	10	25
Y	6	--		13	3	4	3	6	8	6	11	25
	7	--		16	3	4	4	5	8	8	10	25
	8	--		17	2	4	6	4	9	10	9	28
2	9	--		10	2	3	3	4	12	5	8	21
	10	12		11	1	2	3	2	9			
	11	11				5		1	13			
	12	12				5			11			
	13					5			9			
	14					5			8			
	15					5			8			
	16					5			9			
	17					4			10			
	18					5			8			
	19					5			8			
	20					5			8			
	21					5			10			
	22					7			11			
	23					8			10			
	24					7			7			
	1					5			7			
D	2					5			6			
	3					4			4			
A	4					4			6			
	5					3			6			
Y	6					4			8			
	7					4			5			
	8					4			4			
3	9					4			3			
	10					3						
	11					2						
	12					2						
Average		18	2	10	5	4	4	4	7	8	11	25

---

[a] Concentrations in parts per billion by mole (ppb).

Table 7. Hourly Average Concentrations[a] of Sulfur Dioxide Measured by D.C. Government at 24th and L Streets, N.W.

		Starting Date										
	Time	12/2/82	12/6	12/8	12/9	12/15	12/29	1/4/83	1/5	1/12	1/13	1/26
	10		14	24				26				
D	11		4	18		28	10	24			27	29
	12	30	4	16		--	13	21		13	28	26
A	13	41	7	15	--	--	11	15	16	11	25	32
	14	56		14	10	--	15	15	10	10	23	28
Y	15	99		17	8	--	14	21	11	10	28	27
	16	36		23	11	--	8	20	9	18	36	24
	17	49		22	10	47	13	19	10	20	32	26
1	18	15		42	9	61	16	23	12	21	33	26
	19	16		73	12	38	18	23	8	22	35	30
	20	37		35	21	38	28	18	9	20	34	34
	21	34		12	27	33	37	21	8	19	33	34
	22	23		10	22	36	37	20	6	17	32	36
	23	16		10	14	39	26	19	4	17	36	28
	24	17		10	13	36	20	27	4	19	36	28
	1	29		15	20	36	19	24	3	20	40	23
D	2	27		20	27	59	18	25	4	22	42	30
	3	9		16	29	41	19	24	7	22	40	28
A	4	5		16	25	38	22	19	11	23	46	25
	5	5		14	17	40	33	32	12	19	45	23
Y	6	10		16	25	24	28	34	15	20	35	26
	7	26		24	29	10	30	36	23	27	33	29
	8	34		27	47	15	30	25	50	28	32	46
2	9	33		13	48	25	26	24	25	25	32	40
	10	27		7	20	20	30	18	25			
	11	17			29	13		15	25			
	12	28			18	14			34			
	13					13			25			
	14					14			27			
	15					13			29			
	16					13			35			
	17					15			38			
	18					16			44			
	19					15			43			
	20					16			37			
	21					29			35			
	22					25			43			
	23					20			41			
	24					16			26			
	1					17			21			
D	2					12			22			
	3					7			27			
A	4					7			14			
	5					8			18			
Y	6					10			17			
	7					14			20			
	8					19			21			
3	9					19			18			
	10					14						
	11					11						
	12					17						
Average		29	7	20	21	23	22	23	21	19	34	29

---

[a] Concentrations in parts per billion by mole (ppb).

Table 8. Ozone Measured at 24th and L Streets, N.W. by the District of Columbia.

Date	Concentration[a] of Ozone Mean	Maximum
12/6/82	10	18
12/7/82	10	21
12/8/82	3	11
12/9/82	6	16
12/10/82	4	11
12/15/82	3	5
12/16/82	5	12
12/17/82	8	15
12/28/82	3	10
12/29/82	5	20
12/30/82	2	8
1/3/83	5	12
1/4/83	5	11
1/5/83	1	1
1/6/83	2	8
1/7/83	4	11
1/12/83	10	17
1/13/83	8	14
1/14/83	5	13
1/15/83	9	14

[a] Concentrations in parts per billion by mole ($1/10^{-9}$).

Table 9. Summary of Temperature and Relative Humidity Measurements.

Location	Temperature Average	Temperature Range	Relative Humidity Average	Relative Humidity Range
3E3	21.1	20.5-21.4	57	55-58
1E2A	22.0	21.5-22.3	54	49-56
9E1	22.6	21.4-23.5	36	54-57
7E4	21.3	20.4-22.6	48	48-48
10E2	22.7	22.1-22.5	49	45-53
9W4	22.7	20.7-23.5	55	50-60
9W3	22.0	21.2-23.2	52	48-57
9W2	21.3	21.0-22.0	43	36-47
19W2	24.1	22.4-25.2	41	39-42
17W1A	22.2	21.6-22.8	50	49-52
3W2B	22,9	22.4-23.7	35	31-42
Madison Building	21.4	20.8-23.0	55	51-58
East Wing	21.8	21.3-22.2	54	52-56

Figures 1 - 5

A plot of the concentration of oxides of nitrogen measured at the indicated location compared to a plot of the data of the District of Columbia measurements made at 24th and L Streets, N.W., Washington, D.C.

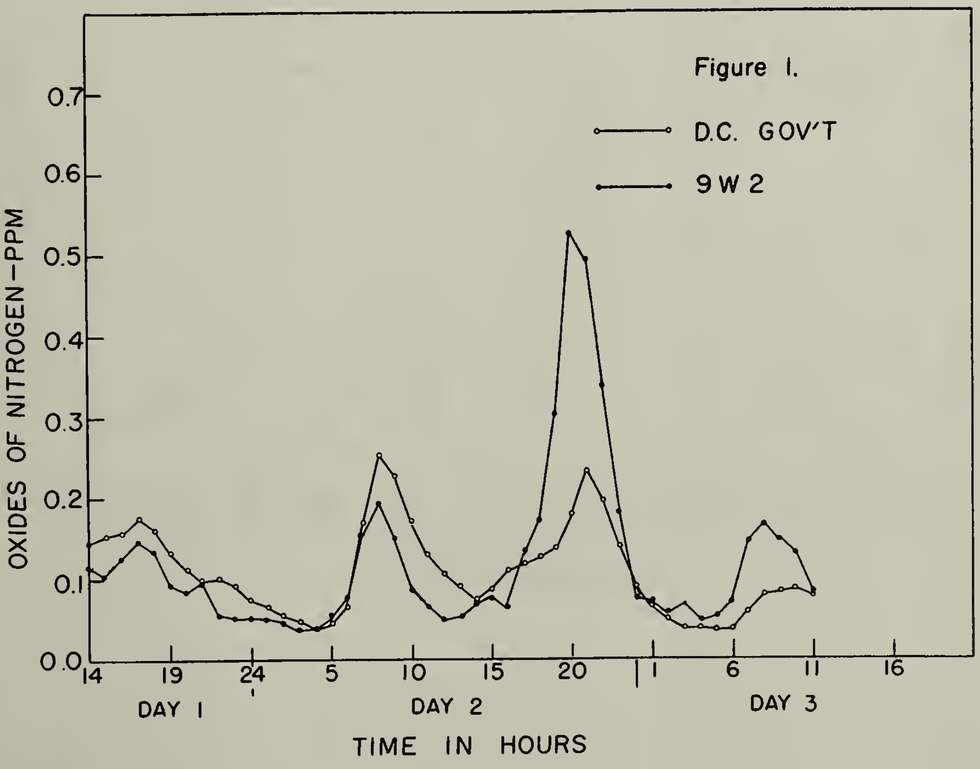
Figure 1.

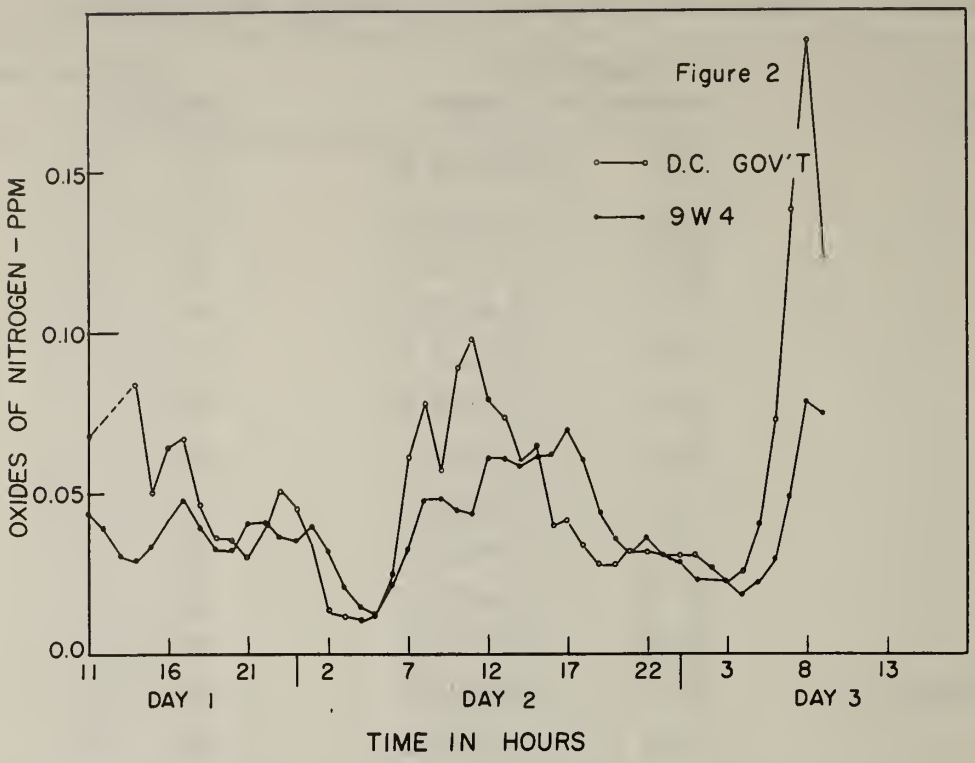
Figure 2
D.C. GOV'T
9W4
OXIDES OF NITROGEN - PPM
0.15
0.10
0.05
0.0
11
16
21
2
7
12
17
22
3
8
13
DAY 1
DAY 2
DAY 3
TIME IN HOURS

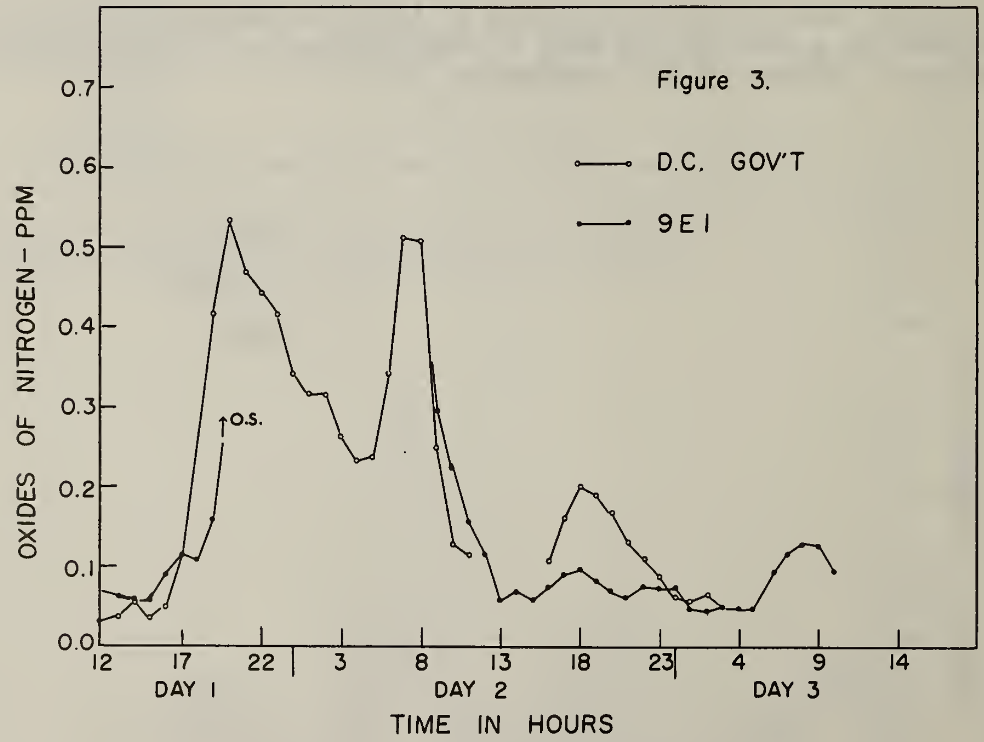
Figure 3.
D.C. GOV'T
9E1
OXIDES OF NITROGEN - PPM
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
O.S.
12
17
22
3
8
13
18
23
4
9
14
DAY 1
DAY 2
DAY 3
TIME IN HOURS

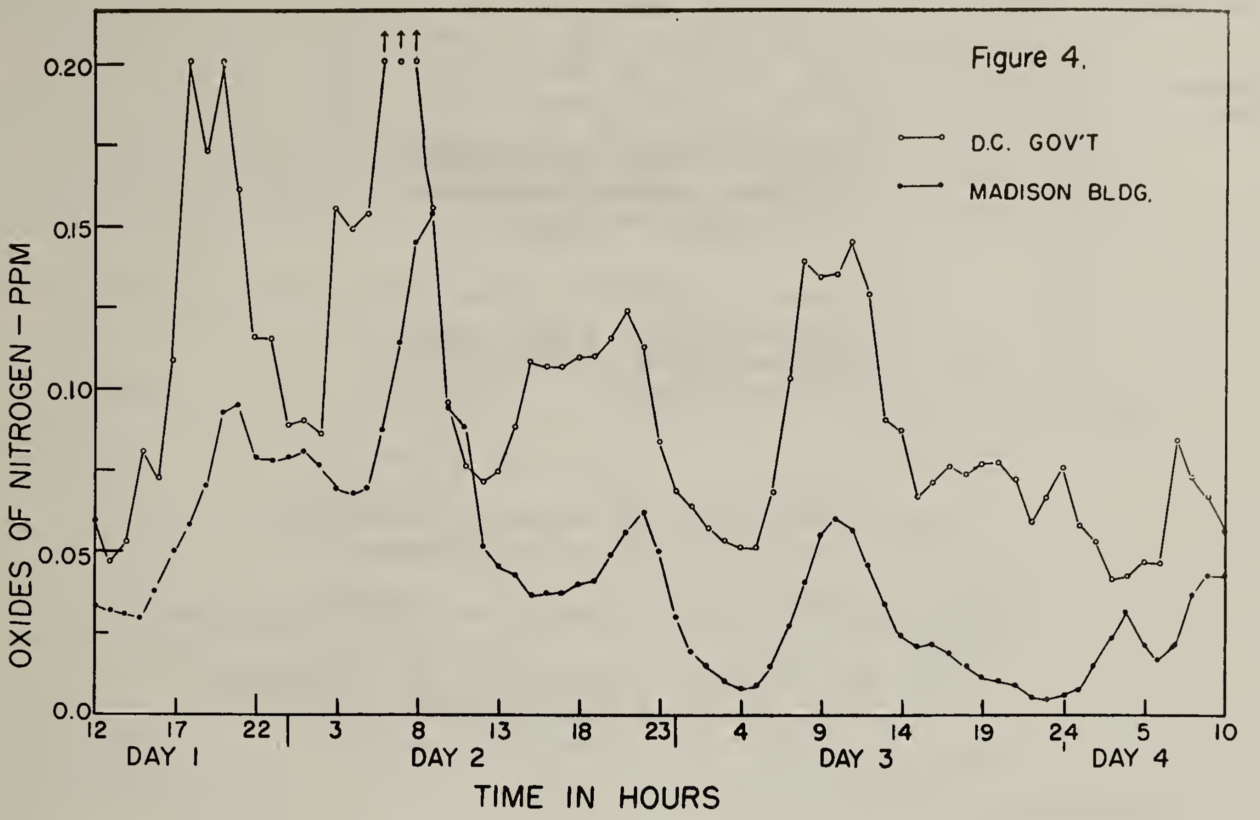

Figure 4.

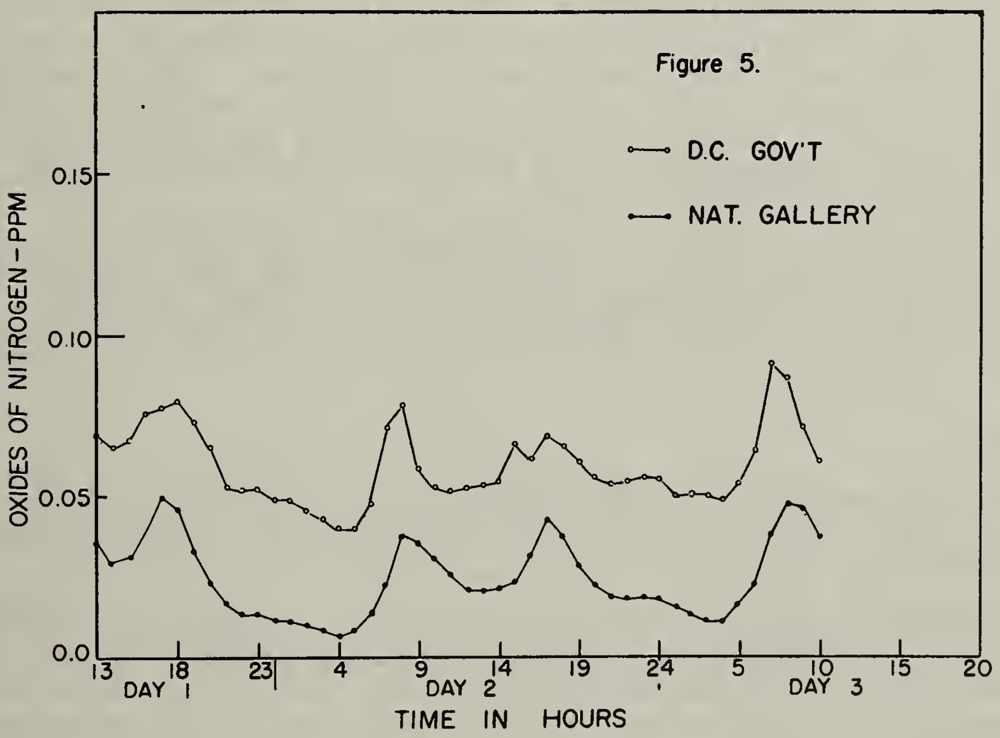

Figure 5.

Attachment: Report of the 1977 study at the National Archives building.

FORM NBS-348
(12-65)

U.S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS
WASHINGTON, D.C. 20234

REPORT OF ANALYSIS

of

The Atmosphere at Several Locations
in the National Archives

Requested by General Services Administration

Act No. 10477380, Document No. B0000051
Project No. 3100645

Introduction

Air from the ventilating system was analyzed for ozone, oxides of nitrogen, and sulfur dioxide. The analyses were performed separately and at different times for each of the substances. Samples were obtained both in the stack areas and at the receiving room loading platform. The stacks are supplied with air from the ventilating system, while the receiving room loading platform receives air from both the interior of the building and directly from the outside.

Ozone was measured with a Dasibi Model 1003 AH ultraviolet adsorption instrument. Oxides of nitrogen were measured with a Monitor Labs Model 8440 Nitrogen Oxide analyzer. Sulfur dioxide was measured with a Monitor Labs Model 8450 Sulfur Monitor.

Ozone

Ozone was measured in the location identified as 18-E-3, 5-E-3, and 7-W-2, and at the receiving room loading platform on September 1, 1977.

The air in the room and the air coming directly out of a register of the ventilating system were sampled in the three stack areas. The ozone concentration in all three areas was essentially the same as the air delivered to the area by the ventilating system. In area 5-E-3 and 7-W-2, the concentration in the room air was the same as in the incoming air, but in area 18-E-3 the ozone concentration in the room air was somewhat higher than the ozone content of the incoming air. No explanation for this anomaly has been found.

The concentration of ozone at the loading platform was considerably higher than that found in any of the stack area inlet air ducts. The high concentration probably reflects the mixing of a large amount of outside air with some inside air. The value of the concentration of ozone at this point is similar to the ozone concentration measured by the District of Columbia Air Monitoring Station at 427 New Jersey Avenue.

The results of the ozone measurements are summarized below:

Area	Source	Concentration Range in Parts per Million by Volume
5-E-3	Incoming Air	0.005 - 0.012
5-E-3	Room Air	0.009 - 0.013
7-W-2	Incoming Air	0.000 - 0.006
7-W-2	Room Air	0.000 - 0.004
18-E-3	Incoming Air	0.009 - 0.020
18-E-3	Room Air	0.031 - 0.042
Rec Rm.	Loading Platform	0.070 - 0.110
Outside Air		0.097*

---

*Value obtained from D.C. Government for period corresponding to sampling at Rec. Rm. Loading Platform.

Oxides of Nitrogen

Oxides of nitrogen were measured in area 5-E-3 and at the loading platform of the receiving room on September 14 and 15, 1977. The value measured in the duct of 5-E-3 remained at a concentration between 0.020 and .030 ppm between 3:00 p.m. on September 14, and 7:00 a.m. on September 15. The concentration in the outside air measured by the D.C. Government ranged between 0.016 and 0.070 ppm during this period. The average value was 0.041 ppm. The values measured in area 5-E-3 did not reflect changes in the concentration of the oxide of nitrogen in the outside air. At 7:00 a.m. on September 14, the value of the concentration in area 5-E-3 began to rise, and reached a maximum of 0.060 ppm at 9:30 a.m. This rise was matched by a similar rise in the concentration in the outside air which began at 4:00 a.m. and which reached a value of 0.080 ppm at 8:30. The measurements by the D.C. Government were interrupted at this time, but the trend in the concentration at the time was definitely rising.

The values of the oxides of nitrogen measured in the receiving room loading dock area ranged from a low of 0.055 ppm to a high of 0.13 ppm during a one-hour sampling period starting at 11:30 a.m. on September 14. The average value for the same period measured by the D.C. Government was about 0.06 ppm. The reason for the higher values inside the building is no doubt due to auto exhaust gases generated by vehicles moving in and out of the receiving room area.

Sulfur Dioxide

Sulfur dioxide was measured in area 5-E-3 and in the loading dock area of the receiving room on November 29 and 30, 1977. The concentration in the air entering the 5-E-3 area through the ventilating system and the room air itself never exceeded a concentration of 0.003 ppm sulfur dioxide.

Measurements made in the receiving room loading dock area varied from a low value of 0.009 ppm to a high of 0.044 ppm. The concentration measured in the area appeared to follow the concentration of sulfur dioxide in the outside air as measured by the D.C. Government. The concentration in the outside air during the period of time when measurements were being made in area 5-E-3 were between 0.032 and 0.040 parts per million.

Conclusion

The maximum concentration of sulfur dioxide in the stack areas does not exceed 0.003 ppm, although the outside air contains more than ten times this concentration. The ozone concentration in the stack area does not exceed 0.042 ppm when the outside air contains as much as 0.097 ppm. It appears, therefore, that substantial amounts of sulfur dioxide and ozone are removed by passage of outside air through the ventilating system.

Nitrogen dioxide concentration in the building appears to respond to changes in the concentration of nitrogen dioxide in the outside air and are probably not removed in substantial quantities by passage through the ventilating system.

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January 30, 1978

APPENDIX C

NBSIR 83-2770

Air Exchange Rate Measurements in the National Archives Building

August 1983

Prepared for and sponsored by:

Public Buildings Service
General Services Administration
7th and D Streets, SW
Washington, DC 20407

and

National Archives and Records Service
National Archives Building
Washington, DC 20408

NBSIR 83-2770

AIR EXCHANGE RATE MEASUREMENTS IN THE NATIONAL ARCHIVES BUILDING

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August 1983

Prepared for and sponsored by:
Public Buildings Service
General Services Administration
7th and D Streets, SW
Washington, DC 20407

and

National Archives and Records Service
National Archives Building
Washington, DC 20408

U.S. DEPARTMENT OF COMMERCE, Malcolm Baldrige, ***Secretary***
NATIONAL BUREAU OF STANDARDS, Ernest Ambler, ***Director***

Abstract

Air exchange measurements were carried out at the National Archives Building under various combinations of temperature and wind speed. The average air exchange rate under normal operation of the heating, ventilating, and air-conditioning system (HVAC) was 0.9 h^{-1} for an average temperature difference of 11.3°C and an average wind speed of 2.7 m/s. This rate is approximately twice those for new General Services Administration (GSA) office buildings. No clear dependence of air exchange rate on temperature differences up to 17°C or wind speeds up to 5 m/s was found.

With outdoor air dampers closed and fans operating, the average air exchange rate was 1.2 h^{-1} for an average temperature difference of 8.2°C and an average wind speed of 1.7 m/s.

A test of interzone air movement showed that air migrates rapidly from non-stack to stack areas with fans operating normally.

The building could not be pressurized beyond an indoor-outdoor pressure difference of 14 Pa. At this pressure difference, the air exchange rate was 1.5 h^{-1}. As in the case of normal operation of the HVAC system, this rate is also approximately twice those for new GSA office buildings.

AIR EXCHANGE RATE MEASUREMENTS IN THE NATIONAL ARCHIVES BUILDING

INTRODUCTION

The National Bureau of Standards (NBS) was asked by the General Services Administration (GSA) and the National Archives and Records Service (NARS) to measure air exchange rates of the National Archives Building under various conditions, including pressurization. This was done to aid in evaluating whether use of the current heating, ventilating, and air-conditionining (HVAC) system is consistent with preservation of archival records. The tests performed by NBS are as follows: 1) The air exchange rate of the building was measured under normal operation of the HVAC system. 2) The air exchange rate was measured with outdoor air dampers closed in order to determine how much air leakage was through dampers. 3) The air exchange rate was measured with dampers closed and fans off in order to determine how much the HVAC system contributes to air leakage. 4) Air leakage from the office and public areas to the stack areas was measured. 5) Fan pressurization measurements were performed in order to measure the intrinsic weather-independent envelope tightness of the building.

METHODS

The National Archives Building

The National Archives Building, located between Pennsylvania and Constitution Avenues, and between 7th and 9th Streets, in downtown Washington, is pictured in Fig. 1. Its volume is 306,253.5 m^3, according to GSA. A schematic diagram of the building is shown in Fig. 2. The northern side of the building, bordering on Pennsylvania Avenue, is composed of ten stories of offices. Each of these stories is subdivided in the center of the building into from one to three floors of stacks, where records are stored. In addition, there are offices located on several of the stack floors. Nine air handling systems serve the building (other than the garage). Each system except for systems 2 and 4 is composed of two supply fans and a return fan; systems 2 and 4 are composed of one supply and return fan each. All fans in each system operate simultaneously. Fig. 2 shows the areas served by each system.

Installation of automated tracer gas equipment

One set of tubes and wires was connected from each air-handling system to a computer and electron-capture gas chromatography detector located in the basement. Each set of tubes and wires consists of 1/16-inch inner diameter (id) plastic tubing for injecting tracer gas into the supply fans, 1/4-inch id plastic tubing for sampling return air, wiring connected to a thermistor to measure return air temperature, and wiring connected to relays to determine whether fans were operating. In addition, a thermistor was placed outside the air intake of fan 1 to measure outdoor temperature, and a weather station was installed on the roof to measure wind speed and direction. All temperature and wind measurements were taken once a minute and the results averaged each hour. In all tests other than those for which fans were manually shut off, all fans operated continuously. Outdoor air dampers were automatically modulated by the building HVAC system and no record was kept of their status.

Automated tracer gas equipment used for all tests

The automated tracer gas system developed at NBS and described elsewhere [1] was used to measure sulfur hexafluoride concentration and calculate hourly air exchange rates for each of the nine zones. The instrument was calibrated against samples containing known concentrations of sulfur hexafluoride. At 50 minutes past the hour, the system injected sulfur hexafluoride tracer gas for up to ten minutes. The maximal flow rate per zone was 80 L/s. Concentrations at each location were measured by a gas chromatograph, electron capture detector at 10-minute intervals thereafter and the results recorded on a floppy disk. The last four concentrations were fit by regression analysis to an equation of the form:

$$C = C_o \, e^{-I \cdot t} \tag{1}$$

where

I = air exchange rate, h^{-1}
t = time after injection, h
C = concentration, ppb
C_o = initial concentration, ppb

A weighted average of the nine air exchange rates was calculted and called the air exchange rate of the building. The weighting factors were closely related to the flow rates of the air handling systems. It would have been preferable to weight air exchange rates by relative zone volumes but these data were unavailable. Table 1 shows these flow rates and the weighting factors. Average indoor temperature was calculated from the nine return air temperatures. Because these temperatures were always very close to each other, they were not weighted. Regression analysis of air exchange rate vs. indoor-outdoor temperature difference (always positive in these tests) was done essentially as described elsewhere [2]. Standard errors were also calculated as described in reference 2.

In the earlier tests conducted from March 24, 1983 through April 2, tracer gas was injected into each of the nine zones each hour and its concentration permitted to decay. It was found that gas was not always completely mixed within the first half hour. It was also found that tracer gas often migrated into zones 1-5. Therefore, for the later tests conducted from April 14 through 21, the system was programmed to inject gas once every three hours for the full 10-minute injection period into zones 6-9 only. During the later tests, the tendency for gas to accumulate in zones 1-5 was no longer noted. Tracer gas was permitted to thoroughly mix during the first hour. During the third hour, concentrations were low. Consequently only data collected during the second hour were used. Fig. 3 shows that there is little difference between earlier and later data.

Test 1. Normal operation of the HVAC system

No modifications of the HVAC system were required for tests conducted under normal HVAC operation.

Test 2. Outdoor air dampers closed

To determine how much air leakage was through dampers, air exchange rates were measured between March 25 and 28 after the Archives maintenance staff shut all outdoor air dampers.

Test 3. Dampers closed and fans off

To determine how much the HVAC system contributes to air leakage, air exchange rates were measured during the evening of April 18 after the maintenance staff shut off the fans. Shutting off the fans automatically closed the outdoor-air dampers.

Test 4. Air leakage from the office and public areas to the stack areas

To determine whether air leaks into areas where archives are stored (stacks) from other areas (non-stack areas), gas was injected only into zones 1-5. Unlike during the earlier tests, it mixed evenly throughout the building. (These data were also used as normal fan-operation data.)

Test 5. Fan pressurization measurements

To measure the intrinsic weather-independent envelope tightness of the building, a fan pressurization test was conducted the evening of April 22. Sampling tubes leading from systems 8 and 9 were rerouted to sample air in stack areas 7W-1 and 14W-1, both served by air-handling system 6, as seen in Fig. 1. Just prior to pressurizing the building, it was determined that tracer-gas concentrations in these two stack areas were nearly equal to that in return fan 6, suggesting that tracer gas was uniformly distributed in that zone.

The maintenance staff shut off all the return air fans, closed the exhaust air dampers, and fully opened the supply air dampers (including dampers and fans serving the garage) prior to tracer gas injection. Tracer gas was manually injected for 30 minutes at a flow rate of 0.25 L/s in order to maintain a high enough concentration for the high air exchange rates anticipated during the test. Differential pressure gauges were installed across the entrance doorways on Pennsylvania and Constitution Avenues. Since the concentrations in the two stack areas (and in fact in the remaining 7 air-handling systems) were all nearly constant during tracer gas injection at about 200 ppb, the air exchange rate was calculated by the equation:

$$I = F/C \cdot V \tag{2}$$

where

F = tracer gas flow rate, m^3/h
V = building volume, m^3

Pressurization was maintained for three hours after injection was terminated. After injection was terminated, the air exchange rate was also calculated by the computer in the usual manner.

RESULTS

Test 1. Normal operation of the HVAC system

The results of air exchange rate measurements under normal HVAC-system operation are shown in Table 2. Fig. 3 shows air exchange rate measurements plotted against temperature difference with wind speeds indicated next to the points. Curves representing one standard error unit about the line are also shown. The average air exchange rate was $0.9 \pm 0.3\ h^{-1}$, corresponding to an average temperature difference (ΔT) of $11.3^{\circ}C$ and an average wind speed of 2.7 m/s. During normal operation of the HVAC system, the average indoor temperature of the Archives Building remained nearly constant at $22.8 \pm 0.5^{\circ}C$ (standard deviation or sd). The best-fit regression line is given by the equation:

$$I = 0.5 + 0.4(\Delta T) \tag{3}$$

where

$\Delta T = T_{in} - T_{out}$, $^{\circ}C$
T_{in} = average indoor temperature, $^{\circ}C$
T_{out} = outdoor temperature, $^{\circ}C$

The correlation coefficient, R^2, is 0.23, reflecting the large amount of data scatter. The uncertainty of the first coefficient, as measured by the standard error, is 97%; the uncertainty of the second coefficient is 21%. It can be seen in Fig. 3 that a linear relationship between I and ΔT going through the origin cannot be excluded. Neither can the possibility that I is independent of ΔT for ΔT below $17^{\circ}C$ be excluded.

At constant ΔT (this can be visualized, for example, by going up any corridor $1^{\circ}C$ wide in Fig. 3), air exchange rate does not incrase with increasing wind speed; if anything, it decreases. In fact, there is no apparent relationship between air exchange rate and wind speeds of 0.6-5 m/s encountered during the study.

Test 2. Outdoor air dampers closed

In order to determine how much air leakage was through outdoor air dampers, a tracer-gas study was performed with outdoor dampers closed. The results of air exchange rate measurements with dampers closed are shown in Table 3. Fig. 3 shows the results of this experiment compared with the results of the previous study. The average air exchange rate was 1.2 h^{-1} at an average temperature difference of 8.2°C and an average wind speed of 1.7 m/s. Two distinct temperature difference regimes make up this study: 1) small ΔT (4 data points below 2°C), and 2) large ΔT (6 data points between 11 and 17°C). There are no data directly comparable to the first regime in the study under normal fan operation, but there are 20 points in the large ΔT region. The two large ΔT results are nearly identical: an air exchange rate of 1.1 ± 0.2 h^{-1} at a temperature difference of 13.4°C and wind speed of 1.6 m/s with dampers closed, compared with an air exchange rate of 1.0 ± 0.3 h^{-1} at a temperature difference of 13.5°C and wind speed of 2.8 m/s.

As in the case of normal HVAC-system operation, the large data scatter make it difficult to assign a definite relationship between ΔT and I. In the present instance, neither a direct nor inverse dependence, nor independence of ΔT and I can be excluded. The standard error bands are not drawn, but are so wide that they encompass the origin and most of the normal HVAC-system operation data. The combined normal HVAC-system operation and damper-closed data are about as well fit by $I = 1$ h^{-1} as by any other relationship.

Test 3. Fans off and dampers closed

In order to determine how much the HVAC system contributes to air leakage, a tracer-gas test was done in which fans were turned on only at the beginning and end in order to mix the air, but left off in the middle of the test for about two hours. During this time, outdoor air dampers were also closed. An air exchange rate could not be calculated from the data obtained by this test because nearly all the gas ended up in zone 8 immediately after injection.

Test 4. Air leakage from the office and public areas to the stack areas

It was determined from information supplied by GSA that air-handling systems 6-9 serve mainly the stacks, while systems 1-5 serve mainly the remainder of the building (Fig. 2). Therefore, tracer gas was injected only into zones 1 to 5 in order to test whether there was significant air leakage into the stack areas from the rest of the building. It was found that there was immediate, thorough mixing between the stack and non-stack areas. The tracer gas concentrations in the nine zones were so uniform during the test, in fact, that it was possible to calculate an air exchange rate for the building (see Fig. 3 and Table 2, 4/19/83, hour 13).

Test 5. Fan pressurization measurements

Fan pressurization measurements were performed in order to measure the intrinsic weather-independent envelope tightness of the building. The building was pressurized by closing off all exhaust air dampers and return fans, including those serving the garage, and opening all supply air dampers and fans. Concentration measurements were made in two stack areas on the 7th and 14th stack floors. (There are 21 stack floors.) The building could be pressurized to maximum pressure differences of only 14 Pa, measured at the Constitution Avenue entrance on the ground floor (corresponding to the fifth stack floor) and 10 Pa at the Pennsylvania Avenue entrance on the main floor (corresponding to the third stack floor). It was noticed during the test that there were strong drafts from the garage through two doorways into the main body of the building. The average temperature difference during the test was 5.9°C and the average wind speed was 1.5 m/s.

The air exchange rate calculated by the constant concentration method (equation 2) was 1.5 h^{-1}. Air exchange rates were also calculated by the concentration-decay method (equation 1) for two hours. As shown in Table 4, these air exchange rates were 0.0 h^{-1} for the 14th floor for both hours and 0.1 and 0.4 h^{-1} for the 7th floor. The rates calculated by the concentration decay method may even be lower than expected in the absence of pressurization (Fig. 3).

CONCLUSIONS AND RECOMMENDATIONS

Air exchange measurements were taken under various combinations of temperature and wind speed. The average air exchange rate was 0.9 h^{-1} for an average temperature difference of 11.3°C and an average wind speed of 2.7 m/s. The indoor temperature was very nearly constant at around 23°C and the outdoor temperature was always lower than the indoor temperature. No clear dependence of air exchange rate on temperature differences up to 17°C or wind speeds up to 5 m/s was found. If a more complete assessment of the National Archives Building is desired, then further air exchange rate measurements would need to be taken at different times of the year, and at higher wind speeds than those encountered during the tests.

The test done with air dampers closed and fans operating showed that at a temperature difference between 11 and 17°C, the air exchange rate was the same as that when dampers were operating automatically. This may be because under normal operation of the HVAC system, dampers would be closed at these outdoor temperatures. It would be useful to conduct this type of test under different weather conditions and record damper opening and closing.

The test with dampers closed and fans off resulted in tracer gas ending up in one zone (8), so no useful results could be obtained.

A test of interzone air movement showed that air migrates rapidly from non-stack to stack areas with fans operating normally.

The building could not be pressurized beyond an indoor-outdoor pressure difference of 14 Pa. There was some doubt about the resulting air exchange rate obtained at this pressure difference since a rate of 1.5 h^{-1} was obtained by the constant concentration method and rates under 0.5 h^{-1} were obtained by the tracer-gas decay method. The first air exchange rate seems more likely because it is at least higher than air exchange rates in the absence of pressurization.

There are uncertainties as to the exact areas served by the various air-handling systems (Fig. 2) and this tubing and wiring could prove invaluable in accurately charting the building. For this reason, and to conduct further tests described below, it is recommended that the tubing and wiring be left in place.

A similar study of eight new GSA buildings in various parts of the United States (unpublished data) shows that the Archives Building is about twice as leaky as new office buildings, both under normal operation of the HVAC system and under pressurization. Their air exchange rates under normal operation of the HVAC systems vary from 0.2 to 0.6 h^{-1} for outdoor temperatures of 4-10°C and wind speeds under 1.3 m/s. Their air exchange rates at a pressure difference of 14 Pa were 0.5 to 0.9 h^{-1}.

ACKNOWLEDGMENT

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REFERENCES

1. R. A. Grot, C. M. Hunt and D. Harrje, "Tracer gas automated equipment for complex building studies," pp. 103-128 in "First Air Infiltration Center (AIC) Conference: Air infiltration and measuring techniques, Proceedings," AIC, Bracknell, UK, 1980.

2. S. Silberstein, "Air leakage measurements of an unpartitioned mobile home," National Bureau of Standards Interagency Report 80-2105, Washington, 1980.

TABLE 1. Air Handling System Flow Rates and Air Exchange Rate Weighting Factors.

System	Flow rate 10^3 cfm,	m^3/s	Air exchange rate weighting factor
1	69	33	1
2	5.9	2.8	0.09
3	62	29	1
4	5.9	2.8	0.09
5	40	19	0.6
6	70	33	1
7	65	31	1
8	66	31	1
9	66	31	1

TABLE 2. Air Exchange Rates under Normal HVAC-System Operation

<u>LEGEND</u>

W SPEED = wind speed, m/s
W DIR = wind direction, degrees clockwise from north
T-OUT = outdoor temperature, °C
T-IN = average indoor temperature, °C
T-DIFF = T-IN - T-OUT, °C
AER = average air exchange rate, h^{-1}
(weighting factors in Table 1)
RET = return air fan

DATE	HOUR	W SPEED	W DIR	T-OUT	T-IN	T-DIFF	AER
3/24/83	18	2.2	45.0	7.7	22.4	14.7	1.23

RET 1 = 1.44
RET 2 = 1.14
RET 3 = 1.63
RET 4 = 1.52
RET 5 = .83
RET 6 = .88
RET 7 = 1.20
RET 8 = 1.20
RET 9 = 1.22

DATE	HOUR	W SPEED	W DIR	T-OUT	T-IN	T-DIFF	AER
3/24/83	22	2.2	45.0	7.3	22.3	15.0	.94

RET 1 = 1.04
RET 2 = 1.39
RET 3 = 1.36
RET 4 = 1.36
RET 5 = .91
RET 6 = .60
RET 7 = .66
RET 8 = .58
RET 9 = 1.37

DATE	HOUR	W SPEED	W DIR	T-OUT	T-IN	T-DIFF	AER
3/24/83	23	2.6	45.0	7.2	22.2	15.0	.87

RET 1 = 1.41
RET 2 = 1.40
RET 3 = 1.33
RET 4 = 1.15
RET 5 = .77
RET 6 = .70
RET 7 = .51
RET 8 = .62
RET 9 = .66

TABLE 2 (continued)

```
  DATE     HOUR    W SPEED  W DIR     T-OUT      T-IN    T-DIFF    AER
 3/25/83    1        3.0     45.0       6.9      22.1     15.2    1.69

          RET 1  =   1.34
          RET 2  =   1.17
          RET 3  =   1.64
          RET 4  =   1.38
          RET 5  =    .77
          RET 6  =   1.56
          RET 7  =   2.13
          RET 8  =   2.19
          RET 9  =   1.90
  DATE     HOUR    W SPEED  W DIR     T-OUT      T-IN    T-DIFF    AER
 3/25/83    8        2.7     67.5       5.1      21.9     16.8     .85

          RET 1  =   1.16
          RET 2  =   1.05
          RET 3  =   1.01
          RET 4  =   1.03
          RET 5  =    .67
          RET 6  =    .59
          RET 7  =    .85
          RET 8  =    .81
          RET 9  =    .73
  DATE     HOUR    W SPEED  W DIR     T-OUT      T-IN    T-DIFF    AER
 3/25/83    9        2.8     67.5       5.4      22.1     16.7    1.43

          RET 1  =   1.48
          RET 2  =   1.72
          RET 3  =   1.75
          RET 4  =   1.53
          RET 5  =    .74
          RET 6  =   1.32
          RET 7  =   1.64
          RET 8  =   1.50
          RET 9  =   1.24
  DATE     HOUR    W SPEED  W DIR     T-OUT      T-IN    T-DIFF    AER
 3/25/83   14        2.7    112.5       8.4      22.4     14.0    1.29

          RET 1  =   1.38
          RET 2  =   1.26
          RET 3  =   1.73
          RET 4  =   1.49
          RET 5  =    .71
          RET 6  =    .90
          RET 7  =   1.48
          RET 8  =   1.58
          RET 9  =   1.00
```

TABLE 2 (continued)

```
 DATE    HOUR    W SPEED  W DIR     T-OUT      T-IN     T-DIFF    AER
3/25/83   15       2.9     90.0       8.9      22.4      13.5     1.32

         RET 1  =  1.98
         RET 2  =  1.54
         RET 3  =  1.97
         RET 4  =  1.45
         RET 5  =   .52
         RET 6  =   .97
         RET 7  =  1.39
         RET 8  =  1.48
         RET 9  =   .58

 DATE    HOUR    W SPEED  W DIR     T-OUT      T-IN     T-DIFF    AER
4/ 1/83   18       1.5    180.0      14.8      23.4       8.6     1.09

         RET 1  =  1.70
         RET 2  =  1.92
         RET 3  =  2.72
         RET 4  =  1.33
         RET 5  =   .36
         RET 6  =  0.00
         RET 7  =   .22
         RET 8  =   .44
         RET 9  =  1.81

 DATE    HOUR    W SPEED  W DIR     T-OUT      T-IN     T-DIFF    AER
4/ 2/83    2        .6     67.5      10.9      23.2      12.3      .81

         RET 1  =  1.36
         RET 2  =  2.30
         RET 3  =  1.30
         RET 4  =   .32
         RET 5  =   .39
         RET 6  =   .16
         RET 7  =   .60
         RET 8  =   .49
         RET 9  =  1.13

 DATE    HOUR    W SPEED  W DIR     T-OUT      T-IN     T-DIFF    AER
4/14/83   13       2.6    157.5      18.5      23.0       4.5      .48

         RET 1  =   .91
         RET 2  =   .43
         RET 3  =  0.00
         RET 4  =   .26
         RET 5  =  0.00
         RET 6  =   .66
         RET 7  =   .45
         RET 8  =   .61
         RET 9  =   .57
```

TABLE 2 (continued)

DATE	HOUR	W SPEED	W DIR	T-OUT	T-IN	T-DIFF	AER
4/14/83	16	4.2	135.0	17.8	22.8	5.0	.55

RET 1 = .73
RET 2 = .38
RET 3 = .78
RET 4 = .32
RET 5 = .63
RET 6 = .38
RET 7 = .43
RET 8 = .74
RET 9 = .26

DATE	HOUR	W SPEED	W DIR	T-OUT	T-IN	T-DIFF	AER
4/14/83	19	3.3	135.0	16.4	23.0	6.6	.93

RET 1 = 1.98
RET 2 = .55
RET 3 = .80
RET 4 = .51
RET 5 = .54
RET 6 = .47
RET 7 = .58
RET 8 = 1.37
RET 9 = .70

DATE	HOUR	W SPEED	W DIR	T-OUT	T-IN	T-DIFF	AER
4/14/83	22	2.1	135.0	16.1	23.0	6.9	.89

RET 1 = 1.92
RET 2 = .49
RET 3 = .57
RET 4 = .70
RET 5 = .74
RET 6 = .60
RET 7 = .56
RET 8 = 1.58
RET 9 = .34

DATE	HOUR	W SPEED	W DIR	T-OUT	T-IN	T-DIFF	AER
4/15/83	1	1.9	157.5	15.8	23.1	7.3	.92

RET 1 = 2.20
RET 2 = .76
RET 3 = 1.18
RET 4 = .31
RET 5 = .30
RET 6 = .31
RET 7 = .76
RET 8 = .68
RET 9 = .82

TABLE 2 (continued)

DATE	HOUR	W SPEED	W DIR	T-OUT	T-IN	T-DIFF	AER
4/15/83	4	1.9	157.5	16.6	23.1	6.5	.91

RET 1 = 1.37
RET 2 = .32
RET 3 = 1.06
RET 4 = .49
RET 5 = .53
RET 6 = .89
RET 7 = .41
RET 8 = 1.20
RET 9 = .84

DATE	HOUR	W SPEED	W DIR	T-OUT	T-IN	T-DIFF	AER
4/15/83	7	2.6	157.5	17.7	23.2	5.5	.54

RET 1 = 1.26
RET 2 = .70
RET 3 = .42
RET 4 = .63
RET 5 = .47
RET 6 = .46
RET 7 = .47
RET 8 = .29
RET 9 = .34

DATE	HOUR	W SPEED	W DIR	T-OUT	T-IN	T-DIFF	AER
4/15/83	10	2.3	180.0	18.6	23.7	5.1	.71

RET 1 = 1.48
RET 2 = .71
RET 3 = .35
RET 4 = .48
RET 5 = .82
RET 6 = .65
RET 7 = .53
RET 8 = .58
RET 9 = .64

DATE	HOUR	W SPEED	W DIR	T-OUT	T-IN	T-DIFF	AER
4/18/83	4	2.5	292.5	9.7	22.2	12.5	1.02

RET 1 = 1.48
RET 2 = 0.00
RET 3 = 1.70
RET 4 = .14
RET 5 = .93
RET 6 = .95
RET 7 = .88
RET 8 = .38
RET 9 = .98

TABLE 2 (continued)

DATE	HOUR	W SPEED	W DIR	T-OUT	T-IN	T-DIFF	AER
4/18/83	7	2.3	292.5	10.8	22.3	11.5	1.24

RET 1 = .71
RET 2 = .90
RET 3 = .91
RET 4 = 1.46
RET 5 = .71
RET 6 = .49
RET 7 = 1.44
RET 8 = 2.55
RET 9 = 1.69

DATE	HOUR	W SPEED	W DIR	T-OUT	T-IN	T-DIFF	AER
4/18/83	10	2.0	270.0	10.0	22.8	12.8	.74

RET 1 = .84
RET 2 = .71
RET 3 = 1.12
RET 4 = .35
RET 5 = .38
RET 6 = .79
RET 7 = .80
RET 8 = .58
RET 9 = .53

DATE	HOUR	W SPEED	W DIR	T-OUT	T-IN	T-DIFF	AER
4/18/83	13	1.8	270.0	11.9	23.0	11.1	.86

RET 1 = 1.46
RET 2 = 1.56
RET 3 = 1.00
RET 4 = .48
RET 5 = 0.00
RET 6 = .62
RET 7 = .31
RET 8 = 1.19
RET 9 = 1.10

DATE	HOUR	W SPEED	W DIR	T-OUT	T-IN	T-DIFF	AER
4/18/83	22	2.1	67.5	11.1	22.9	11.8	.62

RET 1 = .47
RET 2 = .32
RET 3 = 1.01
RET 4 = .74
RET 5 = .72
RET 6 = .13
RET 7 = .56
RET 8 = .56
RET 9 = .92

TABLE 2 (continued)

```
 DATE     HOUR     W SPEED  W DIR      T-OUT      T-IN     T-DIFF    AER
4/19/83    1         2.6    112.5       10.3      22.8      12.5      .96

          RET 1  =   1.52
          RET 2  =    .15
          RET 3  =    .23
          RET 4  =    .68
          RET 5  =    .75
          RET 6  =    .62
          RET 7  =    .64
          RET 8  =    .53
          RET 9  =   2.43

 DATE     HOUR     W SPEED  W DIR      T-OUT      T-IN     T-DIFF    AER
4/19/83    7         3.6    225.0       10.2      22.7      12.5      .96

          RET 1  =    .94
          RET 2  =   0.00
          RET 3  =   1.76
          RET 4  =    .55
          RET 5  =    .34
          RET 6  =    .62
          RET 7  =    .75
          RET 8  =    .57
          RET 9  =   1.62

 DATE     HOUR     W SPEED  W DIR      T-OUT      T-IN     T-DIFF    AER
4/19/83   13         4.5    270.0       10.9      23.7      12.8      .75

          RET 1  =   1.25
          RET 2  =   1.41
          RET 3  =   1.31
          RET 4  =   1.02
          RET 5  =    .08
          RET 6  =    .77
          RET 7  =    .23
          RET 8  =    .61
          RET 9  =    .64

 DATE     HOUR     W SPEED  W DIR      T-OUT      T-IN     T-DIFF    AER
4/19/83   16         4.3    202.5       12.2      23.7      11.5      .65

          RET 1  =   1.29
          RET 2  =    .71
          RET 3  =    .57
          RET 4  =    .47
          RET 5  =    .41
          RET 6  =    .90
          RET 7  =    .23
          RET 8  =    .75
          RET 9  =    .29
```

TABLE 2 (continued)

DATE	HOUR	W SPEED	W DIR	T-OUT	T-IN	T-DIFF	AER
4/19/83	19	5.0	292.5	9.6	23.4	13.8	.68

RET 1 = 1.10
RET 2 = .01
RET 3 = .49
RET 4 = .62
RET 5 = .33
RET 6 = .40
RET 7 = .48
RET 8 = .55
RET 9 = 1.35

DATE	HOUR	W SPEED	W DIR	T-OUT	T-IN	T-DIFF	AER
4/19/83	22	4.1	292.5	8.6	23.2	14.6	.59

RET 1 = 1.02
RET 2 = 1.13
RET 3 = .73
RET 4 = .73
RET 5 = .61
RET 6 = .75
RET 7 = .35
RET 8 = .59
RET 9 = .06

TABLE 3. Air Exchange Rates with Fans Off and Outdoor Dampers Closed

LEGEND

W SPEED = wind speed, m/s
W DIR = wind direction, degrees clockwise from north
T-OUT = outdoor temperature, °C
T-IN = average indoor temperature, °C
T-DIFF = T-IN - T-OUT, °C
AER = average air exchange rate, h^{-1}
(weighting factors in Table 1)
RET = return air fan

DATE	HOUR	W SPEED	W DIR	T-OUT	T-IN	T-DIFF	AER
3/25/83	18	2.1	45.0	9.6	22.5	12.9	.86

RET 1 = 2.01
RET 2 = 1.05
RET 3 = 1.13
RET 4 = .99
RET 5 = .46
RET 6 = .26
RET 7 = .81
RET 8 = .50
RET 9 = .64

DATE	HOUR	W SPEED	W DIR	T-OUT	T-IN	T-DIFF	AER
3/25/83	21	1.5	22.5	9.7	22.2	12.5	1.17

RET 1 = 1.97
RET 2 = 1.05
RET 3 = .97
RET 4 = 1.09
RET 5 = .76
RET 6 = .77
RET 7 = .68
RET 8 = 1.03
RET 9 = 1.86

DATE	HOUR	W SPEED	W DIR	T-OUT	T-IN	T-DIFF	AER
3/25/83	22	1.6	45.0	8.7	22.2	13.5	.83

RET 1 = 1.03
RET 2 = 1.48
RET 3 = 1.03
RET 4 = 1.29
RET 5 = .46
RET 6 = .46
RET 7 = .49
RET 8 = .62
RET 9 = 1.48

TABLE 3 (continued)

DATE	HOUR	W SPEED	W DIR	T-OUT	T-IN	T-DIFF	AER
3/25/83	23	1.6	45.0	8.5	22.1	13.6	1.14

RET 1 = 1.80
RET 2 = 1.43
RET 3 = 1.31
RET 4 = 1.11
RET 5 = .84
RET 6 = .68
RET 7 = .87
RET 8 = .73
RET 9 = 1.64

DATE	HOUR	W SPEED	W DIR	T-OUT	T-IN	T-DIFF	AER
3/26/83	0	1.4	45.0	9.2	22.0	12.8	1.40

RET 1 = 2.50
RET 2 = 1.79
RET 3 = 1.26
RET 4 = 1.08
RET 5 = .90
RET 6 = .73
RET 7 = .93
RET 8 = 1.03
RET 9 = 2.24

DATE	HOUR	W SPEED	W DIR	T-OUT	T-IN	T-DIFF	AER
3/26/83	2	1.1	90.0	6.4	21.4	15.0	.97

RET 1 = 2.10
RET 2 = 2.16
RET 3 = .78
RET 4 = 1.10
RET 5 = .43
RET 6 = .49
RET 7 = .54
RET 8 = .98
RET 9 = 1.14

DATE	HOUR	W SPEED	W DIR	T-OUT	T-IN	T-DIFF	AER
3/27/83	12	3.1	112.5	18.8	19.9	1.1	1.28

RET 1 = 1.79
RET 2 = 1.79
RET 3 = 2.07
RET 4 = 1.63
RET 5 = .46
RET 6 = .81
RET 7 = .54
RET 8 = 1.95
RET 9 = .92

TABLE 3 (continued)

```
 DATE    HOUR    W SPEED  W DIR     T-OUT      T-IN     T-DIFF    AER
3/27/83  18        1.1    270.0      19.6      19.9        .3     1.96

         RET 1  =  1.67
         RET 2  =  2.19
         RET 3  =  3.24
         RET 4  =  1.82
         RET 5  =  1.52
         RET 6  =  1.24
         RET 7  =  1.57
         RET 8  =  1.75
         RET 9  =  2.57

 DATE    HOUR    W SPEED  W DIR     T-OUT      T-IN     T-DIFF    AER
3/27/83  22        2.0    270.0      19.8      19.9        .1     1.09

         RET 1  =  1.91
         RET 2  =  2.08
         RET 3  =  2.16
         RET 4  =   .68
         RET 5  =  0.00
         RET 6  =   .90
         RET 7  =  0.00
         RET 8  =   .91
         RET 9  =  1.25

 DATE    HOUR    W SPEED  W DIR     T-OUT      T-IN     T-DIFF    AER
3/28/83   2        1.4    292.5      19.5      19.7        .2     1.55

         RET 1  =  2.44
         RET 2  =  2.24
         RET 3  =  1.75
         RET 4  =  2.04
         RET 5  =   .92
         RET 6  =   .69
         RET 7  =   .63
         RET 8  =  1.03
         RET 9  =  3.01
```

TABLE 4. Air Exchange Rates with Building Pressurized to 8-14 Pa

LEGEND
W SPEED = wind speed, m/s
W DIR = wind direction, degrees clockwise from north
T-OUT = outdoor temperature, °C
T-IN = average indoor temperature, °C
T-DIFF = T-IN - T-OUT, °C
RET = return air fan
7W-1 and 14W-1 = stack areas

DATE	HOUR	W SPEED	W DIR	T-OUT	T-IN	T-DIFF
4/21/83	19	1.4	292.5	17.9	23.8	5.9

RET 1 = .09
RET 2 = .12
RET 3 = .39
RET 4 = .01
RET 5 = .18
RET 6 = .56
RET 7 = .26
14W-1 = .02
7W-1 = .14

DATE	HOUR	W SPEED	W DIR	T-OUT	T-IN	T-DIFF
4/21/83	20	.9	315.0	17.8	24.0	6.2

RET 1 = .39
RET 2 = .27
RET 3 = .20
RET 4 = .14
RET 5 = .15
RET 6 = .12
RET 7 = .14
14W-1 = 0.00
7W-1 = .43

Figure 1. The National Archives Building, located between Pennsylvania and Constitution Avenues, and between 7th and 9th Streets, in downtown Washington.

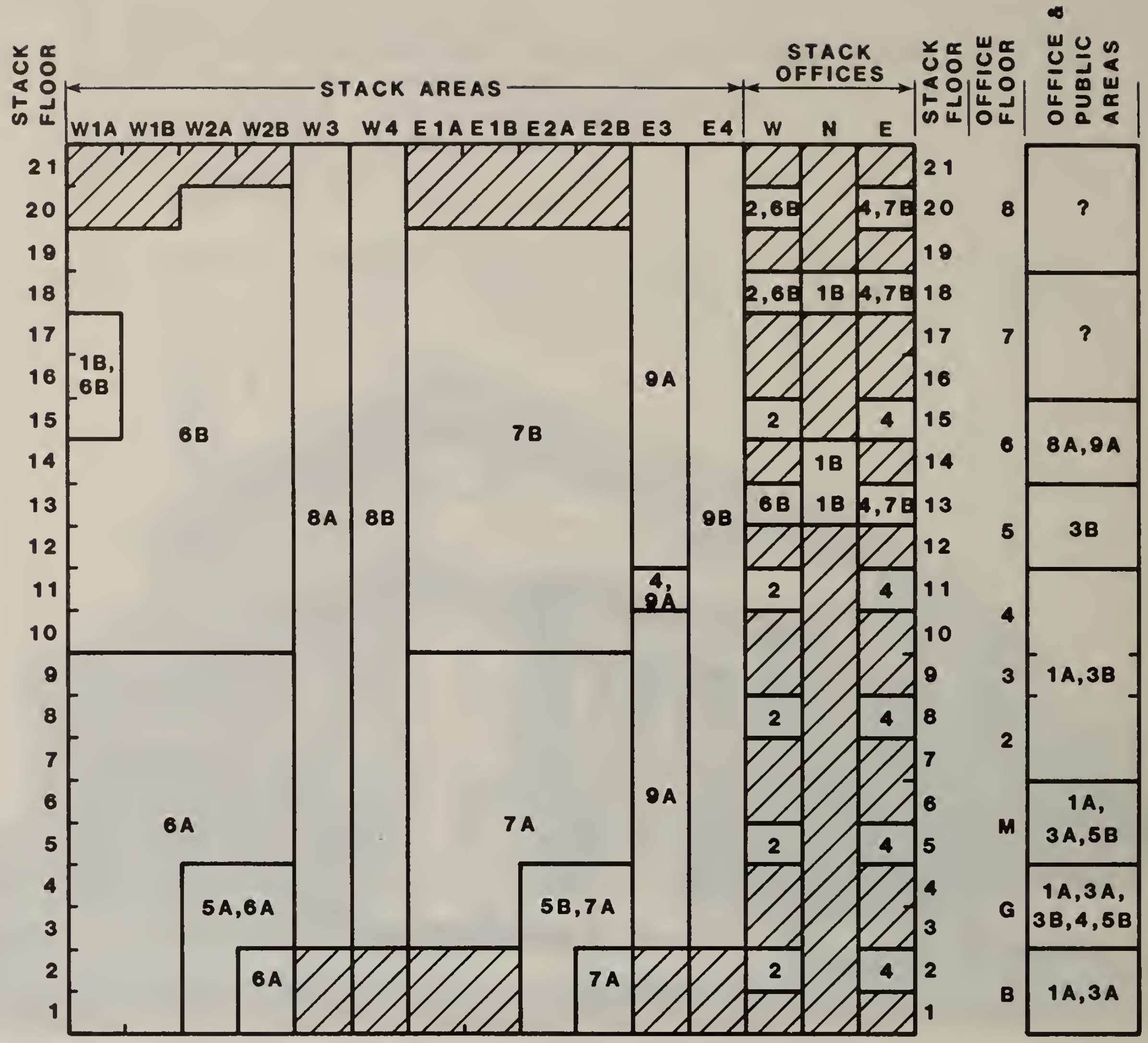

Figure 2. Schematic side view of National Archives Building, showing areas served by air-handling systems, from information supplied by GSA. Each of the nine air-handling systems of the building except 2 and 4 has two supply air fans labelled "A" and "B", and one return air fan; systems 2 and 4 have one supply and return fan each. All fans in each system operate simultaneously. The numbers in the figure above refer to supply fans.

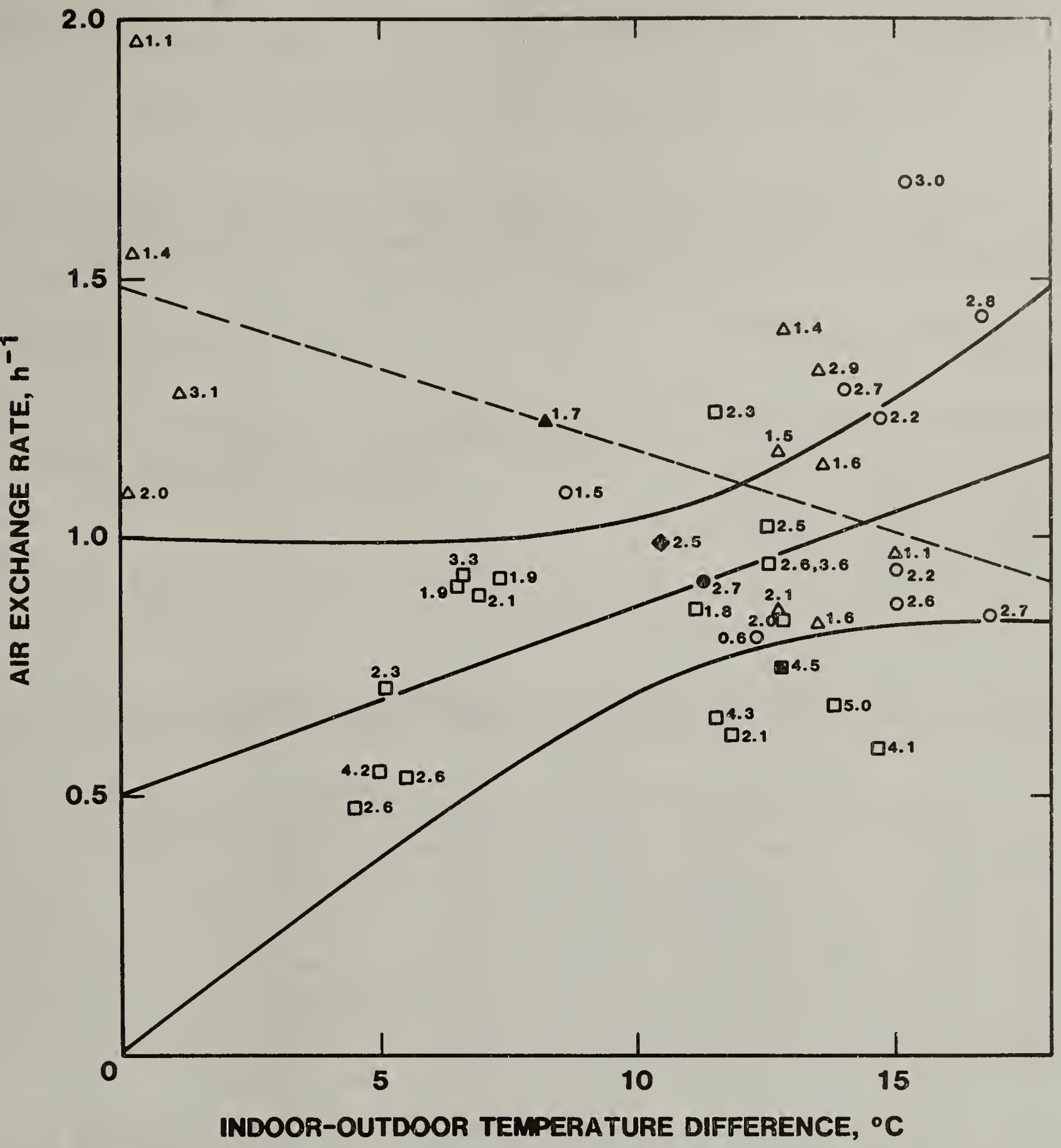

Figure 3. Relationship of air exchange rate to indoor-outdoor temperature difference and wind speed under normal fan operation and with outdoor air dampers closed. Wind speeds (m/s) are shown to the right of data points. Solid line is best-fit regression line for normal HVAC-system operation. Curves represent 1 standard error unit on each side of regression line. Dotted line is best fit regression line for outdoor air dampers closed. O , normal operation, early tests (see Methods); □, normal operation, late tests (see Methods); ■, normal operation (late test), test of air mixing between stack areas and other areas; △, outdoor air dampers closed; ● , normal operation average; ▲ , outdoor air dampers closed average; ◆, overall average.

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10. SUPPLEMENTARY NOTES

This report, NBSIR 83-2795, uses previously approved NBSIR 83-2767 and NBSIR 83-2770 as appendices

☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

11. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)*

Criteria for temperature, relative humidity, and gaseous and particulate contaminant concentrations are proposed for spaces used for storage and preservation of paper-based archival records. The criteria are based on available information from the literature, and recommendations of the January 19-20, 1983, National Bureau of Standards Workshop on Environmental Conditions for Archival Storage. Methods are discussed for meeting these criteria. Air quality criteria are proposed for different categories for archival storage. Factors to consider in the design of archival storage facilities are addressed and recommendations made to aid in the design of environmental conditioning systems for these facilities. A review of literature describes the damage that may be caused by high temperature, high and low relative humidity, and air pollutants to paper-based records.

Results of measurements of temperature, relative humidity, air exchange rate, and gaseous contaminant concentrations (sulfur dioxide, nitrogen oxides, and ozone) in the National Archives Building in Washington, D.C., are presented. These measurements are compared with those made in other buildings having controlled environments.

12. KEY WORDS *(Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)*

air quality; archival storage; criteria; design parameters; environmental conditioning systems; environmental conditions; environmental control; preservation .

13. AVAILABILITY

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