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Are we losing our marbles?

The status of our understanding of pollution effects on monuments and historic buildings in the U. S.

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INTRODUCTION

This paper discusses selected National Acid Precipitation Assessment Program (NAPAP) research efforts related to the decay and long-term conservation of historic buildings and monuments. The implications of various distances from emission sources (both vehicular and tall stack sources) vis a vis cultural properties is considered in broad terms relative to the effects on chemical alteration of original historic materials. The regional characteristics of cultural material distributions are discussed in the context of relating sensitive receptors to emission patterns and deposition fields. To a large extent, this paper summarizes material presented in the NAPAP State of Science and Technology (SOS/T) Report series, in particular SOS/T 20, Processes of Deposition to Structures[19], and SOS/T 21, Distribution of Resources Potentially at Risk from Acidic Deposition[20].

The paper focuses on selected issues relating to delivery of emitted pollutants to sensitive surfaces and to the subsequent chemical interactions. Dry deposition to the geometrically complex surfaces of building facades and outdoor sculpture is enhanced relative to areally-averaged deposition values (e.g., to various vegetative surfaces) by virtue of configuration, relationship to neighboring structures, and urban micrometeorological effects. The hydrodynamics of wet deposition to complex shapes, in particular various turbulent fluid flow regimes, enhances chemically-induced material dissolution. In situ measurements of runoff from marble and bronze monuments of various configurations at Gettysburg National Military Park (NMP), as well as bronze corrosion of monuments of identical shape in a range of deposition regimes are used to demonstrate that deposition damage to historic resources is greater than deposition damage to standard test panels.

ASSESSING THE STATE OF DECAY

Prior to the 1980s, acidic deposition damage to cultural properties was addressed either qualitatively or through case studies of individual resources, but not in a comprehensive or systematic manner. Under the auspices of NAPAP, NPS began development of the analytical tools and gathering of the inventory data needed for evaluating impacts of changes in regional emission patterns. Estimates of the magnitude of damages to historic buildings and monuments, in physical, economic, or cultural terms, if based strictly on the current, incomplete state-of-knowledge without considering the implication of the significant knowledge gaps in all aspects of the issue, will tend to be underestimated. From the viewpoint of managing the decay of cultural resources, the long-term goal is to extend the life of the property to the maximum feasible extent. Thus, pollution effects assessment is a question of predicting the impact of deposition on the material and the performance of preservation intervention options that may be available.

There are three scales of consideration with respect to cultural property conservation. The scale of greatest resolution is at the surface of the resource itself. It is here that pollutants are deposited, weathering occurs, and preservation/repair activities take place. The second scale of consideration is the setting or immediate vicinity of the property. Within the boundary of this sliding scale, be it a park, or a neighborhood, or perhaps a small community, management interventions into the emission→deposition→decay sequence consist of small-scale modifications of the environment: altering vegetation patterns to modulate surface moisture cycles, modifying flow fields with addition or removal of aerodynamic obstacles, changing emission patterns through relocation of parking lots or fuel switching at the most proximate sources. The third scale of consideration is that of a city, state, region, or continent, where there are a multiplicity of development decision-makers, various types of emission sources, and sufficient number of cultural properties to allow generalization. Cultural resources management action at this scale generally entails achieving a balance between new development and heritage conservation.

Figure 1 indicates the types of information needed to evaluate the impact of pollutants from either an individual resource, or a series of resources, a city, or a region. The geographical scope for which the analysis is applicable depends on the availability of location specific data, i.e., deposition regimes (lowest tier of arches) and sensitive resource distribution (top tier of arches). Process-based information, such as the interactions of pollutants/material substrates (middle tier of arches), aerodynamic and hydrodynamic enhancement of deposition (bottom linear tier), preservation treatment performance (top linear tier), etc., once developed, can be applied to any or all resources of the appropriate type. Damage assessments can be undertaken at any of the scales outlined above for which the appropriate location specific data are available. The degree of confidence associated with the analysis appears to depend in large part on the thoroughness and relevance of the process-based information.

Present estimates of physical damages to cultural resources induced by acidic deposition cannot be comprehensive because of the absence of three kinds of data. First, quantitative expressions relating deposition to decay to damage (middle arched tier) are not available for the full range of sensitive cultural materials and decay mechanisms[1]. Notable gaps include wet and dry deposition impacts on sandstone, mortar, and cast stone deterioration, bronze corrosion, and dry deposition effects on limestone and marble. Second, inventories of resources (top arched tier) for which the mechanisms and rates of pollutant/material interactions have been documented are incomplete, thus further underestimating the population at risk[20]. Third, the history of deposition (lower arched tier) prior to the mid-20th century is sparsely documented, but more than likely underestimates dry deposition of sulfur oxides and particles in urban areas[4,10,15]. Historic particle loadings are particularly important for metals and masonry where sulfate and carbon compounds accumulate on material surfaces and cause decay that continues well beyond the era of initial deposition.

URBAN DEPOSITION ESTIMATES

The majority of identified cultural resources at risk are found in cities. Over 95% of architectural stone was found in urban areas and some 60-80% of the documented monuments and outdoor sculpture are located in cities. Thus, it is essential to be able to relate the projected changes in regional as well as urban emissions to changes in urban concentrations and deposition fields. NAPAP has generated regional scale concentration estimates of the impact of Phase I controls specified in the 1990 Amendments to the Clean Air Act using the Regional Acid Deposition Model (RADM)[6]. Regional scale concentration predictions can be useful in estimating the exposure of resources in rural areas, where some larger fraction of monuments and tombstones than historic stone buildings are found. RADM also provides estimates of the concentration of pollutants imported into cities, where historic buildings dominate the stock of cultural properties at risk. In concert with estimates of concentration impacts from tall stack emissions, estimates of urban emissions and dispersion/turbulence characteristics are needed. The third important model component to be incorporated is urban meteorology, including aerodynamics, moisture and temperature regimes[7]. Since most American cities are located on major bodies of water, the role of thermal inversion boundary layers and distillation as a source of condensation warrant close attention in estimating urban deposition fields. Moisture serves to enhance deposition of soluble gases; SO_2 deposition is particularly dependent on surface moisture[7,19]) In addition, urban moisture in the form of fogs and condensation can act as a source of acid species[8]. Thus, the impact of building density and height ranges in modulating delivery of condensation and precipitation to material surfaces are refinements to traditional models that need further consideration.

REGIONAL DISTRIBUTION OF SENSITIVE CULTURAL RESOURCES

In the U. S., regions having the richest cultural histories coincide with the region of greatest acidic deposition. The Northeast is one of the regions with the longest settlement history, and thus the greatest number of pre-Civil War buildings and tombstones. Most of the nation's historic battlefields, especially those with many commemorative monuments, are located east of the Mississippi. Material selection for buildings and monuments has changed over time, with more durable materials replacing pollutant-sensitive marbles, sandstones, and zinc products beginning in the 1850s-1880s. Since the shift to use of more weather-resistant materials occurred before the large scale western expansion and late 19th century population increases, areas west of the Mississippi are expected to show a less dense distribution of pollutant-sensitive historic materials. While inventory and census methods can theoretically be used to identify and to locate cultural resources at risk[3], it was found that the data sources in the U.S. are not, in fact, sufficiently detailed or complete with respect to material or morphology descriptions. Estimation methods are therefore necessary to approximate the distribution of specific materials within the enumerated framework of existing historic structure inventories.

Historic Stone Buildings

It is estimated that there are two to four million historic buildings in the U. S., pending documentation and listing on the National Register of Historic Places (NRHP). Approximately 14% of the 275,000+ historic buildings registered as of 1985 in 17 Northeastern states and the District of Columbia have been documented as being constructed partially or wholly of stone[20]. An additional 10,000 or so stone structures in the 17 state region were documented between 1986-1988. If those structures in the Northeast that were documented prior to 1986 are representative of the wider universe of historic buildings with respect to materials usage, then one might estimate that 10 - 15% of the universe of historic buildings incorporate stone in some part of the facade. Therefore, the approximately 50,000 historic buildings identified in the 17 Northeastern states with stone walls or trim represents the minimum number of historic buildings at risk; 200,000 - 600,000 is a more realistic estimate for stone buildings at risk in the U. S..

Distribution of stone types varies significantly from state to state, as would be expected for a building material that is non-uniformly distributed in nature and difficult to transport (Figure 2). For approximately half of the architectural stone elements registered in the 1986 study, the material type was identified simply as "stone". Of those architectural elements for which the specific stone type was identified, approximately 47% are sandstone, of which some undefined subset is relatively resistant to acidic deposition, by virtue of minimal calcitic or clay auxiliary mineral content. Granite (23%) and limestone (25%) are approximately equally widely used. Marble, while sparsely distributed overall (6%), is the only type of stone found more frequently as carved trim than as wall material. Marble is also used more frequently in National Historic Landmarks than in the general population of registered historic buildings. In the broadest general terms, at least 15% and perhaps as much as 50% of the stone used in historic buildings is sensitive to attack by acidic deposition. A first approximation of the population of at risk, pending field verification and refinement, is between 30,000 - 300,000 historic buildings nationally.

At the time these distribution statistics were derived, the survey and documentation for some of the major limestone, marble, and sandstone producing states (Connecticut, Illinois, Indiana, and Kentucky) were less complete than for the remainder of the Northeast. Thus, it is likely that the above estimates under-represent the use of stone in those areas where the densest distribution of acid-sensitive stone would be expected. Given that the detailed evaluation of material distribution was undertaken in a region where wood frame construction is more prevalent than the rest of the country, these estimates most probably represent a minimum distribution of stone use in historic buildings. Lastly, the nature of the NRHP documentation lends itself to underestimates of pollutant-sensitive stones because of lack of specificity in material descriptions.

Monuments and Outdoor Sculpture

No comprehensive national inventory of American outdoor sculpture and monuments exists at present. Estimates range from 20,000 - 50,000 monuments (excluding gravemarkers) nationwide, depending on the definition of monument and outdoor sculpture, with a minimum estimate of 10,000 monuments located in the 31 Eastern states[14,20]. Architectural sculpture and memorial structures (e.g., the Kennedy Center, Soldiers Field) are specifically excluded from the estimates because of the eclectic nature of the data sources. Attempts to evaluate the materials distribution is more problematic, but it is thought that a minimum estimate of acid-sensitive materials would include 12,000 bronze statues, 2,500 marble statues, 1,500 marble architectural monuments, and 2,000-4,000 monuments of other materials, such as limestone, sandstone, painted metal, etc. The actual distributions may be twice as high. The wide range of estimates stems in part from the incomplete nature of the data sources and uncertainties in extrapolation methods, and in part from debates about the definitions of "monument" and "outdoor sculpture". The National Institute for the Conservation of Cultural Property (NIC) is planning a comprehensive survey, known as Save Outdoor Sculpture (SOS!), that will provide field verification of the sculpture estimates. Identification of unornamented monuments must await a subsequent, as yet unplanned, effort.

Funerary Memorials

It is estimated, based on mortality statistics from the Colonial period to present, that there are between 40 - 120 million gravemarkers exposed to acidic deposition nationwide[20]. Approximately one third of these gravemarkers are made from acid-sensitive materials, based on interpretations of market statistics. Some 2 million marble tombstones commemorate veterans across the country. Given the trend since the mid-1800s away from carbonate stone (except for the Veterans Administration marble markers), and geographical shifts in population over time, a higher proportion of the acid-sensitive gravemarkers are likely to be found in the Northeastern region of the U.S..

CHEMICAL INFLUENCES ON WEATHERING OF HISTORIC MATERIALS

Carbonate minerals (marble, limestone, some sandstones, mortars) and bronzes are chemically reactive with both sulfur dioxide (SO_2) and acids (H+) in rain and snow. Sulfur and particulate pollutants react with stone surfaces to form black crusts which disfigure the surface and cause disintegration and spalling of the stone. Similarly, the green patina on bronzes in polluted environments is largely composed of copper sulfate compounds. Various researchers have documented that carbonate stones and bronze patinas are dissolved much more quickly when rain pH drops below 4.0, which is not uncommon on a rain event basis in today's environment. Complex surfaces, such as sculpture and cornices, are more seriously affected than flat surfaces by air- and rain-borne pollutants. Irregular shapes increase the delivery of wet and dry deposition to surfaces, thus increasing their ability to accelerate weathering processes.

Carbonate Stone

Schmiermund and co-workers[18] experimentally measured calcium dissolution of saturated, inclined limestone and marble surfaces 15 cm long as a function of flow rate and rain pH. The dissolution rates, reported in units of μmolesCa^{2+}/min/cm of width, were essentially identical for limestone and marble under the experimental conditions of pre-saturation. Figure 3 demonstrates that calcium removal rates increase with volumetric flow rate for all initial solution pHs. For a given volumetric flow rate, dissolution increases with acidity for initial solutions with pH less than 4.5, while initial solution acidities of 4.5 and 5.0 (and presumably higher) produce calcium loss rates that are independent of solution pH. At very low volumetric flow rates approaching zero, similar dissolution rates are expected for both materials under all conditions of acidity.

The data for the low flow conditions shown in Figure 3 are analogous to light rain events or very small catchment areas, as typically found in the NAPAP field test sites measured by Reddy and co-workers[1]. Under most ambient wet deposition conditions, material surfaces are likely to experience higher volumetric flow rates, and thus the effect of acidity on stone dissolution is typically further enhanced. Consequently, the dissolution produced by rain of pH 4.5 or more, flowing quickly over a surface is similar to that produced by more acidic solutions for non-flowing or very slowly flowing situations. Conversely, low pH solutions that flow relatively rapidly over marble and water-saturated limestone surfaces will result in dramatically accelerated dissolution. This research indicates that if one where to establish a target ambient rain pH level for protecting marble and limestone resources, the desired condition would be somewhere between pH 4.5 and 4.0.

Field confirmation of the above laboratory results was undertaken at Gettysburg National Military Park (NMP). Gettysburg is located in rural south-central Pennsylvania, with added vehicular traffic typical of several million visitors per year. Event-based rainwater and runoff samples collected from several Carrara marble monuments dedicated in the 1880s have been analyzed for pH, calcium content and various anion species in parallel with work reported by Meakin and co-workers[12]. Experimental results at the Soldiers' National Monument and the 68th Pennsylvania Regimental Monument show that erosion of sculpted marble by rain is 3-5 times greater than dissolution of a flat, vertical surface of an obelisk shaped monument (Figure 4). All runoff samples were taken from Carrara marble surfaces of comparable mineralogy and exposure histories. The primary difference between the collections is the shape of the catchment area, and thus the hydrodynamic characteristics. While the flow rates over these complex catchments have not been estimated with accuracy, it is clear that the turbulence of fluid flow over a curvilinear surface is substantially greater than that over a flat, vertical surface. The obelisk more nearly corresponds to the 1' X 2 ' slabs on which the NAPAP marble dissolution dose-response function is based[1]. As such, application of the dissolution dose-response function to predict erosion of non-uniform stone surfaces must take into consideration the significant hydrodynamic enhancement that occurs, perhaps by exercising the CHEMTRAK model[8] for the appropriate turbulent flow conditions.

Bronze

Bronze corrosion films that form in sheltered, unwashed areas are black, while in areas fully exposed to condensation and precipitation, corrosion products are typically various shades and thicknesses of green. Streaking and pitting are also commonly observed manifestations of pollutant-enhanced corrosion. The most frequently detected corrosion product is brochantite, a hydrated copper sulfate, $CuSO_4.3Cu(OH)_2$, indicating reaction with sulfur pollutants in the air and rain. There was also evidence for cuprite, Cu_2O, malachite $CuCO_3.Cu(OH)_2$, and antlerite, $CuSO_4.2Cu(OH)_2$. The latter material is of particular interest, as it has been proposed that in particularly low pH conditions, antlerite should be the favored form of copper sulfate[10]. Further, antlerite is substantially more soluble than brochantite; thus, increasing the rate of copper sulfate removal by rain, the corrosion rate, and the staining of adjacent masonry materials.

Event-based runoff samples were also collected at Gettysburg NMP from three bronze tablets[12]. These tablets are cast bronze plaques with raised letters, mounted at 30° to the vertical on granite supports, specified as "Government Standard Bronze Metal of the best quality" and confirmed by EDS analyses to be 5% Zn, Sn, and Pb in Cu. The collection gutters were sized to provide an averaged measure of the pH and ion content of the solution leaving the tablet. It would appear to be reasonable to expect that the first runoff, would be particularly rich in species leached from the metal surface. The copper:zinc concentration ratio in the runoff indicates a 5% zinc content and no preferential removal of zinc from the copper base. The copper and sulfate concentrations show excellent correlation (Figure 5). The ratio of dissolved copper to sulfate ratio indicates a cupric sulfate, $CuSO_4$, composition of the corrosion product, and suggests that the concentration of sulfate ions is determining the dissolution rate.

The "Hiker" statue, sculpted by Theo Alice Ruggles Kitson and cast in more than 50 bronze replicas by the Gorham Foundry, Providence, Rhode Island between 1921 and 1966, has been used as a basis to evaluate the role of the environmental exposure in the corrosion of outdoor sculpture. The "Hikers" were erected to commemorate Spanish American War veterans across the U.S.. About 25 of the "Hikers" have been photographed in detail and the surface corrosion characteristics studied in detail for about a dozen statues in New England and the Mid-Atlantic region[12]. The team investigated alloy composition, overall corrosion patterns, streaking characteristics, chemical composition of corrosion layers, and morphologies of the surfaces in the as-corroded state, as well as for one statue after conservation treatment. The metal composition of seven statues cast over a period of 15 years was determined to be very similar; thus variations in corrosion could be attributed to differences in environmental exposure.

Surface pitting and metal loss was determined by casting the surface with a dental molding material, a type of polyalkoxysilane. Extreme corrosion and pitting were found in the Lynn, MA and Chelsea, MA "Hikers", with pit depths up to 0.3 mm after about 60 years of exposure as compared with minimal pitting at the Washington, DC, which has been waxed routinely for most of its 25 year exposure. The areal extent of corrosion on the "Hikers" varied significantly between statues; but corrosion sites within the statue are consistent between geographic locations (Figure 6). This composite corrosion map from 25 "Hikers" confirms that corrosion occurs most frequently in areas with an open sky view, fully exposed to both condensation (and thus enhanced SO_2 deposition) and precipitation[19]. Initial analysis related measured corrosion at 25 "Hikers" to exposure variables, including site characteristics, meteorological patterns and surrogates for historic pollution levels, such as manufacturing and demographic histories of the communities. It appears that the characteristics of the immediate location are very important. "Hikers" distant from streets seem to be less corroded than those sited in trafficked areas. Number of days of precipitation appeared to be the most important meteorological variable with respect to amount of streaking. This observation agrees well with the routine observation that rain acidity decreases rapidly after the initial minutes of the event.

PRESERVATION PRACTICE

Damage Thresholds

The degree to which society responds to the decay of cultural properties depends on several factors, including: awareness of the condition of the materials and its potential for decay, availability of financial resources, availability of treatment technology, and the resource's significance. It is not possible to generalize the relative importance of these factors at this point. Critical aesthetic thresholds of damage are likely to vary depending on the viewing distance, with the tolerance for decay diminishing as the user distance decreases. A building's contribution to a city's skyline is essentially unaffected by soiling or loss of material; replication of the structural form in new material would satisfy the scenic function of the building. The cornice or exterior cladding of upper stories of the same structure would similarly be relatively unaffected until the degree of decay resulted in a maintenance requirement, structural failure, or potential liability from falling building fragments. On the other hand, decay at the entrance to the building, particularly in buildings projecting images of power or stability, would not be tolerated to any significant degree.

Inscriptions and sculptural surfaces represent the extreme lack of ability to tolerate decay. In these cases, the surface can be equivalent to total value of the resource. When the letters carved on a grave marker are illegible, its historic and commemorative value is lost. Surface corrosion that disfigures sculpture depreciates its aesthetic or communicative value. Figure 7 plots the American Numismatic Association's condition grading system versus 1989 market value of $20 gold pieces that are highly sculptural in their design[2]. Very little initial wear incurs a considerable decrease in value. As wear increases, however, the rate of devaluation generally slows down, until its value is solely that of the metal. By analogy, one might construct a quantitative scale for deterioration of sculptural surfaces along the lines of coin grading systems. For inscriptions, an index might be developed based on a large number of field measurements of remaining carving depth versus legibility on tombstones, monuments, and buildings. Rossval[16] has created such a system for evaluating building conditions.

Damage Mitigation Options

In some cases, preservation methods are available to prevent environmental damage to cultural materials, notably the use of protective coatings for metals such as lacquering or waxing. However, once severe corrosion has occurred, it is difficult to restore the original luster of bronze sculptures. Theoretically, all outdoor bronzes could be protected from corrosion by relatively small expenditures, on the order of $10-$100 million per year nationally, based on estimated unit costs of $7,500 for initial cleaning and $1,100 for annual maintenance for a single figure[13]. It is estimated that, at a maximum, about 1,500 outdoor bronzes are protected on a routine basis. In practice, therefore, about 90 - 95% of monuments are unmaintained because of lack of funds at the community level. The costs of monument conservation must generally compete for budget priority with infrastructure repairs. A recognition of the unmet need is seen in the spread of Adopt-A-Monument and other private fund-raising campaigns to finance otherwise neglected monument conservation.

In contrast to metal corrosion control, there are no generally accepted methods to prevent stone decay accelerated by either wet or dry deposition. The use of waterproof and water repellant coatings, applied to retard erosion and other effects of wet deposition, is controversial. Further, such chemical surface treatments tend to enhance deposition of particles and some gases to the surface, thus increasing the adverse impacts of dry deposition. Cleaning is an appropriate treatment to alleviate discoloration and staining caused by dry deposition of SO_2 and particles. Most cleaning processes, however, tend to erode the stone surface being cleaned, by removing the outermost layers of encrusted grime and gypsum. In essence, cleaning is a process similar to erosion induced by wet deposition, the difference being the concentration of acids and flow rates involved. As a remedial measure, deteriorated stone surfaces can be stabilized through chemical consolidation, patching, surface retooling, repair, or ultimately, replacement. The least desirable remedial alternative for stone statuary is to move the work to a protected environment, which usually entails replacing the original work with a replica to maintain the visual contribution to the landscape.

An additional factor in damage assessment is the question of how many cycles of treatment can various classes of resources tolerate. Several mitigation options are based on the trade-off between "some decay now with action" versus "more decay later without action". For example, chemical stone cleaning and consolidation, aggressive removal of corrosion product and metallic stains from masonry, all damage material surfaces to some extent. As the cycle of these sorts of preservation treatments may be relatively short (5-15 years), in practice they could be oft-repeated in the life span of a cultural property. At some point, the repeated small impacts of preventative mitigation will accumulate to an unacceptable level of overall damage.

Economic Considerations

Since no universally accepted means of preventing acidic deposition damage to carbonate stone exists at present, the costs of damage prevention cannot be estimated. The costs of damage mitigation can in part be estimated from the costs of the various means of conservation. Mitigation, however, does not restore properties to their original condition nor does mitigation prevent continuing loss of some part of the societal value of our historic and cultural resources. Therefore, stone decay mitigation expenditures, which reflect some fraction of the societal cost associated with irreversible losses, have potential as partial proxies. Since preservation methods exist to protect outdoor bronzes and other statuary metals from further corrosion from atmospheric acidity, the estimated costs for initial conservation and annual maintenance represent, for the most part, the value of avoiding future aesthetic degradation. Over the last five years, the American economy has supported repair and rehabilitation of older structures in dollar volumes equal to or greater than new construction. Unit costs to restore or repair historic buildings in accordance with preservation standards tend to be higher and more variable than the costs of rehabilitating older, non-historic structures. Restoration/preservation expenditures are difficult to track, but most probably range from $5-10 billion/year for private and public sector work on major historic buildings.

Because Americans are proud of their national monuments, symbols, and cultural resources, extraordinary economic considerations should come into play when valuing damages to these properties. However, economic techniques to estimate non-market values, such as heritage or existence values, are not readily available. Saaby[17] argues that neither adjusted original costs of construction nor present costs of replacement are sufficient proxy. Moreover, heritage value increases rather than diminishes over time, all other conditions being held constant[5]. One measurable aspect of the economic value of cultural heritage is tourism. Tourism planning and marketing professionals concur that heritage-related attractions can dominate an area's tourist industry. For example, studies in Virginia demonstrate that a large proportion of the $3 billion annual tourist revenues come from heritage attractions[9]. Two approaches to looking at the heritage values were set forth in a recent European symposium on air pollution damage to cultural resources. One is diachronic, observing the value of a cultural resource through time and over the entire life of the item; the other is synchronic, studying the value of the resource at the present time specifically and in relation to other resources existing at present[16].

CONCLUSIONS

The influence of acidic deposition on test coupons has been quantified for the impact of hydrogen ion (H+) on marble, limestone, and galvanized steel dissolution, and the impact of SO_2 on galvanized steel corrosion[1]. Similar knowledge is needed for dry deposition effects on marble and limestone; wet and dry deposition effects on bronze, sandstone, mortar, concrete, reinforcing steel, and paint on wood. These cause and effect relationships between atmospheric exposure and weathering are based on small, flat coupons, which tend to seriously underestimate the role of deposition in the failure of larger, more geometrically complex components of buildings, structures, and monuments. Additional effort is needed to quantify the amplification of deposition damage to both curvilinear and large (3 - 30 m) surfaces.

Techniques need to be developed to estimate long-term exposures of materials in urban areas that take into account emissions from inside and outside cities as well as building density, surface temperature, and wetness. Further, techniques to estimate wet and dry deposition to complex shapes need to be refined and integrated within urban pollution climatology models. Over 95% of stone in historic buildings is found in cities, as are some 60 - 80% of monuments and outdoor sculpture. It is estimated that 10 - 15% of the universe of historic buildings incorporate stone in some part of the facade: and that some 15 - 50% of these materials are sensitive to environmental attack. A first approximation of this part of the population of at risk, pending field verification and refinement, is between 30,000 - 300,000 historic buildings nationally. Estimates range from 20,000 - 50,000 outdoor sculptures and monuments (excluding architectural sculpture) nationwide. Additionally, there are about 100 million gravemarkers, of which approximately one third are made from acid-sensitive materials.

In many cases in the United States, the regions having the richest cultural histories coincide with the region of acidic deposition. The Northeast is one of the regions with the longest settlement history, and thus the greatest number of pre-Civil War buildings and tombstones. Most of the nation's historic battlefields, especially those with many commemorative monuments, are located east of the Mississippi. Given demographic patterns and material selection trends, the majority of gravemarkers are found in the Northeast and Midwest; with the exception of the 2 million or so marble tombstones that commemorate Veterans across the country. Since the shift to use of more acid-resistant materials occurred before the large scale western expansion and late 19th century population increases, areas west of the Mississippi are expected to show a less dense distribution of acid-sensitive historic materials. The distributions of materials and cultural properties downwind of emission sources need to be further developed and refined, in order to provide a basis for geographically comprehensive estimates of the benefits of emissions control and trading.

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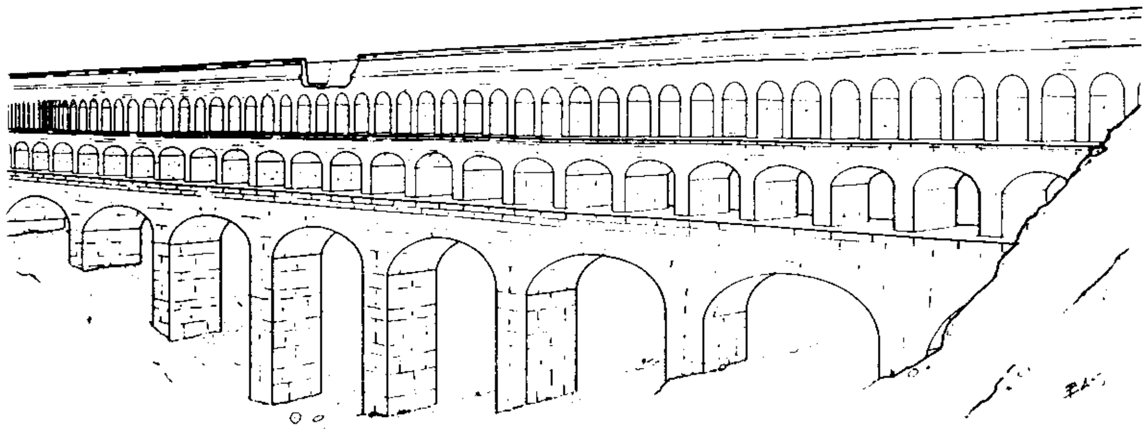


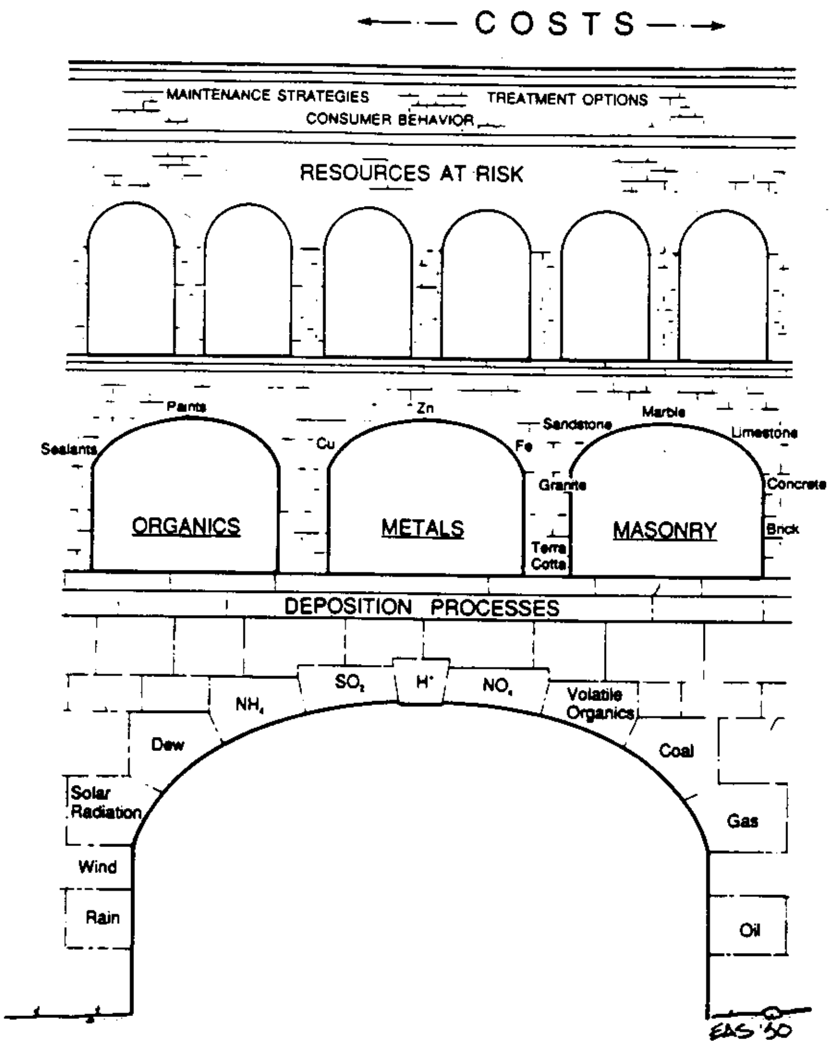


Figure 1 Schematic of damage assessment structure

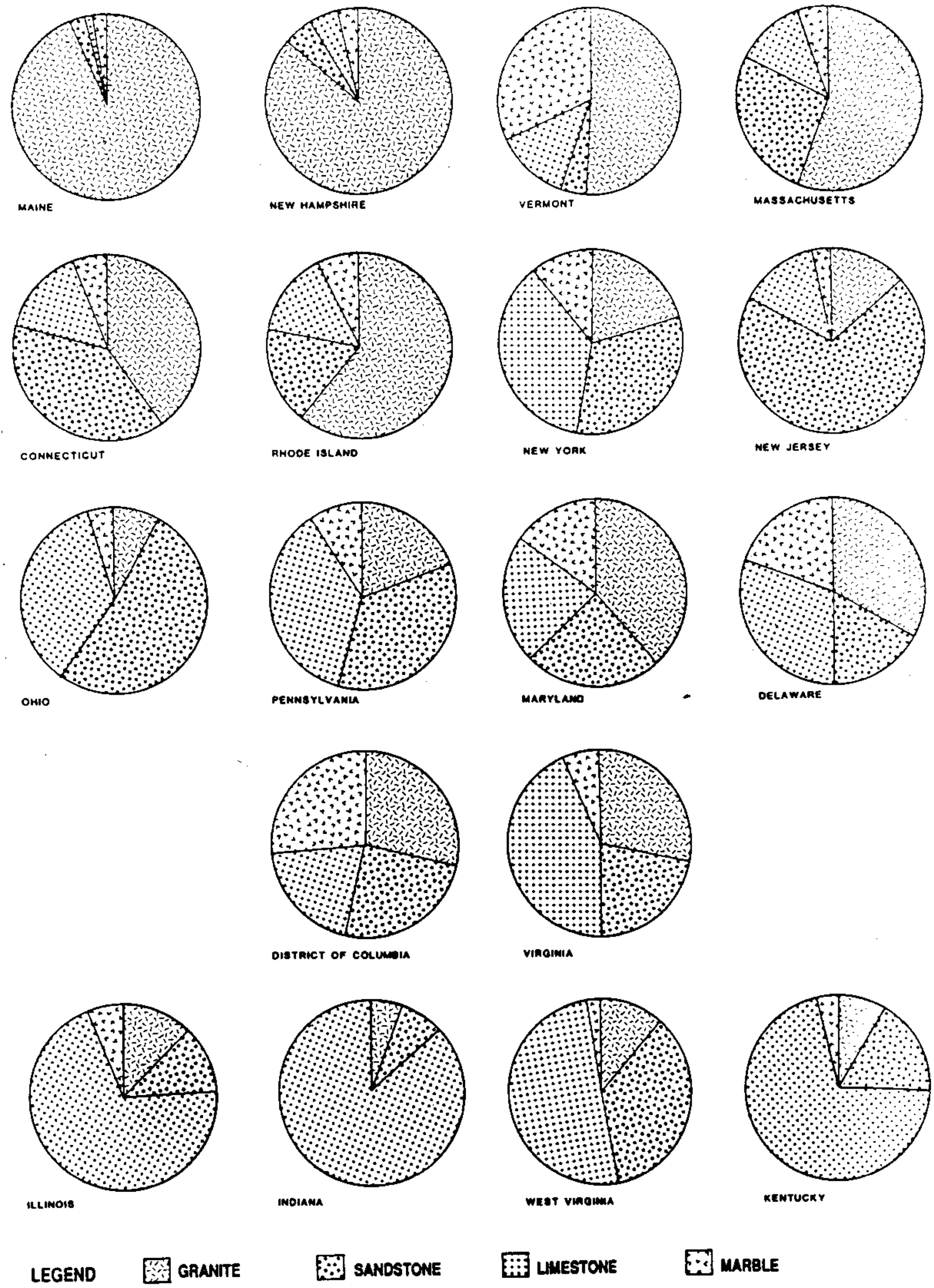
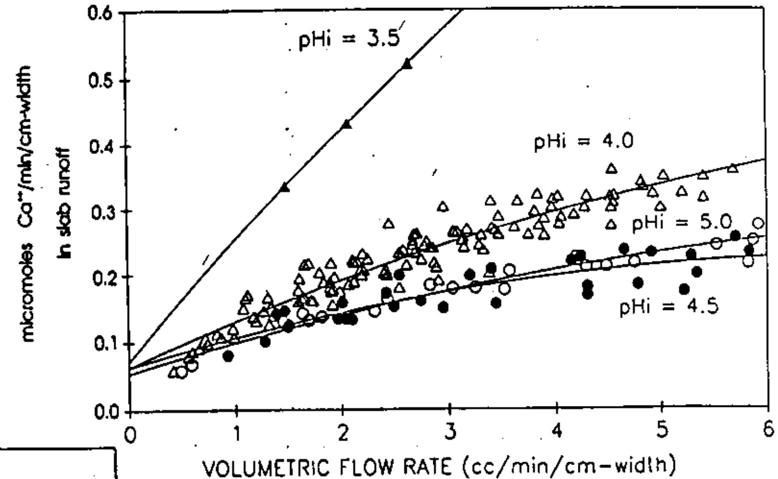


Figure 2 Stone type distribution for carved stone architectural elements. (From Sherwood et al., 1990b)

Figure 3 Hydrodynamic enhancement of limestone dissolution with increased flow rate and acidity. (From Sherwood et al., 1990a)



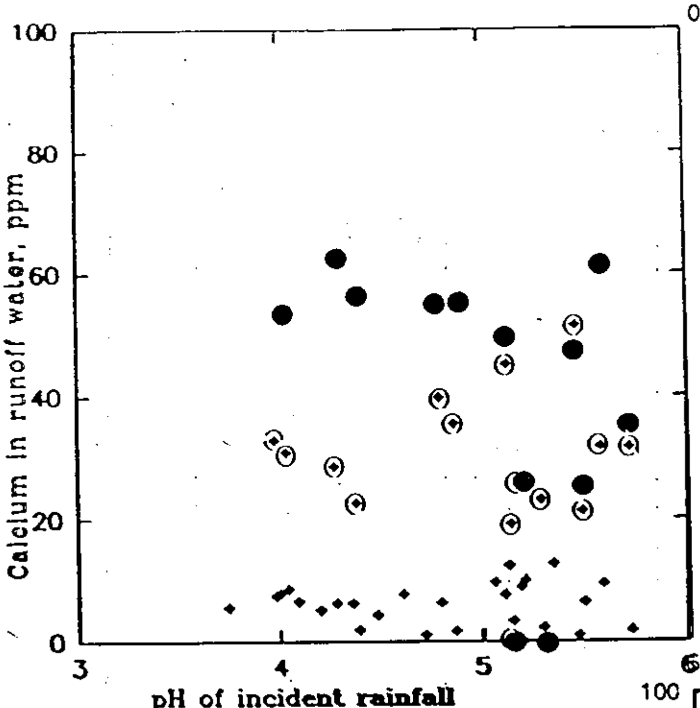


Figure 4 Runoff collected from Carrara marble monuments at Gettysburg NMP. Diamonds indicate runoff from an obelisk; circles indicate runoff from carved areas of 2 seated figures on Soldiers Nat'l Mon.

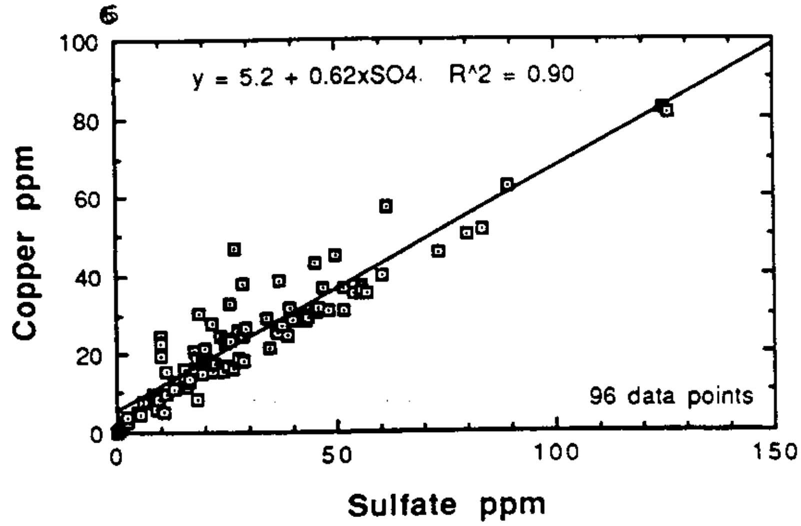


Figure 5 Runoff collected from bronze brigade markers at Gettysburg NMP. (From Meakin et al., 1990)

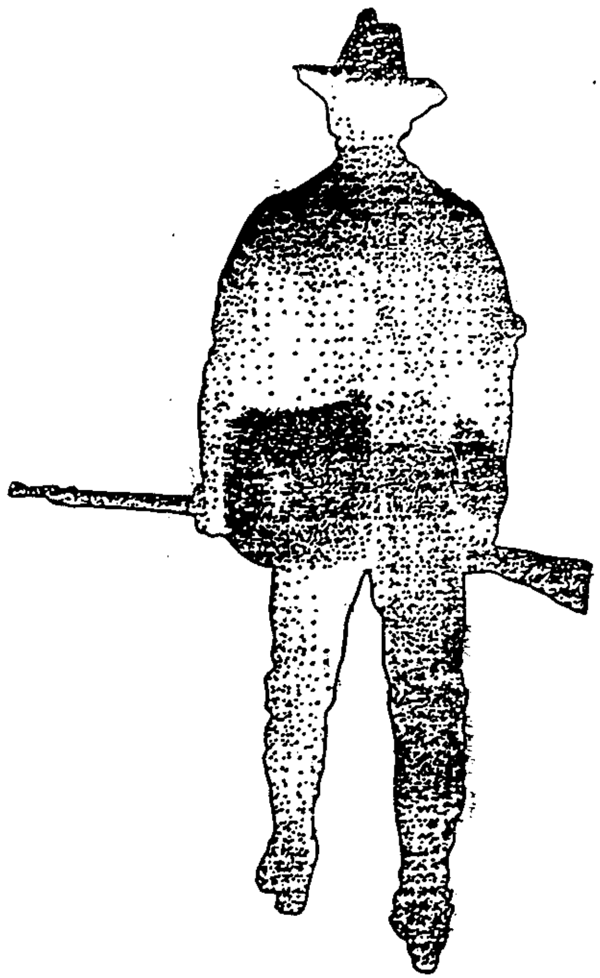


Figure 6 Composite corrosion map of 25 "Hikers". Each dot indicates one "Hiker" exhibited green corrosion in that pixel. (From Sherwood et al., 1990a)

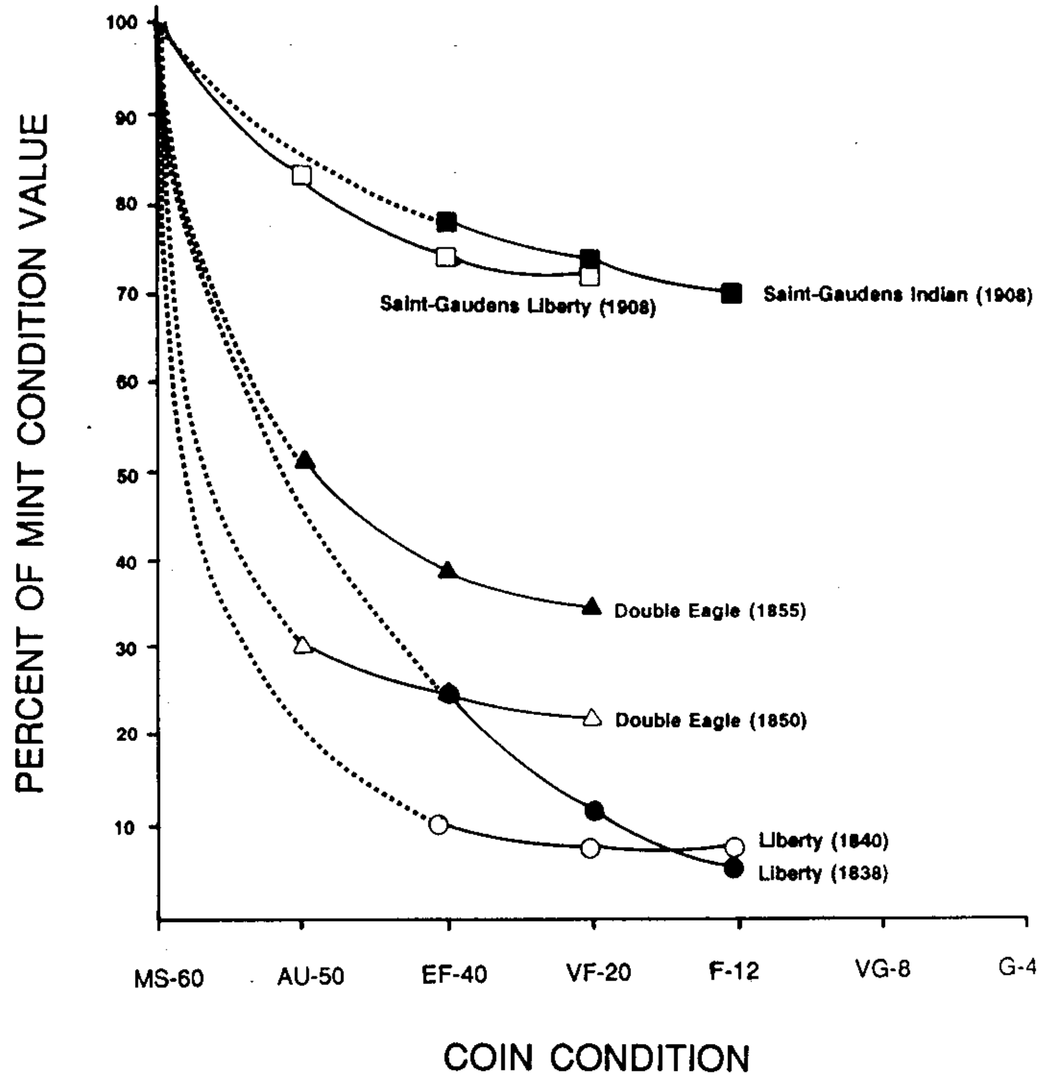


Figure 7 Market value of twenty dollar gold pieces as a function of condition. (From Sherwood et al., 1990b)