ASSESSMENT OF MATERIAL DAMAGE AND SOILING FROM AIR POLLUTION IN THE SOUTH COAST AIR BASIN

FINAL REPORT FOR CALIFORNIA AIR RESOURCES BOARD AGREEMENT A2-120-32

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TRC Project No. 2309-S81

PREPARED BY: Douglas R. Murray
Marshall A. Atwater, Ph.D.
John E. Yocom, P.E.
TRC Environmental Consultants, Inc.
East Hartford, Ct. 06107

800 Connecticut Boulevard
East Hartford, CT 06108
(203) 289-8631

ABSTRACT

This report describes a study to provide and apply a methodology for estimating some of the costs of air pollution and soiling damage to selected materials in the California's South Coast Air Basin (SCAB). A combination of land use and census data plus field and telephone survey techniques were used to estimate the types and quantities of exposed materials in the SCAB. The total exposed area of materials on structures was estimated at 5.6 x 12^9 sq. ft. for the SCAB based on census data. Painted wood and painted stucco accounted for 60 percent of the total exposed material.

Published damage functions that relate damage (e.g., corrosion or soiling) to air quality together with geographically distributed air quality measurements were applied to the materials inventory to develop quantitative estimates of pollutant induced materials damage in the SCAB. The total amounts of damage for each material for which there was a damage function were converted to maintenance costs based upon assumptions of use and maintenance.

The monetary cost of increased maintenance from air pollution induced effects in the SCAB was estimated to be $42 million per year. This economic loss was dominated by soiling and erosion of latex paint. This project did not estimate the costs of damage to several important materials found in the SCAB, such as glass and concrete, because air pollution damage functions do not exist for these materials.

SUMMARY AND CONCLUSIONS

A study of the South Coast Air Basin (SCAB) was made to estimate costs associated with air pollution induced materials damage during the period 1978-1980. The study developed an inventory of the exposed materials and an estimate of the additional maintenance costs of damage and soiling to selected materials. The following conclusions are the result of the study;

1. The materials inventory assembled for the South Coast Air Basin is based on a combination of readily available data, field surveys and telephone surveys. This multipronged approach makes efficient use of resources and permits reliable estimates of materials in place to be assembled. The methodology should be readily transferable to other locations.

2. Extrapolations of materials based on an exhaustive census of total housing units and businesses appear to be more reliable than estimates based on material densities (i.e., the square feet of exposed materials per square feet of land area). This is because there is greater variability in the density of buildings from urban to rural areas, than there is in the amount of exposed material per building. For example, both urban and rural areas may contain refineries in regions classified as industrial land-use. The total exposed materials for two refineries of similar capacity are likely to be similar, while the material densities for the refineries and their surrounding areas classified as industrial land-use will be significantly different. Therefore, to extrapolate materials in place beyond the immediate region of the survey, it is more reasonable to count the total number of refineries and extrapolate, than to extrapolate based on an estimate of the number of square feet of exposed material per refinery type land-use area. Fortunately, the U.S. Census Bureau and several private agencies maintain detailed records of the number of housing units and the numbers and types of business, farms, etc.

3. On a gross area basis, as well as for most types of materials, the residential sector dominates the commercial/industrial and public sectors. The notable exceptions are for masonry (brick and stone), concrete, and metals. Approximately seventy-two percent of the total exposed materials are in the residential sector in the basin.

4. Paint, as painted stucco and painted wood, dominates the exposed surface area, accounting for about sixty percent of the total exposed materials. Latex paint accounts for most of this area.

5. Damage functions are available for a limited number of materials, and their applicability to environmental conditions in the South Coast Air Basin has not been generally demonstrated. Common materials for which damage functions are not available include glass, brick, concrete and tile. The damage functions for paint selected for this project are based upon results of chamber studies performed at elevated concentrations. While they are useful for estimating the portion of damage due to pollutants, these functions cannot be used reliably to estimate total damage in the real world. The damage function selected for galvanized steel agreed reasonably well with the limited field measurements collected for loss of thickness of zinc on transmission towers.

6. Estimates of the incurred damage costs, based on a maintenance strategy, are presented below. The estimates have been made based on the survey of materials in place (presented in Section 3), materials damage functions (presented in Section 4) relating pollutant levels to rate of damage, and the observed pollutant levels and estimated costs of maintenance per square foot of material exposed (presented in Section 5). These estimated costs include the cost of the increased frequency of painting various building structures and fencing due to pollutant induced damage estimated from the damage function presented in Table 4-3 and the estimated costs for cleaning cemetary markers and statuary: other cleaning and maintenance costs have not been included. Other aspects of economic loss, such as preventative maintenance costs, substitution of more resistant materials, replacement costs, and aesthetic losses are not contained in these estimates. The figures are in 1979 dollars and are estimates for the damage to materials in place in the basin circa 1979. Further, inadequate data exists to quantify the potential errors associated with these estimates, and caution should be applied in using these figures for quantitative purposes.

Materials	Incurred Pollutant Induced Damage Costs	Comments
Elastomers	Minimal	Protected by addition of antiozonants.
Marble	< $50,000/yr	Cost of cleaning cemetery markers and incidental monuments.
Textiles	Minimal	Negligible use of textiles in permanent outdoor exposures, and most textiles use-life limited by non-pollution wear.
Latex Paint	$38.2 million/yr	Residential plus commercial/industrial, public sectors.

Materials	Incurred Pollutant Induced Damage Costs	Comments
Oil Paint	$2.2 million/yr	Residential plus commercial/industrial public sectors.
Vinyl Top Coat Paint	$45,000/yr	Commercial/industrial and public sectors.
Soiling (Stationary, Painted Surfaces)	$44 million/yr	Not additive to paint erosion damage as calculated for the above three items.
Galvanized Fence	$1,169,000/yr	
Other Galvanized	$240,000/yr	
Outdoor Statutory	$27,500/yr	
Total (approximate)	$42 million/yr	Excludes soiling to paint as distinct from erosion to paint.

There are approximately eleven million people in the South Coast Air Basin, therefore this is about $4 per person per year. Costs are dominated by the predicted erosion damage to latex paint and/or soiling of surfaces. The lack of preciseness in the damage functions precludes estimates of the variability of the costs.

7. Several assumptions and extrapolations have entered into this estimate and have been noted throughout this report. The quality of the information required to make the estimates is summarized below:

   - the distribution and exposure of materials was developed specifically for the SCAB and is representative of the basin.

   - the pollutant levels and climatological data for the basin have been subject to external quality assurance, and are of known high quality.

   - the applicability of damage functions to exposures in the basin is uncertain. Selection of different damage functions can lead to large differences (more than an order of magnitude) in the predicted damage rates. Further, no damage functions are available for several common materials, and estimates of damage to these materials have not been possible.

   - the critical damage levels are generally poorly defined. Surveys of actual maintenance frequencies appear to be more reliable for estimating maintenance costs.

- the costs of maintenance are available from survey data and from commercial estimating firms. These estimates, on average, are probably fairly reliable although costs for individual projects may vary widely.

- finally, costs of replacement where maintenance is not possible, have not been included for this estimate. All costs for this program have been based on a maintenance strategy and estimates for processes like textile dye fading (where maintenance cannot be done) have not been made.

In summary, the cost estimates presented are subject to wide error bands. Significant classes of materials have not been included in these estimates (such as damage to concrete and soiling of windows). Therefore, it is likely that the estimated costs represent a minimum of the increased costs of material damage from pollutants, and that the actual costs may be significantly higher.

RECOMMENDATIONS

Based on the work performed for this project, the following recommendations are presented for further studies:

1. The extrapolation of materials in place using land use data produces unreliable results. Future material surveys will produce better estimates if extrapolations are based on the absolute number of housing units and businesses in various census categories.

2. On a gross area basis, and an incurred damage cost basis, latex paints are the most significant material to which damage is incurred in the SCAB. Careful study of a variety of available formulations of latex paint should be undertaken to refine the potential range of costs associated with these materials in the SCAB. Further, it is recommended that these studies be done in the SCAB to ensure the representativeness of the results to the basin's environment.

3. Damage estimates for glass, concrete, brick and tile were not made because no damage functions or critical damage levels have been established for these materials. Research to develop these relationships should be initiated, and the results of the research combined with the estimates for total areas of these materials presented in this report to produce economic estimates.

4. No estimate has been made of pollutant induced damage to materials in the indoor environment. Research should be carried out to establish these estimates, such as:

   - Indoor pollutant levels attributable to outdoor concentrations and indoor sources.

   - Critical damage levels associated with pollutant induced damage for "indoor materials" (e.g., paper, electronic components, etc.)

5. No damage estimates were made for acid deposition due to the current lack of acid deposition damage functions. Damage functions applicable to acid deposition phenomina should be developed, and, if significant damage is expected, estimates of the costs of acid deposition induced damage should be compiled.

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1.0 INTRODUCTION

Maintenance costs attributable to material damage induced by air pollution provides an estimate of a portion of the real costs of atmospheric pollution. Pollutants degrade the environment in several ways; however, assigning a dollar value to the degradation is not straightforward. For example, assigning a disbenefit value to decreased visibility involves not only quantifying the visibility decrease, but also determining the increment in lost value of the visibility decrease. The value of a lost scenic vista is highly subjective and varies widely from individual to individual. However, assigning costs to materials damage, based upon the costs of maintenance of the damaged material, provides a much more direct, quantifiable indication of one aspect of the economics of air pollution.

The purpose of this project is to investigate the monetary loss due to pollutant caused damage to man-made materials exposed outdoors in the South Coast Air Basin (SCAB) during the period 1978-1980. SCAB includes Los Angeles, Orange, and the adjacent, non-desert portions of San Bernadino and Riverside Counties in California.

In order to determine the costs associated with the damage to materials caused by air pollution, the following information is necessary:

- the distribution and exposure of materials;
- the ambient pollutant levels to which the materials are exposed;
- the rate at which damage is incurred as a function of pollutant levels;
- the amount of damage that triggers remedial actions (i.e., the critical damage levels), or alternatively the frequency of maintenance in polluted atmospheres;
- the costs of remedial or preventive actions; and
- if remedial action is not possible, an estimate of the value associated with the loss.

Specific tasks to meet the project's objectives include:

- Review the technical literature relating to pollutant induced materials damage.
- Determine the material/pollutant combinations of significance in the SCAB.
- Select the most appropriate set of damage functions that describe the interactions between the materials and pollutants of concern.
- Construct a data base of land-use, demographic information, material-in-use survey results, air quality, and climate across SCAB.
- Apply the information in the data base to produce estimates of physical and monetary effects of local air quality on materials damage.
- Determine the potential error of the estimates produced in the program.

This document provides the final report for this project and summarizes the data bases, analytical approaches and results of the project. Previously, an interim report (summarized in Section 4) was approved by the California Air Resources Board (CARB) in which the damage functions to be applied and the materials to be included for this cost assessment were selected.

This report is organized in the following way:

- Section 2 describes the information sources and data bases used to estimate the materials distribution in the SCAB.
- Section 3 discusses the materials inventory calculations.
- Section 4 presents the damage functions used to calculate the rate at which materials degradation occurs.
- Section 5 presents the calculated costs associated with the incurred damage.
- Section 6 contains the report's summary and conclusions.

2.0 DATA BASE

2.1 Basic Approach

A critical element in determining the economic losses due to damage to materials from gaseous and particulate air pollution and acidic deposition is the estimation of the amount of material at risk. In a number of early air pollution damage economic studies, the amount of material-in-place was estimated by determining the amount of the material produced or shipped to an area over a period equal to the material's standard use-life. It was then assumed that this material remained exposed in the area until the use-life was exhausted. This approach has several weaknesses: the standard use-life of a material varies widely with environmental and economic factors and the information available on standard use-life is often based more on tax considerations than actual practice. In addition, exposure factors are difficult to estimate accurately since they are usually based on assumptions of "common practice" which may vary widely. Further, this approach leads to "double counting" of some materials (i.e., materials sold to producers of other materials).

Three recent studies have used actual field measurements as the basis for predicting material-in-place. Koontz, et al. (1981) modeled the amount of material-in-place in Baltimore and St. Louis using materials distribution estimates based primarily on an analysis of Sanborn maps (discussed in Section 2.2) and a limited ground truth survey. Step-wise multiple linear regression was used to analyze the materials data by deriving empirical relationships between statistically significant predictors and estimates of material-in-place.

A second approach to estimate material distributions was performed by TRC for the Electric Power Research Institute (Stankunas, et al., 1983). The greater metropolitan Boston area was divided into 260,236 sites on aerial photographs. A random sample of 502 sites was selected from this population and analyzed using high-resolution photographs and ground surveys. Survey crews visited all nonvacant sites and identified, photographed, and measured all the exterior structural materials present there. The results of the survey were statistically analyzed and extrapolated to provide an estimate of the total amount of three key materials present in the entire population of sites and in subsets (neighborhoods) of sites within the area. The results of this study provided an estimate of the amount of materials-in-place in in an urban northeastern U.S. environment. Reanalysis of the Boston set by Daum and Lipfert (1984) suggests that the original analysis technique may have over-estimated the amount of material in place.

In the third study, McCarthy, et al. (1984), estimated materials in place for suburban and rural areas around Lincoln, NB; Charlotte, NC; and Tuscon, AZ. United States Census Bureau tracts were selected in each study region to represent a spectrum of housing ages and median income levels, and photographs were taken of representative homes in each tract. Subsequently, the area of exposed material for each home was determined from the photographs and linear regression equations based on census data were developed to extrapolate the measured areas for materials to all homes.

The directed sampling approach of Koontz et al. (1981) and McCarthy et al. (1984) makes use of readily available data to direct the field sampling effort and to extrapolate the results of the sampling program. The approach used by Stankunas et al. (1983) is entirely random and requires far more samples to ensure that the spectrum of material types and uses has been included.

For the purposes of this study, the materials are quantified by the following four use categories:

1. Residential Housing (where externally exposed walls, roofs, fences, awnings, building trim, etc. are considered);

2. Commercial and Industrial structures (where externally exposed walls, roofs, fences, pipes, tanks, sheds, towers, etc. are considered); and

3. Agricultural Structures (where barns, sheds, feed lots, storage bins, etc. are considered).

4. All other structures (excluding agricultural), where light poles, street signs, rail lines, etc. are considered.

For each of the four categories of structures a separate and different approach was used to identify, locate, and quantify the amount of exposed material. An overview of the three approaches is given below.

A field survey approach was used to estimate the type and amount of material exposed on the approximately 2 million single family residences which are located in over 1,800 census tracts in the South Coast Air Basin. The 1,800 census tracts in the basin were stratified by median household income per census tract and by the predominant age of the houses in the census tracts. The three income and the three age-of-housing groupings combined to give nine separate categories of census tracts. All 1,800 census tracts were sorted into the nine defined categories. Nine census tracts were selected, one from each of the 9 categories. The basic assumption is that houses built in a given period of time for a given income level are of similar size from the street. About 10 houses are then photographed at random from each of the nine tracts. The photographs were analyzed to determine the area of the exposed material on each house. Each of the exposed materials were identified and quantified separately.

Multiple regression equations based on the average house area for each census tract and socio-economic predictors were developed. These regression equations were used in conjunction with the census data for SCAB to estimate the exposed materials on single unit residential structures in the basin.

Multiple residential units were based on the Sanborn maps used in the commercial and industrial land use categories. The exposed area for each multiple unit building on the 20 Sanborn maps was measured and an average exposed area was computed. The results were extended to the 857,518 units in multiple unit buildings in the basin.

The quantification of materials for commercial and industrial structures is based on estimates of square footage of building materials obtained from material maps developed by the Sanborn Co. and land use data developed for the SCAB. For the purpose of the study, the commercial and industrial sector structures were stratified into fourteen land-use categories (heavy industry, light industry, ports, railroads, highways, retail, office buildings, airport/military, public facilities, cultural, and four mixed categories).

A total of twenty Sanborn maps covering about 3 million square feet of land area each were used to characterize structures in the land-use categories. Ten of the fourteen land-use categories were represented by one Sanborn map each, and four of the fourteen by two maps each. The Sanborn maps were not selected at random, but a "directed sample" approach was used. The census tracts were sorted to find areas with a heavy concentration of each industrial/commercial land-use, and survey areas were selected on that basis. The Sanborn maps for the selected geographical locations were ordered.

Estimates were derived of the "materials density", i.e., the building materials in units of square feet of exposed material per hectare of land for each of the land-use categories. These estimates were extrapolated to the air basin as a whole using a computerized land-use data base which specified land use in hectares for each census tract in the basin. The extrapolation is based on the assumption that each land use category has a uniform distribution of material density throughout the basin.

An alternative procedure for estimating the total exposed materials in the commercial/industrial sector used MacRae's Industrial Directories and the U.S. Census of Country Business patterns. The MacRae Industrial Directory was used to estimate the square footage of building space per employee. The value was extrapolated to exposed materials per employee and the census data was used to estimate the exposed area of commercial and industrial building for the SCAB. The distribution of material was based on the same proportions as the land use approach. The exposed area using this approach was about 50 percent less than the land use approach.

Agricultural buildings in the eastern portion of the SCAB were sampled using field survey photographs to identify the types of construction materials in place, and aerial photographs with additional information obtained from agricultural representatives in the region to determine the average number of agricultural buildings per unit land area of agricultural land use. Materials used in the oil industry for the extraction of crude oil were based on the number of oil wells in the SCAB and an estimate of the exposed area of equipment per well.

The distribution of materials such as signs, light poles, municipal storage tanks, bridges, guardrails, railway tracks, etc., were estimated via a telephone survey of the agencies responsible for their maintenance. Large municipalities and area-wide agencies such as CALTRANS were contacted to determine the amounts and types of materials that they maintain.

2.2 Data Sources

The data sources that describe the land uses and types and number of structures in the SCAB were reviewed and assembled into the project's data base. These include:

- The South Coast Air Basin Geocoded Land Use Inventory, 1975 (Loscutoff, et al., 1979)

- Census of Population and Housing, 1980 (Bureau of the Census, 1982)
- Sanborn Map Company, Black and White Sanborn Mapping Series
- MacRae's Industrial Directory, California
- Census of County Business Patterns
- USGS 7-1/2 minute topographic map series and aerial photographs.

The SCAB Geocoded Land Use Inventory provides a land-use summary on a one kilometer by one kilometer square grid for 11,413 grid cells making up the air basin. Table 2-1 presents the land-use classes available on this data set. The classification system contains sufficient detail for distinguishing different types of anthropogenic land use. The data are presented as the percentage of each type of land use in each grid square. The United States Geological Survey (USGS) also has land use data available; however, the USGS classifications are rather broad, and do not distinguish urban and suburban land use classifications as completely as the SCAB Geocoded Land Use Inventory. A summary of land uses in the SCAB by percent and area in square kilometers is presented in Table 2-2. On a land-area basis, land-use in the basin is dominated by open space uses (agriculture, non-forest undeveloped, forest, non-forest developed, mixed open space, and water) followed by residential; commercial and services; industrial, and finally transportation uses. For this project, the "Military/Airport" and "Airports and Heliports" land uses have been combined and treated as one.

The Census of Population and Housing compiled by the United States Census Bureau each ten years contains detailed demographic data, on a census tract by census tract basis. Census tract boundaries are established by the local Census Statistical Area Committees and the Census Bureau. The tracts "are designed to be relatively homogeneous areas with respect to population characteristics, economic status, and living conditions. The tracks generally have between 2,500 and 8,000 residents" (Bureau of the Census, 1980). For the

TABLE 2-1

INVENTORY LAND USE CLASSIFICATION SYSTEM (Loscutoff, et al., 1979)

CATEGORY	DESCRIPTION
Low Density Residential	0.2 to 19 dwelling units per hectare
Medium Density Residential	20 to 99 dwelling units per hectare
High Density Residential	100 or more dwelling units per hectare Also included under residential land uses are: mobile home and trailer parks; dormitories; retirement homes; orphanages
Retail Operations	Strip commercial; shopping centers (regional, community, neighborhood); showrooms (associated with mail order houses and direct selling organizations); grocery and retail stores; service stations; food services; repair services; hotels and motels
Office Buildings	Office building services include: finance, insurance, and real estate services; personal services; business services (excluding warehouse and storage services); professional services; transportation terminals
Public Facilities	Schools; hospitals; correctional facilities; churches; governmental services (police, fire, postal); colleges and universities
Cultural, Entertainment and Recreation	Cultural activities (e.g., nature exhibits, art gallargest, museums); stadiums; auditoriums
Light Industry	Warehouses[1]; wholesale - centers and services; communications; printing and publishing; trucking companies; utilities[2]; manufacturing (e.g., textiles, apparel)[3]
Heavy Industry	Utilities; trucking companies; manufacturing (e.g., canneries, chemical manufacturers, petroleum refineries)
Extractive Industry	All industries involving the extraction of natural resources; dumps and sanitary landfills
Highways	Freeways; interchanges
Railroads	Railroad tracks, switching and marshaling yards
Ports	Piers and berths associated with commercial shipping an ocean traffic; marinas

TABLE 2-1
(Continued)

INVENTORY LAND USE CLASSIFICATION SYSTEM

CATEGORY	DESCRIPTION
Airports & Heliports	Facilities associated with the take-off and landing of aircraft; undeveloped land between runways is included
Vehicle Parking	Parking and storage lots
Non-Forest Developed	All lands having a dominant vegetation pattern of grass, brush or landscaping, and which contain a formally developed open space land use--including the minimum associated structural development (e.g., cemetaries, government sponsored parks and beaches, private campgrounds, golf courses)
Non-Forest Undeveloped	All lands having a dominant vegetation pattern of grass, brush or landscaping, and which do not contain a formally developed land use (e.g., some beaches, non-forested wetlands, rock, dry salt flats, tundra, vacant urban lots)
Forest	All lands where tree cover is the dominant vegetation
Agricultural	All lands used primarily for the production of food and fiber (includes range)
Water	Reservoirs, natural channels, ocean bodies, and lakes
Mixed Residential Mixed Transportation Mixed Commercial & Services Mixed Industrial Military/Airport Mixed Open Space	These categories are used in the case of an undetermined land use or combination of land uses. "Military/Airport" services in cases where the distinct land uses within an airport or military facility are not indicated on the source maps.

[1] Warehouses associated with direct selling organizations are classified as Light Industry. Public contact areas (showrooms) are identified under Retail Operations.

[2] Utilities include gas, electric, and water systems. Water systems include all pipelines, pumping stations, canals, reclamation centers and diversion structures associated with water delivery and hydroelectric power generation (all other water bodies are classified as open space). The classification of utilities as either light or heavy is dependent upon associated emissions.

[3] Overlaps within the industry categories (e.g., trucking companies, manufacturing) are classified according to the associated emissions.

TABLE 2-2

LAND USE CATEGORY PERCENTAGES AND AREAS
SCAB 1975

Category	Percentage of Total Study Area	Area (Km^2)
Agriculture	23.885	2717
Non-Forest Undeveloped	19.221	2194
Low Density Residential	18.469	2108
Forest	15.583	1778
Mixed Open Space	4.255	486
Mixed Industrial	3.398	388
Mixed Residential	2.941	336
Non-Forest Developed	2.134	244
Public Facilities	1.934	221
Water	1.690	193
Retail Operations	1.314	150
Military/Airport	1.141	130
Highways	1.109	127
Extractive Industry	1.012	115
Mixed Commercial and Services	0.919	105
Medium Density Residential	0.303	35
Cultural, Entertainment, and Recreation	0.303	35
Railroads	0.197	22
Mixed Transportation	0.087	10
Heavy Industry	0.053	6
Office Buildings	0.044	5
Vehicle Parking	0.038	4
Light Industry	0.032	4
Ports	0.017	2
High Density Residential	0.003	0.3

1980 Census there were 1842 census tracts in the basin, and a wide variety of information was available describing each tract. TRC obtained data for the tracts that either directly describes the housing in each tract (e.g., mean number of rooms per unit) or that may indirectly relate to the housing stock (e.g., median income). The census tracts served as the basic geographical divisions for this project and each of the land use grid cells was assigned to a census tract based on geographical superposition of the tracts and the cells. If a cell fell in two or more tracts, it was assigned to the tract containing the largest amount of the cell's area.

A data base of land use, pollutant levels (described in Section 5), and Census Bureau housing information was assembled on a tract by tract basis. Table 2-3 presents a list of the variables in this data base. The variable definitions are largely self-explanatory, however, precise definitions of each census variable are available in the Census of Population and Housing 1980: Summary Tape File 3, Technical Documentation. In addition to the data obtained from the Census Bureau, the data archive contains the area of each tract, the land use associated with each tract, and the average pollutant concentrations (1978-1981) for each tract. Land uses and the area of each tract were assembled from the Geocoded Land Use Inventory and from a Census Bureau tape containing the geographical coordinates of each tract. The pollutant concentrations were based upon the California Air Quality Data Summaries 1978-1981 (CARB). Average concentrations for 26 stations that reported for at least two of the four years in the SCAB were calculated and pollutant levels were linearly interpolated to each census tract.

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* Sanborn Map Co. Inc., 829 Fifth Avenue. Pelham, NY

TABLE 2-3

VARIABLES CONTAINED ON THE PROJECT'S DATA ARCHIVE

Category	Variable
Header	County
	Census Tract
	Km^2
Land Use in Hectares	Agriculture
	Non-Forest Undeveloped
	Low Density - Residential
	Forest
	Mixed Open Space
	Mixed Industrial
	Mixed Residential
	Non-Forest Developed
	Public Facilities
	Water
	Retail Operations
	Military/Airport
	Highway
	Extractive Industrial
	Mixed Commercial and Services
	Medium Density Residential
	Cultural, Entertainment, Recreational
	Railroad
	Mixed Transportation
	Heavy Industry
	Office Buildings
	Vehicle Parking
	Light Industry
	Port
	High Density Residential
	Airport
Pollutant Concentration	NO_2 (Nitrogen Dioxide) ppm
	NO_3 (Nitrate) $\mu g/m^3$
	O_3 (Ozone) ppm
	SO_2 (Sulfur Dioxide) ppm
	SO_4 (Sulfate) $\mu g/m^3$
	TSP (Total Suspended Particulate) $\mu g/m^3$

TABLE 2-3
(Continued)

VARIABLES CONTAINED ON THE PROJECT'S DATA ARCHIVE

Category	Variable
Rooms/Unit, and Unit/Address	Total Units
	One Unit/Address
	2-9 Units/Address
	>10 Units/Address
	Mobile Homes
	Mean Rooms/Unit
	Owner Occupied Mean Rooms/Unit
	Vacant Mean Rooms
	Renter Occupied Mean Rooms/Unit
	Vacant for Rent Mean Rooms
	Vacant Other
Mean Housing Value and Rent	Value of Total Houses
	Value Occupied Houses
	Value of Houses for Sale
	Value of Total Condominium
	Value of Occupied Condominium
	Value of Condominium for Sale
	Rent
	Occupied Rent
	Vacant for Rent
Population, Housing, Families, Households	Total Population
	Urbanized Population
	Rural Population
	Urban Population
	Total Housing
	Urbanized Area Housing
	Rural Housing
	Urban Housing
	Families
	Households
Farm Residence	Total Population
	1980 definition:
	urban
	rural farm
	rural non-farm
	1970 definition:
	urban
	rural farm
	rural non-farm

TABLE 2-3
(Continued)

VARIABLES CONTAINED ON THE PROJECT'S DATA ARCHIVE

Category	Variable
Household Income	Median Income
	Mean Income
	Total Earnings
	Wage/Salary
	Non-Farm Self-Employed
	Farm Self-Employed
	Interest/Dividends
	Social Security
	Public Assistance
	Other Income
Occupancy	Total Units
	Vacant Units
	Total Occupied
	Owner Occupied
	Renter Occupied
	Rent 1 Unit, Detached
	Rent 1 Unit, Attached
	Rent, 2 Units
	Rent, 3,4 Units
	Rent, $\geq$5 Units
	Rent, Mobile Home
Stories and Elevator	Total Units
	1-3 Stories
	4-6 Stories
	7-12 Stories
	$\geq$13 Stories
	With Elevator
	Without Elevator
Housing Year	Total Units
	Vacant
	Occupied
	Built 1979-80
	Built 1975-78
	Built 1970-74
	Built 1960-69
	Built 1950-59
	Built 1940-49
	Built Before 1939

TABLE 2-3
(Continued)

VARIABLES CONTAINED ON THE PROJECT'S DATA ARCHIVE

Category	Variable
Bedrooms	Total Units No Bedrooms 1 Bedroom 2 Bedrooms 3 Bedrooms 4 Bedrooms ≥5 Bedrooms
Air Conditioning	Total Units None Central One Room Two or More Rooms

Two data sources are readily available that contain building information for the commercial/industrial sector. The Sanborn Map Company* provides the detailed maps of the building types for use by planning commissions, the insurance industry, etc. Figure 2-1 presents a portion of a Sanborn Map for the port area in Long Beach, and Figure 2-2 is the map legend. The Sanborn Maps provide exhaustive data on the size (wall lengths and heights) and exterior materials for all "fireproof" buildings. Thus, exterior materials on buildings with public access or subject to commercial-type fire codes (i.e., commercial, industrial, utility, public service, etc.) are available from these maps. Unfortunately, frame-type buildings of non-fire resistant construction (i.e., typical, detached residential) are not sufficiently detailed on these maps to permit the classification of materials for the residential sector.

MacRae's Industrial Directory (MacRae Blue Book Company, Inc., 1983) provides a compilation by city and county of industrial and commercial firms. Among the data presented are building size (square foot of floor space), number of employees, and Standard Industrial Classification (SIC) codes for broad selection of companies. The U.S. Census County Business Patterns, published every three years provides the number of companies by numbers of employees for individual SIC codes on a county by county basis.

The USGS 7-1/2 minute topographic map series and the corresponding aerial photographs provide a convenient data source for determining the number of buildings in agricultural areas. Three quadrangle maps and associated aerial photos were acquired and analyzed to determine the building number density in the agricultural land use areas.

The land use inventory, census data, Sanborn Maps, MacRae's Industrial Directory and rural area topographic and aerial photos provide a strong data basis for understanding the distribution of residential construction, and

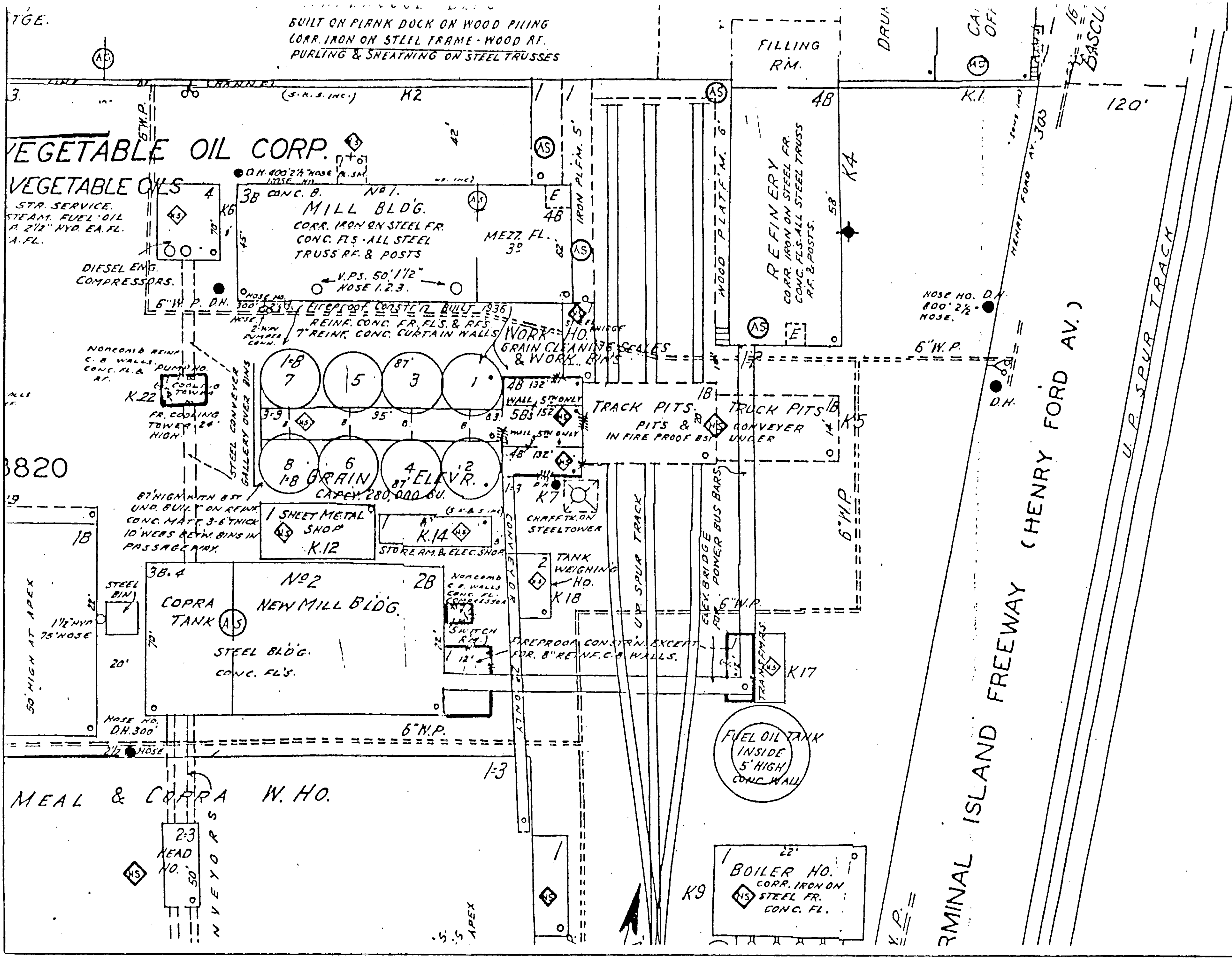
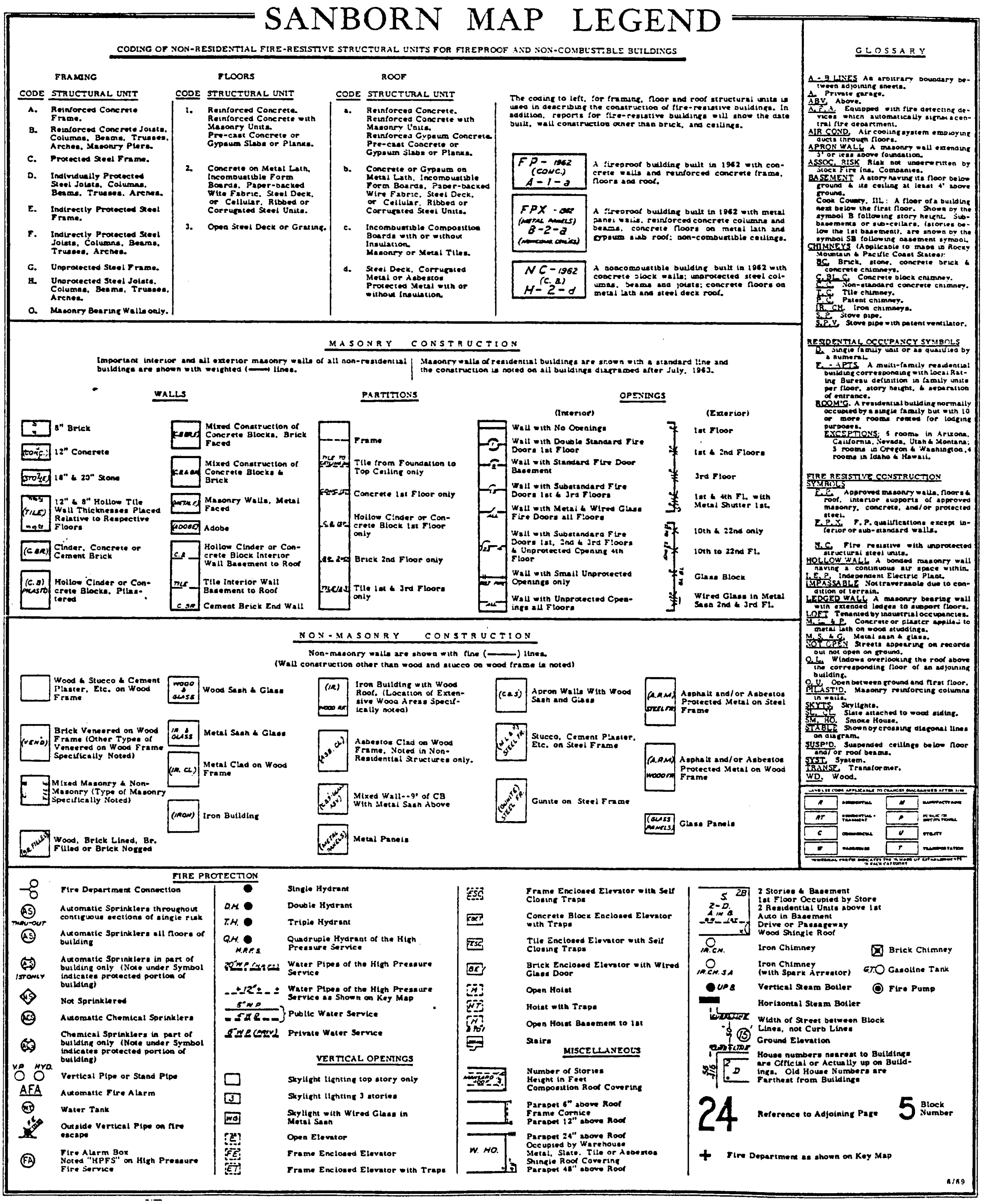


Figure 2-1. Part of the Sanborn Map for the port area at Long Beach, CA.



This map is the property of Sanborn Map Company, Inc. and is loaned to the subscriber subject to the provisions of the subscription agreement. In accordance with this agreement this map may not be used by other than the subscriber, except with the written permission of Sanborn Map Company, Inc.

Figure 2-2. Map legend for the Sanborn Maps, detailing the types of information available.

further provide detailed information on the actual materials in place for fire-resistant commercial/industrial construction and an estimate of the density of agricultural buildings. Unfortunately, the available data are not complete (e.g., percentage of windows on industrial buildings), and it is still necessary to conduct field surveys, as described in the next section, to quantify the residential construction materials and the percentage of glass on industrial buildings.

2.3 Field Surveys

A limited field survey was performed to supplement the available data assembled from external sources as listed in Section 2.2. The objectives of the field survey were to:

- Quantify the distribution of exposed materials in representative residential census tracts.
- Identify the type of materials exposed on agricultural properties.
- Field verify selected Sanborn Maps.
- Measure the thickness loss of galvanized surfaces with known exposure histories.

The selection of census tracts to be sampled was based upon a review of the census data. All of the tracts in the SCAB were sorted by age of the housing stock and median income levels. This was done to ensure that the spectrum of residential housing stock ages and income levels was surveyed.

Survey tracts were selected to represent three income strata and three housing stock ages:

Median Household Income

- less than $15,000 per year
- $15,000 - $35,000 per year
- Over $35,000 per year

Construction Date of Housing Stock

- Before 1950
- 1950 - 1969
- After 1969

An initial sort of all census tracts was made to identify those tracts dominated by housing stock in each age category. The resulting list was then reviewed to select one tract in each housing age group with a median income in the desired range. Thus, a total of nine tracts were selected for the field survey with the characteristics given in Table 2-4:

TABLE 2-4

HOUSING STOCK AGE AND MEDIAN INCOME LEVELS
IN THE SURVEYED RESIDENTIAL TRACTS

County	Tract Number	Housing Stock	Median Household Income
Los Angeles	6016	82% after 1969	$13,889
Orange	1100.11	98% after 1969	$32,744
Orange	992.23	100% after 1969	$40,896
Los Angeles	4070	100% 1950-1969	$14,205
Orange	876.02	100% 1950-1969	$23,000
Orange	758.06	100% 1950-1969	$57,712
Los Angeles	2345	76% before 1950	$13,320
Los Angeles	2143	94% before 1950	$22,870
Los Angeles	2116	84% before 1950	$43,878

Figure 2-3 shows the approximate locations of the sampled tracts.

Each of the survey tracts was visited and ten houses were selected on each tract. The chosen homes were selected to be typical (in terms of size and materials) of the housing stock on the tracts. Distinctly atypical houses (i.e. houses of unusual size or clearly constructed during a different time from the dominant housing age on the tract) were not included. The housing stock within each tract was found to be quite uniform, and atypical homes were a rare occurrence. Each chosen home was photographed and a survey form was completed (see Figure 2-4). The photographs were taken with a 35 mm camera with a recording data back that uniquely identified each picture by imprinting a date/time group on each photograph. An optical range finder was used to record the distance from the camera to the home to assist in subsequent data

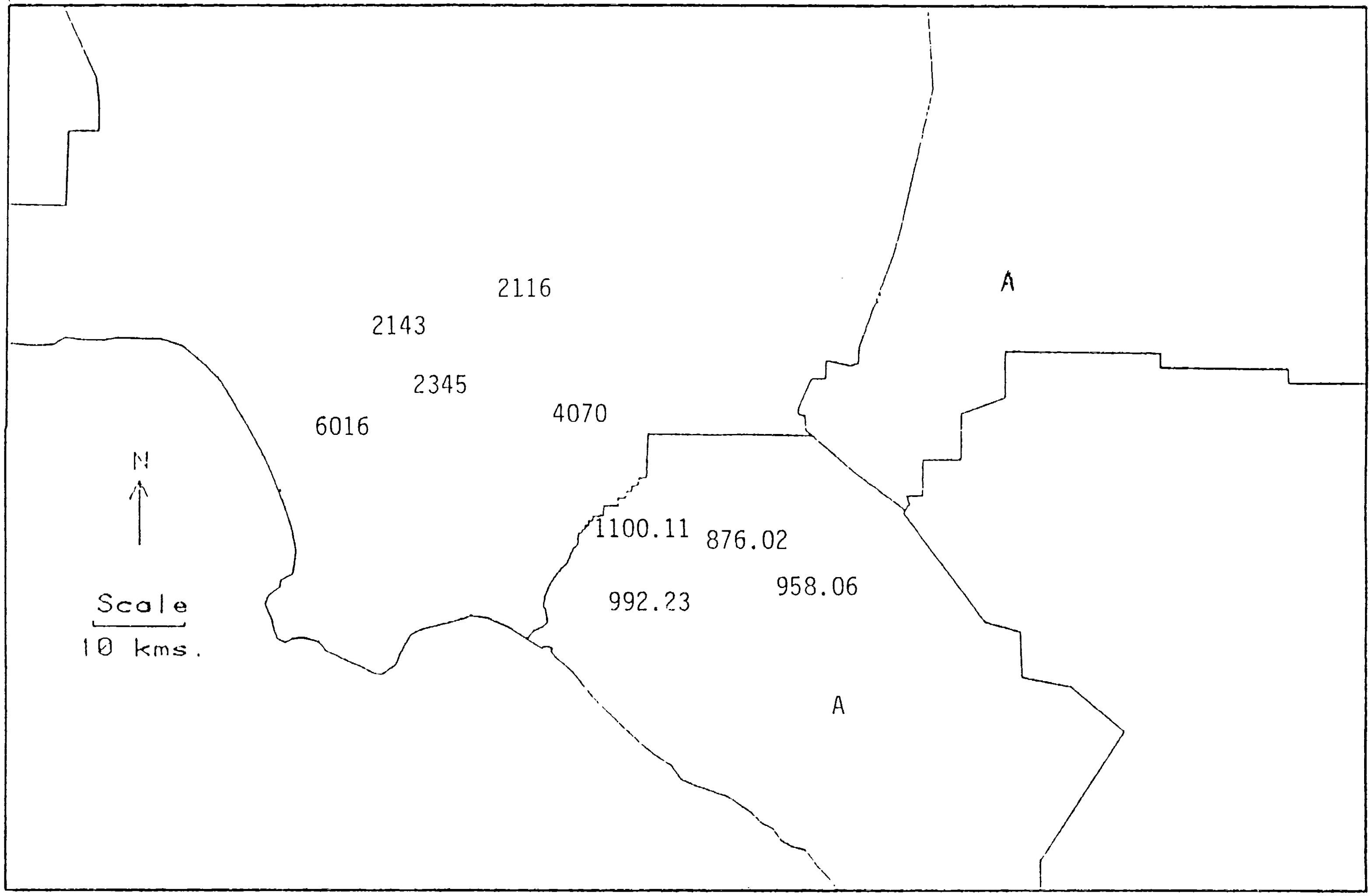


Figure 2-3. Location of numbered census tracts and agricultural areas (indicated by "A") surveyed.

2309-S81-03

MATERIAL SURVEY

Page 2 of 3

Date: 8/30/84

Street:

City: Anaheim Tract No. 876.02

STREET ADDRESS	1829 CRIS		1819 CRIS	1815 CRIS	[illegible]
BUILDING USE	Res		Res	Res	Res
PHOTO NUMBER (TIME)	13:58	14:00	14:06	14:12	14:23
DISTANCE (ft.)	80' Lattice 68' Corner	90' wall 70' Corner wall	90'	85'	90' - Door 85' Garage Corner
ROOF	Gravel/Tar		Asph	Gravel/Tar	W(S)
WALLS	Stuc(P)/W(P)		Stuc (P)	Stuc(P)/W(P)/Br(P)	W(P)/[illegible]
TRIM	W(P)		W(P)	W(P)	W(P)
WINDOW FRAMES	W(P)		Al / W(P) Trim	Al / W(P) Trim	Al
GUTTERS/DOWNSPOUTS	Al		Al	Al	
FOUNDATION					
FENCE	Br/C.L. Grt.				W(S)
GARAGE	Stuc/W(P) door		Stuc/Metal(P) door	Stuc/W(P) door	W(S)/W(S) Do[illegible]
OUTBUILDINGS/SHEDS					
OTHER	Br(P) Chim		Br Chim	Br Chim.	TV Ant
	TV. Ant.		Flat Plastic Solar Panels	W(P) Shutters	Br. Flowerbed
(Plastic Domed)	Solar Panels		Br Flowerbed	Br. Flower Bed	W(P) Shelf
	W(P) Lattice		W(P) Lattice (in between windows)	WrI railing TV Ant.	

Figure 2-4. Typical completed materials survey form.

reduction. The construction materials of all permanent structures on the property (house, garage, sheds, fences, patios, etc.) were noted on the survey form, along with the date/time identifier group for the photograph. Binoculars were used, if necessary, to assist in distinguishing each material. The photographs were subsequently analyzed to determine the area of exposed materials, and the data on the survey form identified the types of materials.

The land use data base was querried to identify areas dominated by farms, and the areas sampled by this project are shown in Figure 2-3. The types of materials exposed on all permanent buildings and fixtures on the agricultural properties were noted and photographs were taken. Eleven agricultural properties were sampled in the materials survey and these included nurseries, orchards, vegetable and feed lot operations for both commercial and smaller private farms.

Seven of the Sanborn maps were field verified by selecting a major intersection on each map, and cross-checking the actual materials in place versus the indicated materials. Photos were taken of each of the corner buildings (generally four per map) and a material survey form was completed. A spot-check of three businesses listed in the MacRae's Industrial Directory was also performed, and the materials on each building were noted.

The final objective of the field survey was to measure the thickness of galvanized coatings with quantifiable exposure histories. This information was intended to be used as a field verification of the calculated damage rates. Transmission towers for high tension electric lines provide a good medium for measuring damage. They are usually exposed unprotected (without paint), the length of the exposure period can be readily determined, and the original coating thickness has been specified by the American Society of Testing and Materials Guideline A123 Section 6 as at least 3.4 mils (2 ounces of zinc per square foot). Two sets of transmission towers were sampled for the survey: those from the Haynes Generating Station in Long Beach and those from the Harbor Generating Station in Wilmington. The towers were installed in 1965 and 1943, respectively. The thickness of the galvanized coating was measured on the upright tower legs four feet above ground level using an Elcometer film thickness gauge. Four thickness readings (one for each tower leg in each direction) were recorded. A comparison of the measured zinc loss to the zinc loss predicted by damage function is given in Section 4.2.2.

2.4 Telephone Survey

TRC conducted a telephone survey (see Appendix A) of materials suppliers and maintenance organizations to obtain information on non-uniformly distributed materials (e.g., the number of miles of railroad track) and to determine common maintenance practices in the SCAB. Municipal authorities were contacted in Los Angeles, Riverside, Pasadena and Long Beach to determine the amount and type of material exposed as guardrails; fence; streetsigns; streetlights; and parking meters, and their routine maintenance practices. Electric utility companies were called to gather information on the transmission towers and lines, substations, storage tanks, fences, etc. Water companies provided data on tanks and maintenance practices. Cemetary associations provided data on the distribution and material of monuments, mausoleums and fencing. Paint wholesalers and painting contractors provided data on the percentage of paint types sold for exterior use, and the typical residential repaint frequency. Tire distributors provided data on the types of tires sold in the SCAB, and their average lifespan. Fencing and siding contractors and suppliers provided some additional data on these materials for residential use.

Besides the general classes of groups contacted in each of the four cities, three other area-wide, significant users of materials were contacted. District 7 of CALTRANS, the California state agency charged with maintenance of transportation systems, provided data on the distribution of materials along state maintained highways. The Southern Pacific Railway Company provided data on their buildings and 3,544 miles of roadbed in the basin area. Refiners including Atlantic Richfield Co., Edgington Oil and Shell Oil Co. provided information on their maintenance practices and exposed materials for their facilities in the SCAB.

3.0 MATERIAL INVENTORY

3.1 Single-Family Residential

The materials in place in the single-family residential sector were estimated using a regression procedure based upon data from the field survey, discussed in Section 2.3, and the census data. The following sections describe the data reduction procedures, the results of the field survey, and the regression analyses used to extrapolate the data.

3.1.1 Photo Analysis

Photography provides a convenient method for the rapid collection of quantitative field data. Photographs and subsequent photogrammetric analysis permit the field survey of exposed materials to be done efficiently, thus maximizing the number of properties that can be surveyed. Further, because photographs can be taken from the street, this method eliminates the very time-consuming process of obtaining homeowner permission to measure each house surveyed. Photographic slides were taken during the field survey of each of the selected houses and the materials on each house were identified. For each of the nine census tracts, ten house fronts and the sides of two to four houses were examined in detail to determine exposed area and materials.

A program written by TRC for the Apple II computes the area of any vertical surface shown on a photo, regardless of the angle of the surface in relationship to the camera. Photos of each house were displayed on a screen gridded with an X and Y coordinate system. The X and Y corner coordinates for the parts of the house, such as walls, windows, and doors, were entered into a computer program and the area was computed. The distance from the camera to the house is either entered by the computer operator (based upon measurements using an optical range finder) or the distance can be computed based upon the standard height of a door. Comparison of the two methods showed that the optical range finder introduced errors when the distance was greater than 60 to 70 feet. The measurements based on the height of the door were used for the photo data reduction in this project.

For each tract, typical house sizes and materials distributions were developed based on the average size and the materials of all the surveyed houses in the tract. The assumption of symetery was used to estimate the size and distribution of the materials on the sides of the houses not photographed. Using this assumption probably increases the estimated amount of brick and stone, and decreases the estimates of the more common wall surfaces, such as painted stucco and painted wood. This bias results from the use of brick or stone facades on the fronts of some homes. The data for the mean area of houses and the materials are summarized for each of the census tracts in Table 3-1.

Painted stucco was the most common wall material, and in fact was dominant in eight of the nine tracts, with painted wood the second most common exposed material. Glass accounted for 10 to 15 percent of the total area of the walls. Most of the trim, shutters and doors were painted wood. The gutters were primarily coated metal, probably aluminum, and the steps and foundations were concrete. In several of the tracts, foundations were not distinct from the stucco walls, i.e., houses were stucco to the ground and thus no foundation materials were listed. Other common items included wood lattices, and coated aluminum awnings.

The average vertical areas, including windows and doors, are shown in Table 3-2 and range from 1,153 ft^2 in tract 6016 to 4,633 ft^2 in tract 2116. The largest houses of the survey were located in the high income regions with houses built before 1950 in Beverly Hills. The smallest houses were in the low income tracts and were built between 1950 - 1969. The middle

TABLE 3-1

MEAN DISTRIBUTION OF MATERIALS (SQUARE FEET) ON A PER HOUSE BASIS IN EACH SURVEYED TRACT

TRACT	2116	2143	2345	4070	6016	758.06	876.02	992.23	1100.11
MATERIAL									
WALL									
Painted Stucco	2462	1381	832	717	567	269	1070	670	1678
Painted Wood	273	40	287	195	200	816	121	468	747
Brick	491	10	0	0	59	61	107	34	60
Painted Brick	430	22	0	80	0	16	0	0	0
Concrete	45	0	0	0	0	0	0	0	0
Stone	4	0	0	0	0	19	0	50	17
Asbestos	0	2	4	0	184	0	0	0	0
WINDOW									
Glass	597	256	253	137	156	241	156	131	143
WINDOW TRIM									
Wood	246	105	115	61	76	50	44	15	0
Aluminum	141	13	10	11	21	63	47	48	63
DOOR									
Painted Wood	89	83	71	26	48	28	50	48	5
Stained Wood	5	0	0	0	0	0	0	0	0
Aluminum	14	0	0	2	0	2	10	18	0
DOOR TRIM									
Painted Wood	33	33	27	11	20	11	19	23	16
Aluminum	6	0	0	0	0	1	3	0	3
Stained Wood	2	0	0	0	0	0	0	0	0
SHUTTERS									
Painted Wood	8	20	0	18	9	5	17	11	4
TRACT	2116	2143	2345	4070	6016	758.06	876.02	992.23	1100.11
FOUNDATION									
Concrete	0	0	16	6	6	45	0	28	0
Stucco	0	0	0	47	22	0	0	0	0

TABLE 3-1
(Continued)

MEAN DISTRIBUTION OF MATERIALS (SQUARE FEET) ON A PER HOUSE
BASIS IN EACH SURVEYED TRACT

WALL TRIM									
Painted Wood	286	104	114	160	96	198	180	218	146
Painted Brick	0	14	0	0	0	0	0	0	0
GUTTERS									
Aluminum	194	46	59	9	25	83	82	130	4
Galvanized	3	0	0	0	0	0	0	0	0
PORCH/STEPS									
Painted Concrete	24	0	181	12	0	0	0	0	0
Concrete	12	0	83	0	120	39	104	0	0
Brick	45	447	9	0	0	0	0	0	0
RAILING/LATTICE									
Wrought Iron .	7	8	15	0	0	0	1	4	36
Painted Wood	8	2	3	5	52	1	0	2	10
Painted Iron	4	0.2	23	0	0	0	0	0	0
AIR CONDITIONER									
Painted Metal	0	0	1	0	0	14	0	0	0
Galvanized Iron	0	0	5	2	1	0	0	0	0
AWNINGS									
Aluminum	0	87	59	0	0	58	0	0	0
Galvanized Iron	13	1	0	6	6	0	0	0	0
Tile	0	0	13	0	0	0	0	0	0
Painted Wood	0	0	0	0	21	4	0	0	0
Cloth	21	0	0	0	0	0	0	0	0

TABLE 3-2

MEAN FRONT, SIDE AND TOTAL ESTIMATED AREA (SQUARE FEET) OF DETACHED RESIDENTIAL HOUSING

Housing Age	Household Median Income >$35,000	$15,000-$35,000	<$15,000
FRONT AREA			
Pre 1950	1033	432	388
1950-1969	356	490	378
Post 1969	378	525	302
SIDE AREA			
Pre 1950	1283	501	372
1950-1969	402	347	213
Post 1969	334	665	343
TOTAL AREA			
Pre 1950	4633	1866	1520
1950-1969	1516	1676	1183
Post 1969	1424	2382	1290

income houses in the area built since 1950 were larger than the high income houses built during the same period.

Table 3-3 shows the percentage of the material distribution of the front wall as a function of tract characteristics. Brick is the most common in old, high income homes and in the middle income medium age homes. Stucco is used less in the high income homes than in the lower income homes. Painted wood is more predominate in the upper income homes. Based on the overall census data for the basin thirty percent of the units were built before 1950 and twenty percent after 1970.

3.1.2 Regression Analysis

The data for materials and exposed area of each of the surveyed houses were combined with the census data to form a data base for the nine survey tracts. A step-wise regression procedure was used to quantify the relationship between census data and the amount of each type of exposed material. The regression procedure develops an equation of the form:

$$S = a_o + \sum_{i=1}^{k} a_i P_i \qquad (3\text{-}1)$$

where: S = the amount of exposed material
a_i = coefficients developed by the regression procedure
a_o = constant developed by the regression procedure
P_i = Census data predictors

In determining the regression coefficients, all combinations of available predictors must be searched and the most significant predictor selected. A forward step-wise regression technique was utilized. At each step in the analysis, a new predictor was added to the regression equation, or an existing

TABLE 3-3

AVERAGE PERCENTAGE OF WALL MATERIAL
WHEN COMPARED WITH TOTAL FRONT AREA

Median Tract Income

	>$35,000	$15,000-35,000	<$15,000
Stucco			
Pre-1950	45	67	50
1950-1969	24	47	52
Post-1969	33	46	47
Brick			
Pre-1950	22	3	0
1950-1969	7	21	4
Post-1969	6	6	3
Painted Wood			
Pre-1950	8	2	18
1950-1969	35	11	22
Post-1969	22	23	13
Glass			
Pre-1950	16	17	19
1950-1969	19	12	12
Post-1969	15	14	16

predictor was deleted. The predictor selection criterion is based on predefined statistical measures using the F value (the ratio of the variance explained to unexplained variance).

There are several methods for assessing the accuracy of the regression model. The first test is the F value when the predictor is selected. The second is the coefficient of multiple determination, the square of the multiple correlation coefficient (R), which indicates the proportion of the total variation in the response explained by the fitted model. The third test for the significance of the regression equation is the standard error of Y.

To test the inclusion of a single variable, an F test was applied to check whether the variable is statistically significant. The F values were computed from:

$$F = \frac{MSR}{MSE} \qquad (3\text{-}2)$$

where MSR is a mean square regression given by:

$$MSR = \Sigma(Y_i - Y)^2/n \qquad (3\text{-}3)$$

where $Y_i - Y$ is the deviation of the fitted regression line. A mean square error, MSE, is computed from the error sum of the squares:

$$MSE = \frac{\Sigma\ (Y_i - Y_i')^2}{n - k - 1} \qquad (3\text{-}4)$$

where n is the number of cases, k is the number of predictors and y_i and y_i' are the observed and predicted Y at point i. MSE is also defined as the sum of the squares of the deviation divided by n-k-1, or an unbiased estimation of the variance.

The F level test is used to determine whether an indicated regression coefficient, a_x, is significant, i.e., whether the inclusion of an individual predictant reduces variance. The critical values of the F distribution for α and n-k-1 for n=9 were shown in Table 3-4. The minimum F value selected for the analysis was 0.4. Choice of this relatively low F value ensures that all potential predictors, even relatively weak ones, are initially included. Then each set of equations can be examined to determine the equations that will provide the most significant results.

The correlation coefficient is given by:

$$r = \sqrt{1 - \frac{\Sigma (Y_i - Y'_i)^2}{\Sigma (Y_i - \bar{Y})^2}} \qquad (3\text{-}5)$$

where Y'_i is the predicted value for a particular value of α, $\bar{Y}$ is the mean value of Y along the regression line, and Y_i is the actual or observed value of Y. A correlation coefficient of 0.95 implies 90.25 percent, i.e. r^2, of the variation in the response is explained by the regression equation. A correlation coefficient on the order of 0.5 implies the regression equation explains only 25 percent of the variation.

The standard error of Y is given by:

$$SE = \frac{\sum (Y-Y')^2}{n} \qquad (3\text{-}6)$$

The standard error gives the absolute amount of unexplained variance in the regression.

The predictors of the regression equation were selected from the set of possible predictors in a step-wise procedure based on the entry F value of the selected predictor and the reduction of the variance over the previously

TABLE 3-4

CRITICAL VALUE OF THE F DISTRIBUTIONS FOR n = 9

α	k 1	2	3	4	5
0.5	0.49	0.75	0.85	0.90	0.94
0.90	3.36	3.01	2.81	2.69	2.61
0.95	5.12	4.26	3.86	3.63	3.48
0.99	10.6	8.02	6.97	6.42	6.06

Where: α = statistical significance level
k = the number of predictors in the regression equation
n = the number of independent data points

predicted regression equation. If the F values showed an abrupt decline or the reduction of variance declined more slowly or increased, the additional predictors are insignificant additions to the equation and are not included in the final equation.

The regression analysis procedure described above was used to find relationships between the amounts of exposed materials observed for single-family homes, and the demographic characteristics of the census tracts in which the observations were collected. The selected regression equations are shown in Table 3-5.

Predictors of the quantity of materials in place that were most often selected and had a high level of statistical significance include the age of the house and the mean number of rooms. The coefficients for the age of the house were negative for painted brick and painted wood, indicating that more of these materials are used on the newer homes. The income of the area was only significant in regards to the painted wood where more was observed on the higher income houses.

The resulting regression equations were used with the data for all census tracks in the region to predict the total exposed materials. The projected area of the different exposed materials for the basin are shown in Table 3-6 for the 1.9 million single family homes.

Additional data on other materials were not sufficient to develop regression equations. Gutters, generally aluminum were found on 37 percent of the homes with an average total length of 41 feet. Shutters were found on 20 percent of the homes with an average of 28 ft^2 each, and were generally painted wood. Awnings, generally coated aluminum, were found on 7 percent of the homes. The data are summarized in Table 3-7, with simple extrapolation based upon the frequency of occurrence and area of the material.

TABLE 3-5

REGRESSION EQUATIONS USED FOR VARIOUS MATERIALS

Painted Stucco (PS)

$$PS = -969.84 + 239.04\ R + 24.654\ A$$

r = .67 SE = 574.1
F of R = 2.27 Total F = 2.42

Painted Wood (PW)

$$PW = 430.6 - 251.9\ S + .015173\ I$$

r = .88 SE = 136.2
F of S = .48 Total F = 10.17

Painted Brick (PB)

$$PB = -236.52 - 501.84\ S + 102.69\ R + 4.7922\ A$$

r = .88 SE = 83.8
F of S = 3.78 Total F = 5.81

Stone (ST)

$$ST = -77.95 + 18.047\ R - .000145\ V$$

r = .88 SE = 9.8
F of V = 3.4 Total F = 8.5

Glass (G)

$$G = 74.56 + 6.595\ A$$

r = .68 SE = 114.2
F of A = 6.12 Total F = 6.12

Brick (B)

$$B = -1543 + 1159\ S + .001845\ V + 14.359\ A$$

r = .96 SE = 79.3
F of S = 4.2 Total F = 14.6

A = Average age of house
S = % single family homes in tract
V = Mean value of house
R = Mean number of rooms per unit
I = Median income

TABLE 3-6

TOTAL AMOUNT OF EXPOSED MATERIALS (ft^2) IN THE LOS ANGELES BASIN FOR RESIDENTIAL DETACHED HOMES

	Area	Percentage of total area
Painted Stucco	15.73×10^8	48%
Painted Wood	10.94×10^8	33%
Brick	$.72 \times 10^8$	2%
Painted Brick	$.64 \times 10^8$	2%
Stone	$.10 \times 10^8$	<1%
Glass	4.48×10^8	14%
Total Area	32.61×10^8	
Total number of single family units	1.933×10^6	

TABLE 3-7

SUMMARY OF NON-STRUCTURAL MATERIALS ON
SINGLE FAMILY HOMES

Item	% of Homes	Typical Area ($ft.^2$)	Material (typical)	Total Area ($x\ 10^6 ft^2$)
Gutters	37%	41	Coated Aluminum	28
Shutters	20%	28	Painted Wood	10
Awnings	7%	50	Coated Aluminum	7
Porch	20%	75	Concrete	30
Flower Bed	10%	30	Brick	6

3.2 Multiple Residential Units and Mobile Homes

Apartments and other multiple living unit dwellings in 108 buildings were examined using the Sanborn maps. The total wall area of multi-unit buildings was computed and the buildings were categorized according to the number of units per building. There was no apparent trend in the wall area per unit based on the number of units per building.

The analysis of multi-unit dwellings shows the exposed areas range from 433 ft^2 to 1,574 ft^2 per unit with a tract weighted average area of 875 ft^2. All multiple units that ranged up to 20 units per building had stucco walls. Glass areas were assumed at 15 percent and 2 painted wood doors were assumed with an area of 35 ft^2. Within the basin, there are 857,518 units in multi-unit dwellings. The total exposed area for each material based on the extrapolation is shown in Table 3-8.

The census data shows 60,787 mobile homes are present in the SCAB. Mobile homes were not sampled in this study but were included in McCarthy, et al. (1984). Based on McCarthy's results a standard size of 55 x 10 x 8 feet was used with aluminum siding and trim. This yielded a total area of 0.97 x $10^8 ft^2$ and 7 percent was assumed to be windows.

3.3 Commercial and Industrial

The commercial and industrial building area inventory was computed using the Sanborn maps and the land use data for the South Coast Air Basin. Sanborn maps, discussed in Section 2.2, were obtained for each of the land use categories that included commercial and industrial uses. Two maps were analyzed for each of the land use categories that represented more than two percent of the total land area in the basin. The land use categories with two map segments each include mixed industrial, public facilities, cultural

TABLE 3-8

EXPOSED AREA OF MULTIPLE UNITS

Material	Average $ft.^2$	Basin Total ($10^8 ft^2$)
Stucco	710	6.09
Glass	130	1.11
Wood-Painted	35	0.30

entertainment, and mixed residential. One Sanborn map was analyzed for the other land use classes. The military/airport and airport/heliport categories were combined and a single map was obtained for these categories. No buildings were present for the land use categories of non-forest undeveloped, forest, mixed open space, non-forest developed, and water. All residential buildings, including those in the commercial and industrial land use areas were included with the residential categories and were not "double counted" during the Sanborn Map analysis.

Sanborn maps covering land areas of up to 4,320,000 ft^2 per map (approximately 0.4 x 0.4 miles) were examined in detail and the materials and length of each building wall were recorded on worksheets. The height of the walls were obtained from the maps. The areas for each of the walls were summed and recorded on map summary worksheets. The material categories were consistent with the materials reported on the Sanborn map (as was shown in Figure 2-2).

Using photo data obtained during the field survey for seven Sanborn map locations, the window areas associated with each land use classification were estimated. The window area estimates were extended to other land use tracts that contained similar commercial/industrial uses. Estimates of glass areas varied from 10 percent (for warehouses) to 50 percent (for office buildings) of the total wall area as shown in the first column of Table 3-9. The ratio of the area for each exposed material to the land area was computed, and the results are shown in the remaining columns of Table 3-9.

The ratio of wall area to the land area for each land-use class was multiplied by the total area of each land use to compute the total area of each material within the basin. The resultant values were summed from each land use category for the South Coast Air Basin. The results are shown in Table 3-10. Masonry (brick, concrete and reinforced concrete) is the major

TABLE 3-9

THE RATIO OF AREA OF MATERIAL TO AREA OF LAND (x 10^{-2}) FOR COMMERCIAL AND INDUSTRIAL BUILDINGS

	% Glass	Stucco or Wood	Iron	Brick	Concrete	Reinforce. Concrete	Glass	Gunite	Steel	Metal	Tile
Mixed Industrial	40	1.68	-	3.22	2.84	0.08	6.59	-	-	2.08	-
Mixed Residential	25	1.98	0.04	1.07	1.37	0.62	1.69	-	-	-	-
Public Facilities	40	0.29	0.13	3.50	8.36	-	8.29	-	-	-	0.16
Retail Operations	16	2.52	0.18	1.39	10.30	1.50	3.00	-	-	0.03	0.04
Airport/Military	14	0.51	2.16	2.74	0.56	2.24	5.61	-	0.06	0.14	-
Mixed Commercial	40	0.75	-	4.19	9.06	16.12	20.08	-	-	-	-
Cultural	10	0.18	-	2.98	0.87	0.13	0.47			0.10	-
Railroad	25	1.78	3.65	1.44	0.05	0.62	3.44	0.58	1.46	0.75	-
Mixed Transportation	30	1.79	2.51	4.97	0.85	-	4.52	-	-	.42	-
Heavy Industry	40	1.74	-	0.53	-	2.14	2.95	-	-	-	-
Office Building	50	2.42	-	4.50	1.10	-	8.00	-	-	-	-
Light Industry	30	14.41	-	1.61	4.50	2.21	9.75	-	-	-	-
Ports	20	1.03	12.61	0.19	9.63	0.52	15.61	2.48	30.72	5.25	-
Highway	30	-	0.14	-	-	-	0.06	-	-	-	-
Mixed Open Spaces	0	0.51	-	-	0.03	-	-	-	-	-	0.08

TABLE 3-10

AREA OF EXPOSED MATERIAL IN COMMERCIAL AND INDUSTRIAL SECTORS ($10^8 ft^2$)

	Stucco or Wood	Iron	Brick	Concrete	Reinforce. Concrete	Glass	Gunite	Steel	Metal	Tile
Mixed Industrial	0.70	-	1.34	1.18	0.03	2.75	-	-	0.87	
Mixed Residential	0.72	0.01	0.38	0.49	0.22	0.61	-	-	-	-
Public Facilities	0.07	0.03	0.83	1.99	-	1.97	-	-	-	0.04
Retail Operations	0.41	0.03	0.22	1.66	0.24	0.48	-	-	-	0.01
Airport/Military	0.07	0.30	0.38	0.08	0.31	0.79	-	-	0.01	0.02
Mixed Commercial	0.08	-	0.47	1.02	1.82	2.27	-	-	-	-
Cultural	0.01	-	0.11	0.03	0.00	0.02	-	-	-	-
Railroad	0.04	0.08	0.03	0.00	0.02	0.08	0.01	0.04	0.02	-
Mixed Transportation	0.02	0.03	0.05	0.01	-	0.04	-	-	-	-
Heavy Industry	0.01	-	0.00	-	0.01	0.02	-	-	-	-
Office Building	0.01	-	0.03	0.01	-	0.04	-	-	-	-
Light Industry	0.06	-	0.01	0.02	0.01	0.04	-	-	-	-
Ports	0.00	0.02	0.00	0.02	0.00	0.03	0.01	0.06	0.01	-
Highway	-	0.02	-	-	-	0.01	-	-	-	-
Mixed Open Spaces	0.27	-	-	0.02	-	-	-	-	-	-
Extractive	-	-	-		-	-	-	0.02	-	-
Total*	2.47	0.54	3.87	6.53	2.68	9.15	0.02	0.13	0.93	0.04

* May not add exactly because of rounding. Totals originally based on 4 fractional digits.

wall material in the commercial/industrial sector. Glass is the next largest amount of exposed material.

Materials exposed on oil wells and on agricultural properties were estimated in the following manner. The exposed area in the extractive land use category was computed by using an estimate of 200 ft^2 exposed painted steel for each of the 9500 oil wells in the basin. Materials for residential structures on agricultural property have been included with the extrapolations for single family residential properties. Materials for non-residential use in agricultural regions (barns, sheds, etc.) have been based on a sample of 232 buildings over a 25 square mile (about 65 km^2) area. The agricultural materials estimates are based on field surveys of materials combined with analysis of aerial photographs and topographical maps for the eastern portions of the Basin. Building widths and lengths were determined from the analysis of aerial photographs, and the agricultural buildings were assumed to be one story (fifteen feet) tall. Analysis of TRC field survey photographs and the telephone survey results showed that these buildings were predominantly galvanized steel pole barn structures used for feed lot and grazing operations. All agricultural buildings were assumed to be of this type of construction. Orchards, vegetable farms and other agricultural land uses had far fewer, and generally smaller buildings than the livestock operations. Buildings for non-livestock farms were assumed to be of the same materials type as the metal pole barns. An estimated 0.10 x 10^8 square feet of galvanized steel is exposed on agricultural use buildings. Undoubtedly, some of the buildings on both the livestock and the non-livestock farms were of painted wood or other construction, however an adequate sample to determine their number and size was not available. Therefore, an unknown, but probably small percentage of these agricultural buildings is actually painted wood or other materials, not galvanized.

3.4 Non-Building Materials

Non-Building materials are a significant portion of the total materials inventory of the South Coast Air Basin, and include fencing and guardrails, lights and sign materials, transportation structures, tires, and monuments. The distribution of some of these materials can be based on the photo survey of the residential area. In other cases, telephone surveys were used to obtain the data.

Data from the photo survey showed that sixty percent of the homes had fencing or a freestanding wall for portions of the property. The most common freestanding wall material was brick. Painted wood and stucco, and galvanized wire (chain link) fences were also common. The distribution of fence type is summarized in Table 3-11. In general, the brick and concrete fencing were generally limited to the front of the house and covered areas of 50 to 100 ft^2. Chain link fencing was generally 4 to 5 feet high and surrounded large portions of the property. In order to estimate the amount of galvanized fencing, an initial estimate of a length of 100 feet is used at 11 percent of the single family homes in the basin. Thus, a total chain link fence area of $10^8 ft^2$ is estimated for residential properties. Television antennas, primarily of aluminum, were exposed on approximately one-half of the homes, however, antennas are not included in the data base.

Chain link fencing in the public sector is primarily used along roads. The telephone survey indicates there is approximately 2,600 miles of chain link fence in the urban areas and galvanized wire mesh and barbed wire in rural areas. Replacement generally occurs after auto accidents.

Most guardrails on highways are also galvanized steel. Estimates of amount of guardrails obtained from various public agencies indicated about 470 miles of guardrail, mostly on state maintained highways. Current plans are to replace the metal guardrails in SCAB with the concrete barriers of the New

TABLE 3-11

FENCING AT RESIDENTIAL PROPERTIES BASED ON
THE SAMPLE OF 90 HOMES

Material	Percentage of Homes
Brick	28
Painted Wood or Stucco	17
Chain Link	11
Concrete	4
Total	60

Jersey type. Guardrails are generally replaced after auto accidents and routine maintenance is not performed.

Street light poles are generally galvanized steel and aluminum and extend to 30 to 40 feet high. Older ones are concrete and cast iron. The telephone survey indicated in excess of 275,000 streetlights in the SCAB. No routine maintenance is done except to replace the lamps. Parking meters are made of Duncan Vault reinforced steel with maintenance (painting) every two years. There were over 30,000 parking meters in the cities surveyed.

Street signs are generally made of painted aluminum or steel and are placed on pressure treated Douglas Fir posts or galvanized supports. There are over 550,000 street signs in the SCAB. Signs on the freeways are generally 40 by 10 feet or less. According to the maintenance departments, any paint on the posts "seems to last", and painting is infrequent.

A summary of the highway materials are shown in Table 3-12. The highway fencing was assumed to be 6 feet high and the street lights to be 35 feet high. The average area of each street sign was assumed to be 400 ft^2 (20x10x2 sides). No estimate was made of the amount of exposed materials within the road beds or bridges, and no estimates of damage to road beds or bridges have been included.

There are about 20,000 towers and poles of galvanized steel or wood ranging up to 120 feet tall for 2,880 miles for high voltage transmission lines. The exposed area of a typical galvanized tower is estimated at 400 square feet. An estimated one-half of the towers are expected to be galvanized yielding about 0.04×10^8 ft^2 of galvanized exposed on towers. No maintenance, other than washing in coastal areas, has been generally undertaken on the poles. No estimate was made of the number of distribution poles from the substation to the end user.

TABLE 3-12

MATERIALS ALONG HIGHWAY IN THE SOUTH COAST AIR BASIN

Responsible City or Agency	Fencing (Miles)	Guardrails Metal (Miles)	Guardrails Wood (Miles)	Guardrails Concrete (Miles)	Streetlights	Street Signs	Parking Meters
Los Angeles	2	30	60		190000	500000	280000
Riverside	40	20			23000	15000	
Pasadena	12	1			14500	6000	
Long Beach	–	–			24000	25000	3000
Caltrans	2600	420		500	25000	Unknown	
Total Exposed Area ($10^8 ft^2$) from the surveyed cities and agencies	1	0.5	0.01	0.1	0.2	2.2	0.002

Blanks indicate no information received.
Unknown indicates that the agency did not have a record of the information requested.

The largest exposure of monumental stone is within the large cemeteries. The estimated 750,000 monuments in the cemetaries surveyed are generally 4 to 20 ft^2 each and are usually either bronze or granite. Some of the older monuments are made of marble and require a periodic cleaning. Only Glendale Cemetary, in Long Beach, reported any cleaning activities for the markers, and this was limited to washing the few marble markers they have. The newer monuments received no maintenance.

Data collected by the telephone survey was not exhaustive. Four large municipalities and the area-wide agencies were contacted, however, the numerous smaller municipalities were not included in the survey results and no estimates have been made for the materials exposed by the unsurveyed municipalities. The area of the non-building related materials indicated by the telephone survey results is two to three orders of magnitude smaller than the material area found in the residential and commercial/industrial sectors. The materials estimates from the telephone survey form a lower bound of the exposure totals for the materials along the highways, or used by electric utilities or exposed in cemetaries. Actual totals for the materials exposed along highways, used by electric companies and exposed in cemetaries may be as much as an order of magnitude higher than indicated, however, when compared with materials used in the residential and commercial/industrial sectors, they are still very small.

3.5 Independent Methods of Inventory Computation

A key question in this type of materials inventory is whether the results are accurate. To answer this question, fundamental properties of the data sample will be examined. The data sample was developed in a systematic procedure to obtain buildings that were representative of particular land use categories. We will examine independent methods to determine the possible range of material inventory.

3.5.1 Residential

The residential survey examined the fronts of 88 homes and one side of 26 of these homes. The homes were selected from 9 census tracts that showed high uniformity of the age of the homes and covered different median income levels. The basic assumption is that homes built at a given time for a given income level are approximately the same size and similar in construction. The sample standard deviations for the areas of the front of the homes in each of the 9 tracts are shown in Table 3-13. The standard deviations range from 12 to 41 percent of the mean area. The largest percentages are in the high income area and range from 25 to 41%. The middle income homes are most uniform.

The distribution of the size of the front of the homes are shown in Figure 3-1 with a double peak distribution with maximum peak number of homes near 325 and 525 ft^2. Of a total of 90 homes photographed during the field survey, 88 were processed to determine the front area. The photographs for the remaining two houses were "unprocessable" because of obstructions (shrubs, parked cars) obscuring significant portions of the two houses. The distribution shown in Figure 3-1 is skewed with the inclusion of the pre-1950, high income tract in Beverly Hills, where eight of the homes in the tract were the 8 largest homes in the total sample. That tract was not used in computing the confidence level of the mean size of the front listed in Table 3-14. The confidence limits for the side of the houses are included in Table 3-14. Then the total area of the house was computed using the minimum and maximum areas of the confidence level for the front and side of the house. The total area of the house have a mean area of 1572 ft with a 90 percent confidence limit of 1428 to 1724 (or $\pm$ 10%) of the mean.

TABLE 3-13

SAMPLE STANDARD DEVIATION AND MEAN OF THE AREA OF THE FRONT OF THE HOUSES IN EACH TRACT (ft^2)

STANDARD DEVIATION

Housing Age	Annual Income >$35,000	$15,000-35,000	<$15,000
Pre-1950	265	103	104
1950-1969	103	72	101
Post-1969	155	63	84

MEAN AREA

Housing Age	Household Median Income >$35,000	$15,000-$35,000	<$15,000
Pre 1950	1033	432	388
1950-1969	356	490	378
Post 1969	378	525	302

PERCENT OF STANDARD DEVIATION OF MEAN

Housing Age	Annual Income >$35,000	$15,000-$35,000	<$15,000
Pre 1950	26	24	27
1950-1969	29	15	27
Post 1969	41	12	28

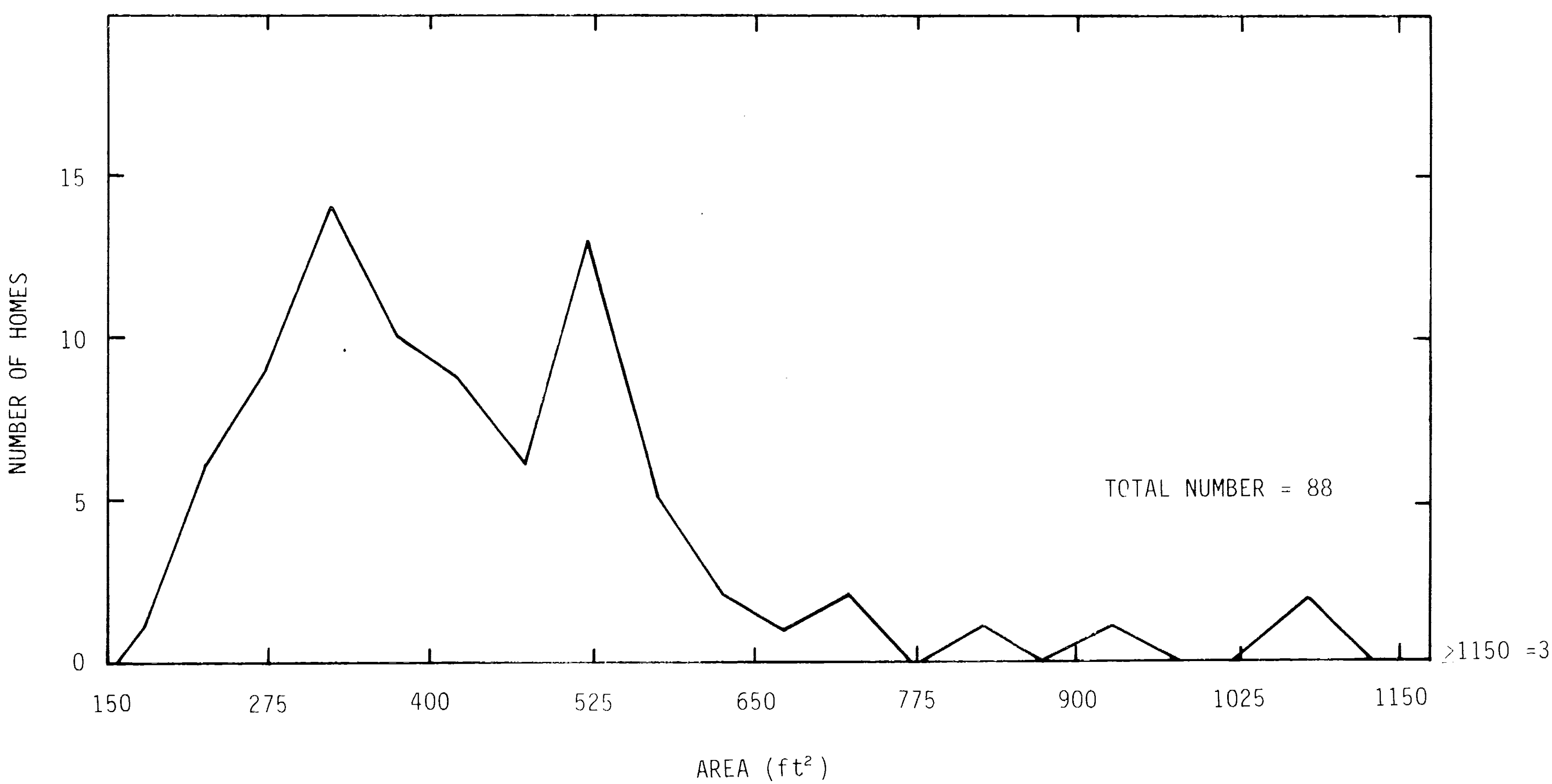


Figure 3-1. Number of homes catagorized by front area in 50 ft^2 segments from the field survey.

TABLE 3-14

CONFIDENCE LEVELS OF EXPOSED WALL AREA
FOR SINGLE FAMILY HOMES

	Number of Houses	Mean Area (ft^2)	Confidence Levels (ft^2) 90%	95%
Front Area	88	404	382-426	378-430
Side Area	22	382	332-432	322-442

The regression equations were developed from the field survey photo data and extrapolated over the 1.93 x 10^6 single family units in the basin. As a basic check of the regression procedures, take the mean total area and multiply the mean by all houses in the basin. The resultant area or 30.3 x 10^8 (if the pre-1950, > $35,000 income houses are omitted), is within 10 percent of the area (32.61 x 10^8) generated by the regression equation. All vertical areas are included in this estimate.

One way to examine for the bias of the materials as a function of house size within a tract is to determine the average ranking of the house for given materials. Each house in a tract was ranked against the nine other houses in the tract according to size and material. The average ranking of the homes across all tracts are shown in Table 3-15. The average ranking of stucco and wood surfaces are within one location of the average ranking (5) of all houses. Completely brick houses were only reported in one tract, the >$35,000 income houses built before 1950. However, brick and stone were reported as facades having less than half of the front side in the other tracts.

One of the possible sources of error in the photo analysis is an accurate computation of the distance from the camera to the house. Tests of the method showed errors of 1 to 2% when the distance was accurately known by measurement. Early in the analysis, it became apparent that the optical range finder was unreliable and produced errors that were greater than 10%. Therefore, the height of a doorway on each photo was assumed to be 80 inches, which is an architectural standard and the remainder of the analysis was scaled for the doorway measurement. Random errors of 2 to 4 inches are to be expected, leading to overall area estimate errors of 2 to 5%.

In view of these results, the error for the total single-family residential wall area computed here for the basin is within 15% of the total wall area with 10% of the variance about the sample mean and 5% in computing

TABLE 3-15

AVERAGE RELATIVE HOUSE RANKING OF MATERIAL WITHIN A GIVEN TRACT

Material	Number of Tracts	Relative House Ranking
Stucco	9	5.5
Wood Paint	7	4.9
Brick	1	6.5

Note: House ranking is the average out of 10 houses in each tract. A value of 5 indicates the same number of large houses and small houses are covered with the material without intra tract bias.

the sample mean. The materials with the most reliable area estimates are stucco and painted wood. Other computed areas will have a somewhat larger variability. The total amount of residential stone or brick may be biased on the high side because they often are only used on the front. A lower limit would probably be about 40% of the reported results.

3.5.2 Commercial, Industrial, and Multiple Unit Residential Building

The use of the Sanborn maps posed a problem in that several of the maps were more than 10 years old and it is questionable whether they depict the buildings on-site during the period of 1978-1980. As discussed in Section 2.3, field verification of the Sanborn map was made by visiting seven intersections shown on seven different maps and photographing the buildings around the intersections. A comparison of photos at two of the seven locations showed a complete change of buildings. However, the maps are probably the best source of data and, even if out of data, are representative of a given land use. It is unlikely that there have been substantial changes in the types and amounts of materials used in a given commercial/industrial sector land use.

The Sanborn maps were used to determine the wall area of 109 multi-unit residential buildings that contained 631 units. The largest uncertainty would be in the assumption of the window area, which was not indicated on the maps. The 109 multi-unit buildings had a mean wall area of 899 ft^2/unit without any tract weighing with a standard deviation of 544 ft^2. The 90 percent confidence intervals are 813 and 983 ft^2. The 95% limits are 795 and 1000 ft^2. Thus, the limits are within 12% of the mean. In the earlier section, the tract weighted average of 875 ft^2 was the value used, or within the range of the confidence limits for the mean area computed here.

Uncertainties in the commercial and industrial sectors are more difficult to quantify because of the large diversity in size and use of structures. Therefore, we used a completely independent method to estimate the exposed materials in the industrial sector and provide estimates to extend the analysis to the commercial sector.

The MacRae Industrial Directory was examined to find companies that reported both the number of employees and the square feet of the building floor space. Data for approximately 1000 firms were used to determine an average amount of floor space per employee. Examination of the data showed that there were approximately 1000ft^2 per employee. There was a large variation about the mean, but generally the floor area ranged between 300 to 1800 ft^2 per employee. The companies in the data sample provided by MacRae's covered the U.S. Government's Standard Industrial Code (SIC) numbers from 2000 to 4000. It was assumed that the values apply on average to all commercial establishments. Further work would be necessary to check this assumption which may overestimate the area for warehouses and some retail outlets.

The square footage of exposed wall is computed by assuming an aspect ratio, A, of the length and width of the building to determine the wall area of the building. Thus the wall area W will be given by computing the perimeter surrounding the floor area, F, by

$$W = H\,2(\mu + Am);$$

where m in the length of the shorter side are H is the height of the wall and will be assumed to be 10 feet. The floor area μ given by:

$$F = A\,m^2 \qquad \text{and from the MacRae Index}$$

$$F = E\,M$$

where E is the number of employees and M is the factor for square feet of floor area per employee. Solving the above two equations for m and substituting into the perimeter equation yeilds:

$$W = \frac{20\ (1 + A)\ E^{0.5}\ \ M^{0.5}}{A^{0.5}} \tag{3-7}$$

where A is the aspect ratio, E is the number of employees, and M is the square foot of floor area per employee.

The census data for county business pattern tabulates on a county basis the number of outlets with a given number of employees (e.g., 1-4, 5-9, 10-19, etc.), Eq. 3-7 was applied to compute the total exposed wall for each employee grouping and summed. The resultant total exposed wall area was computed as $10.05 \times 10^8 ft^2$. This is considerably less than the comparable areas computed by the Sanborn map method that totaled $18.79 \times 10^8 ft^2$ with the agricultural, public services, cultural and entertainment, and extractive areas omitted.

One reason for the difference is that the land use data overstates the land use for the commercial sector by using all potential land use, and not just the actual current land use. Another explanation is that the maps were available for the more built up sections of the basin, and are not representative of the material density (square feet of exposed material per hectare) over the whole basin. Thus the results would be heavily weighted to the urbanized region.

Originally the limited mapped area examined for each land use, 160,000 ft^2, introduced errors. An analysis of the Sanborn map showed that the 160,000 ft^2 sections contained large amounts of materials on a per square foot basis, i.e. high materials density, due to undercounting of streets and parking lots. The 5 maps that were originally analyzed on a 400 by 400 ft^2 sample square were reanalyzed to cover the entire area of the map and thus include all streets and parking lots. A reanalysis showed the ratio of wall area to land area was greatly reduced due to the inclusion of street and parking area. Subsequently all Sanborn map analyses were performed using the entire map area (1,080,000 ft^2 or 3,840,000 ft^3 depending on the map scale).

Based on the large differences and the more detailed business inventory used for the MacRae Industrial Directory method, the total material amount in the commercial/industrial sector derived from the Sanborn map analysis was adjusted downward to a value close to the MacRae Industrial Directory value. As no data are available for types of materials in the MacRae analysis, all materials were reduced proportionally. The Sanborn map data was reduced by 47 percent for subsequent analyses.

3.6 Summary of Material Inventory

The inventory of buildings is based on a sample of 805 buildings covering the various land use categories, as shown in Table 3-16. Photos were taken of more than 100 buildings with the exposed area computed using a microcomputer program.

The resulting material distribution for the major materials are shown in Table 3-17. The results are summarized in Figure 3-2.

TABLE 3-16

NUMBER OF BUILDINGS USED IN THE SURVEY

	No.	Source[1]
Agriculture	230	USGS
Mixed Open Space	6	S
Mixed Industrial	20	S
Mixed Residential	56	S
Public Facilities	22	S
Retail Operations	73	S
Military/Airport	11	S
Highway	1	S
Mixed Commercial and Service	6	S
Cultural, Entertainment	18	S
Railroads	40	S
Mixed Transportation	10	S
Heavy Industry	5	S
Office Building	14	S
Light Industry	74	S
Ports	23	S
Mutiple Unit Residential	108	S
Single Family Homes	88	P
Total	805	

[1] USGS USGS Map
S Sanborn Map
P Photo Survey

TABLE 3-17

SUMMARY OF THE AREA ($10^8 ft^2$) OF MAJOR MATERIALS IN SOUTH COAST AIR BASIN BUILDINGS (STRUCTURAL MATERIAL, ONLY)

Material	Residential			Commercial	Total
	Single	Multi	Mobile		
Stucco Painted	15.73	6.09		.53	22.35
Wood-Painted	10.94	0.30		.37	11.61
Iron				.28	.28
Brick	.72			2.42	3.14
Painted Brick	.64				.64
Concrete				4.15	4.15
Reinforced Concrete				1.30	1.30
Glass	4.48	1.11	.07	5.46	11.12
Gunite				.01	.01
Steel				.06	.06
Metal Clad			.90	.49	1.39
Tile				.02	.02
Stone	.10				.10
Galvanized				.01	.01
Total	32.61	7.50	.97	15.06	56.18

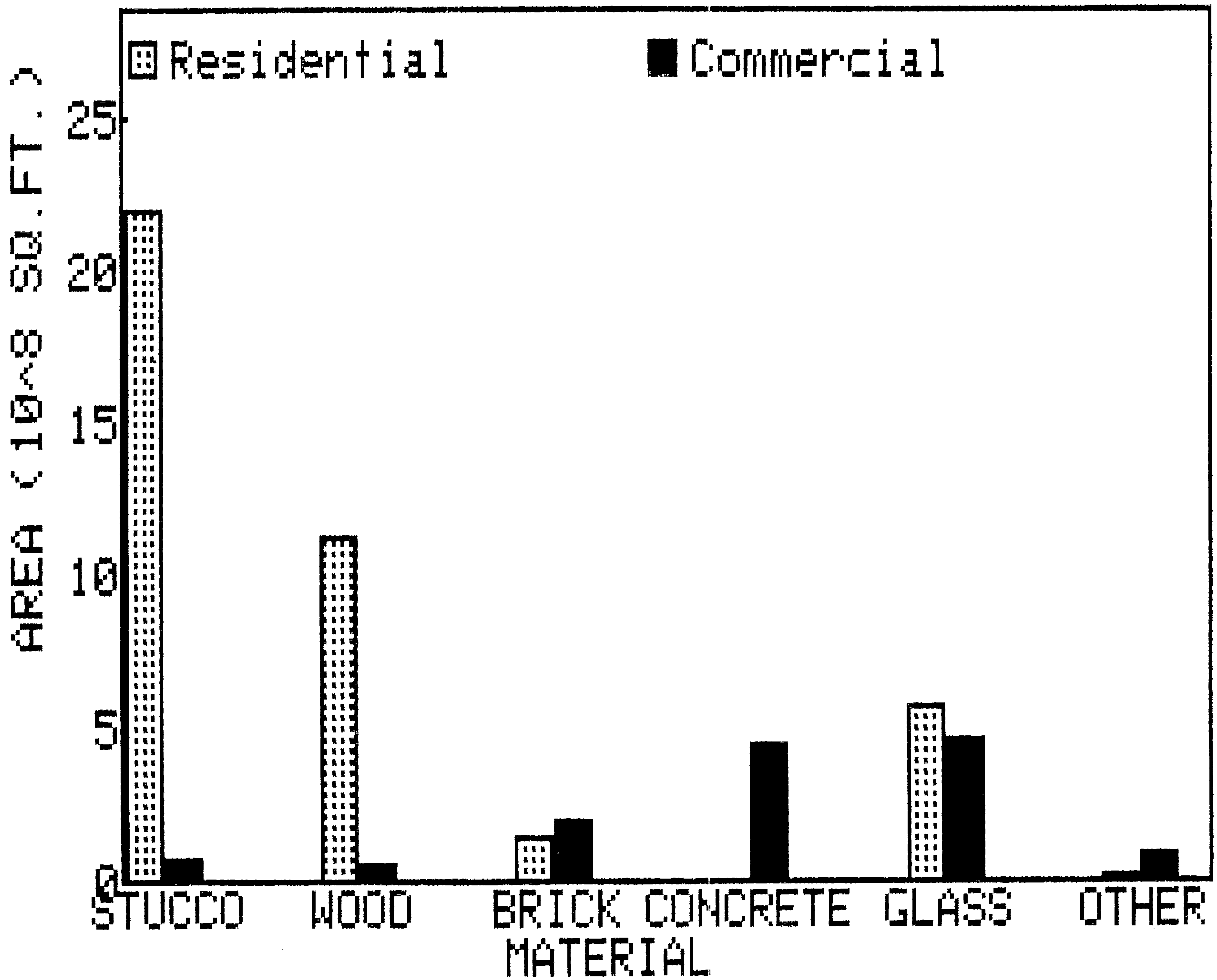


Figure 3-2. Distribution of materials in the commercial and residential sectors.

4.0 MATERIALS DAMAGE FUNCTIONS

4.1 Damage Functions

Damage functions are mathematical expressions that quantify the amount of change in a measurable characteristic of a material in terms of environmental factors, such as pollutant concentration and/or climate, and time. The material damage functions currently available in the literature are based on two different methods of study: field tests and chamber tests. Field tests of materials are inherently representative of actual exposure. Chamber studies where individual pollutants are introduced to sensitive materials, are conducted under a much more ideal, controlled environment. Chamber studies have been used to determine the impact of one or more damaging agents to the overall damage process.

Damage functions exist in the literature for a limited number of pollutants and materials, primarily sulfur dioxide and metals, ozone and rubber (elastomer), sulfur dioxide and paint, and TSP and soiling.

A review of material damage functions, uncertainties in their application, and the appropriate functions for application in SCAB are presented in subsequent sections.

4.2 Review of Specific Damage Functions

4.2.1 Ferrous Metals

Most ferrous metal alloys (with the exception of stainless steels and weathering steels, such as Corten-A) do not produce reaction products which protect against further reaction. Common rust is usually only loosely attached to the substrate and is easily penetrated by atmospheric reactants and may even serve to accelerate the corrosion process due to retention of moisture and other reactants. The most rapid corrosion of the metal occurs when the surface of the metal is wet. Thus "time of wetness" is an important consideration in any material damage function for ferrous metals.

Most steel surfaces exposed to the outside atmosphere are treated with protective coating (e.g., paint or zinc galvanizing) to minimize the corrosion damage to the steel itself. However, once the protective surface has been removed by corrosion or erosion, the steel itself will begin to corrode.

The sensitivity of steel to corrosion in an aggressive atmosphere depends on the type and composition of the steel. Copper steel and low alloy copper steel (containing 0.2 to 0.5 percent copper) are more resistant to corrosion in an industrial environment than carbon steel (Larrabee, 1953). Similar results are reported by Legault and Leckie (1974), Brauns and Kalla (1965), Schwenk and Terres (1968), Guttman and Sereda (1968), Hudson and Stanners (1953), and Briggs (1968).

Moisture and the natural constituents of the atmosphere, such as sea salt particles, can greatly affect the corrosion rate of steel. The American Society for Testing and Materials (ASTM) reported that a 1/16-inch mild steel panel completely disintegrated after 1-1/2 years of exposure at a test site along the San Francisco coast, while a similar panel at Davis, California, located in a rural area 30 miles from the coast, lost only 2.67 grams after 5 years' exposure.

Briggs (1968) reported that cast steels have greater corrosion resistance than malleable iron and wrought steels in an industrial atmosphere. He also reported that the rate of corrosion decreases with time. A similar dependence of the rate of corrosion on the length of exposure was reported by Upham (1967) from a short-term (3 to 16 months) field study in seven sites in Chicago.

Several damage functions for steel have been reported in the literature. Comparisons between these functions are difficult because the rate of corrosion of steel depends on the length of exposure and the specific composition of the steel alloy.

Upham (1967) studied the corrosion of low carbon (0.019 percent), low copper (.028 percent), and mild steel in the St. Louis and Chicago area, and reported several damage functions for the corrosion rate as a function of the sulfation rate and sulfur dioxide concentration. Different damage functions were reported for each urban area. The damage function also changes with the averaging time for the SO_2 concentration as well as the length of exposure. The different damage functions are summarized in Table 4-1. The differences between St. Louis and Chicago may be explained by the difference in average relative humidity during the exposure period since relative humidity was not reported by Upham.

Haynie and Upham (1970a) reported damage functions for carbon steel, copper-bearing steel and weathering steel:

Carbon Steel

$$y = 9.013 \quad e^{0.00161\, SO_2} \quad (4.768t)^{(0.7512 - 0.00582\, OX)} \qquad (4\text{-}1)$$

Copper-Bearing Steel

$$y = 8.341 \quad e^{0.00171\, SO_2} \quad (4.351t)^{(0.8151 - 0.00642\, OX)} \qquad (4\text{-}2)$$

Weathering Steel

$$y = 8.876 \quad e^{0.0045\, SO_2} \quad (3.389t)^{(0.6695 - 0.00544\, OX)} \qquad (4\text{-}3)$$

where:
- y is corrosion in μm
- SO_2 is the annual average concentration of SO_2 in $\mu g/m^3$
- OX is the annual average concentration of oxidants (ozone) in $\mu g/m^3$
- t is the time of exposure in years

TABLE 4-1

DAMAGE FUNCTIONS FOR MILD STEEL
(Upham 1967)

Damage Function	Independent Variable	Location	Length of Exposures	Starting Date
Y = 1.73 x +0.74	Sulfation rate in mg SO_2/100 cm^2, day	St. Louis	2 months	April 1963
Y = 1.10 x +6.56	Sulfation rate in mg SO_3/100 cm^2, day	St. Louis	16 months	April 1963
Y = 2.87 x -0.03	Sulfation rate in mg SO_3/100 cm^2, day	St. Louis	3 months	December 1963
Y = 74.6 x +2.8	SO_2 concentration in ppm 24-hour average	St. Louis	3 months	December 1963
Y = 88.6 x 2.8	SO_2 concentration in ppm 24-hour average	St. Louis	3 months	December 1963
Y = 18.7 x +3.7	SO_2 concentration in ppm. Mean for the exposure period	Chicago	3 months	September 1963
Y = 26.8 x +6.5	SO_2 concentration in ppm. Mean for the exposure period	Chicago	6 months	September 1963
Y = 54.1 x +9.5	SO_2 concentration in ppm. Mean for the exposure period	Chicago	12 months	September 1963

In a more recent laboratory study (Haynie, Spence and Upham 1976), it was shown that the rate of corrosion of steel is independent of ozone concentration. Haynie and Upham (1974) reported that the corrosion of enameling steel can be described as:

$$corr = 325 \sqrt{t} \exp [0.00275SO_2 - (163.2/RH)] \tag{4-4}$$

where: corr is the corrosion in µm
SO_2 is the annual average concentration of sulfur dioxide in µg/m^3
RH is the annual average relative humidity in percent
t is the exposure time in years

Similar dependence on the square root of time of exposure was reported by Haynie, Spence and Upham (1976). The corrosion of weathering steel was expressed as:

$$corr = 5.64 \quad SO_2 + e \left[55.44 - \frac{31,150}{RT}\right] t_w \tag{4-5}$$

where: corr is the corrosion in µm
SO_2 is the annual sulfur dioxide concentration in µg/m^3
T is the absolute temperature
R is the gas constant = 1.9872 cal/g-mole
t_w is the time of wetness in years

Ateraas et al. (1978) have developed damage functions which relate gaseous SO_2 concentrations with corrosion of carbon steel and zinc. For carbon steel, the damage function is:

$$\text{Corrosion } (g/m^2) = 5.28\ SO_2 + 176.6 \tag{4-6}$$

where: SO_2 = annual average SO_2 (µg/m^3)

For zinc, the damage function is expressed as:

$$\text{Corrosion } (g/m^2) = 0.22\ SO_2 + 6.0 \tag{4-7}$$

where: SO_2 = annual average SO_2 (µg/m^3)

In contrast to the work of others, note that neither of these equations includes a moisture factor as a variable.

The effects of acid rain on exposed materials may be accounted for by damage functions developed in the Scandinavian countries. Through long term corrosion testing of different types of metallized, metallized and painted, and painted steel in Norway, Haagenrud (1977), using a linear regression analysis, developed the following equation to account for the effects of acid precipitation and gaseous SO_2 on the corrosion of carbon steel:

$$\text{Corrosion } (g/m^2) = 1.5x_1 + 2.3x_2 + 0.05x_3 - 15.2 \qquad (4\text{-}8)$$

where: x_1 = concentration of SO_2 ($\mu g/m^3$)

x_2 = days with precipitation

x_3 = concentration of strong acid in precipitation (μ eqv H^+/liter)

4.2.2 Zinc

Although strip zinc is rising in popularity, the primary use of zinc is in galvanizing steel to make it resistant to corrosion. Because of its widespread use in exterior exposures, the effects of SO_2 on corrosion of zinc has been studied intensively.

Guttman and Sereda (1968) proposed that the corrosion rate of zinc panels exposed to the atmosphere is:

$$Y = 0.00546A^{.8152}(B + 0.02889) \qquad (4\text{-}9)$$

where: Y is weight loss due to corrosion in g per 3 in. x 5 in. exposure panel
A is the time of wetness in hours
B is the concentration of SO_2 in ppm

This relation was proposed after an extensive field program in Birchbank, British Columbia in which panels of pure zinc were exposed for different lengths of time to the atmosphere. After the exposure, the corroded layer was removed and the corrosion was determined by loss of weight. During the experiment the degree of wetness was measured by a dew meter and the concentration of SO_2 was measured by a sulfation plate.

Haynie and Upham (1970b) found in their 5-year study in eight U.S. cities that the corrosion rate varied linearly with SO_2 concentration and the relative humidity according to the equation:

$$Y = 0.001028\ (RH - 48.8)\ SO_2 \qquad (4\text{-}10)$$

where: Y is the corrosion rate in µm/year
RH is the average relative humidity
SO_2 is the average concentration of SO_2 in $\mu g/m^3$

This is similar to the damage function reported by Hershaft (1976) (corr = $.000128 f(RH) SO_2$, where f(RH) is an unspecified function of the relative humidity). Note that according to this equation the corrosion rate will be zero at an SO_2 concentration of zero. This result contradicts the findings of many researchers, showing that zinc corrosion also occurs in clean atmospheres although at a much slower rate than when SO_2 is present. In a chamber study, Haynie (1980a) reported that the corrosion rate of zinc can be expressed as:

$$corr = [.0187\ SO_2 + \exp\ (41.85-(23240/RT)]\ t_w \qquad (4\text{-}11)$$

where: corr is thickness loss in µm
SO_2 is SO_2 concentration in $\mu g/m^3$
T is the temperature in °K
R is the gas constant (1.9872 cal/g-mole)
t_w is the time of wetness in years

In recent work, Haynie (1982) summarized the results of a Tennessee Valley Authority (TVA) study and used this data to derive a material damage function.

Based on the results of the survey and assuming an average relative humidity of 70.6 percent and a time of wetness equivalent to 25 percent of exposure time, the corrosion rate may be expressed as:

$$corr = (3.9 + 0.0383\ SO_2)\ t_w \quad (4\text{-}12)$$

where: corr is loss of thickness in µm
SO_2 is concentration of SO_2 in µg/m^3
t_w is time of wetness in years

In another study on the effect of sulfur dioxide on building material Haynie (1980a) suggested that the damage function of SO_2 to galvanized surfaces can be expressed as:

$$corr = (2.5 + .02\ SO_2)\ t_w \quad (4\text{-}13)$$

Further refinement of the data used to derive this equation led Haynie to propose separate approaches to calculate corrosion for zinc surfaces used in different applications. The deposition velocity to large flat surfaces such as roofing and siding is much less than that for lattice structures used in transmission line towers. In addition, chainlink fencing has a deposition velocity nearly twice as large as that of flat sheets. Based on these differences, the damage function for the rate of zinc corrosion can be expressed as:

$$C = (A + B\ SO_2)\ t_w \quad (4\text{-}14)$$

where: C is the zinc corrosion rate
A is the corrosion rate when wet in a clean environment (2.4 µm/yr)
B is the 0.0225 for roofing and siding and 0.0450 for fencing
t_w is the time of wetness in years

A spot check of the above equation can be made by comparing the predicted zinc erosion rates against the measurements of zinc thickness on electric transmission towers made by the field survey technician (see Section 2.3).

The technician measured the thickness of the galvanized coatings on eight transmission towers at the Haynes Generating Station and the Harbor Generating Station. Four thickness measurements were recorded, one on each side of the eight towers (i.e., a total of thirty-two observations). The towers for Haynes have been in place since 1965, and those at Harbor since 1943. Unfortunately, at Harbor Station all but one of the towers had been painted during the 1960's, and those twelve observations had to be discarded. Of the remaining towers, the following was observed:

	Mean thickness (μm)	Standard Deviation (μm)	Number of Observations
Haynes Generating Station	69	17.9	16
Harbor Generating Station	46.8	13.6	4

Assuming the initial coating thickness was equal to the ASTM Standard, 86μm, the observed erosion rates were 0.94μm per year at Haynes, and 0.99μm per year at Harbor.

Erosion rates using Haynie's equation can be predicted if time of wetness is calculated using:

$$T_w = \exp [-3.35 (100-RH)/RH] \quad (4-15)$$

where T_w is the annual time of wetness in years.
RH is the annual average relative humidity.

The time of wetness is estimated as 0.32 years per year by using Los Angeles County's average relative humidity of seventy-five percent. North Long Beach air quality station average annual SO_2 level of 0.002 ppm, is selected for the comparison because of the proximity of the station to the location of the transmission lines. Using B equal to 0.0225 (the value for large aerodynamic diameter deposition), the predicted erosion rate is 1.02 µm/year. This value compares reasonably well with the average observed erosion rates of 0.94 and 0.99 µm discussed above.

4.2.3 Paint

A paint surface is subject to several types of damage which affect its usefulness. Cracking, peeling, erosion and discoloration are all considered unacceptable. Modern formulations are designed to minimize cracking and peeling, which lead to premature failure of the coating system. Erosion or wearing away of the paint surface is the type of damage most closely associated with the impact of ambient gaseous pollution, and is the usual cause for repainting.

Several damage functions for SO_2 induced erosion of paint have been reported in the literature. Such functions are based on either accelerated chamber studies or long term outdoor exposure studies. Unfortunately, all such studies to date have significant flaws which render their results highly questionable. These flaws are inherent in the nature of the problem and cannot easily be overcome.

Damage to a paint surface is the cumulative effect of the conditions to which the surface is exposed. In the real world, the conditions include various combinations of temperature, moisture, sunlight and pollution level. No outdoor exposure study to date has been able to separate the impact of the SO_2 factor from all the others.

Haynie et al. (1976) exposed oil based house paint, latex house paint, vinyl coil coating, and acrylic coil coating to "high" (0.5 ppm) and "low" (0.05 ppm) concentrations of SO_2, NO_2, and O_3 in various combinations. This experiment was done as a chamber study, and permits estimation of the amount of damage due to pollutants alone. A statistical regression analysis of the data was used to derive the following relationship between erosion of oil based house paint and concentrations of SO_2:

$$\text{Erosion } (\mu m/yr) = 14.3 + 0.0151\ (SO_2) + 0.388\ RH \qquad (4\text{-}16)$$

where: RH = annual average relative humidity, %
SO_2 = annual average SO_2, $\mu g/m^3$

Application of this model using typical ambient SO_2 concentrations indicates that a small but quantifiable portion of the total annual erosion can be attributed to SO_2.

In this chamber study, Haynie found that the vinyl coil coating and latex-acrylic coil coatings eroded at a much slower rate than the oil based house paint exposed under similar conditions. A regression analysis of the data was used to derive the relationship between the erosion of vinyl coil coating and SO_2:

$$\text{Erosion } (\mu m/yr) = 2.51 + 1.60 \times 10^{-5} \times RH \times SO_2 \qquad (4\text{-}17)$$

where: RH = annual average relative humidity, %
SO_2 = annual average SO_2, $\mu g/m^3$

For latex-acrylic coil coating, ozone was found to be the most likely factor to affect the erosion rates. As with oil based house paint and vinyl coil coatings, a regression analysis was used to derive the relationship between the erosion of acrylic coil coatings and O_3:

$$\text{Erosion } (\mu m/yr) = 0.159 + .000714\ O_3 \qquad (4\text{-}18)$$

where: Ozone is expressed in $\mu g/m^3$ (annual average)

In a comprehensive study done by Campbell et al. (1974) of the Sherwin Williams Company, panels painted with different exterior paints (automotive refinish, latex coating, coil coating, industrial maintenance and oil house paint) were exposed to air pollutants in an environmental chamber under accelerated weathering conditions. The panels were exposed to a low (0.1 ppm) and high (1.0 ppm) concentration of ozone and sulfur dioxide. After exposure the panels were examined with a scanning electron microscope and were assayed for total erosion, gloss, surface roughness, tensile strength, and infrared, attenuated total reflectance (IR-ATR). The panels were examined after 0, 400, 700 and 1000 hours of chamber exposure (considered as equivalent to 0, 200, 350 and 500 days of exposure).

The relative sensitivity of coating to pollutant damage depended on the particular test used to define it. For example, when tested for the IR-ATR, oil-based house paint exhibited the greatest change in properties while automotive paint exhibited the least change. On the other hand, the automotive paint exhibited the largest change in gloss while the oil house paint suffered no change.

If erosion is considered the most important form of damage studies, the chamber studies at Sherwin Williams indicated that SO_2 at concentrations of 2620 $\mu g/m^3$ (1.0 ppm) caused measurable effects. Exposures at 262 $\mu g/m^3$ (0.1 ppm) resulted in such variable degrees of damage that they were statistically equivalent to no effect, or at least within the experimental error range.

A comparison of both chamber studies indicates that not only are the predicted rates of damage at a given SO_2 concentration in the two studies completely different, but the predicted rate of damage in a "clean" SO_2 free atmosphere differs as well.

Haynie and Spence (1984) evaluated the exposure of white oil-based and latex-based paint samples from the material exposure portion of the St. Louis RAPS Program. These samples, mounted on a rack at 90° angles in both north and south facing postures, where removed after 3, 6, 12, 24, and 30 months of exposure and the film weight loss was analyzed. A multiple regression approach was taken to analyze the weight loss versus exposure variables. These independent variables included sun exposure, temperature, time of wetness, wind speed, total gaseous sulfur compounds, total gaseous NO_x and oxidants. From the results of the regression analyses, it was concluded the two white household paints exposed in the RAPS Program were eroded primarily by the effects of time of wetness, temperature, and sunlight. Of the gaseous pollutants, only nitrogen oxide appear to be primary causative agents in latex paint film loss. A possible effect of ozone on the latex paint was masked by the strong covariances between ozone, temperature, and nitrogen oxides.

4.2.4 Building Materials (Soiling)

Soiling is defined as the accumulation of particulate matter on the surface of a material exposed in the outdoor environment. An excellent review on the effects of particulate pollutants on materials has been done by Lodge, et al., (1981). Two types of material damage result from soiling. Particulate matter, under the proper conditions, can enhance surface damage through accelerated corrosion and erosion by serving as centers for the condensation of moisture or absorption of gaseous pollutants such as SO_2. The synergistic effects of such combinations have been reported in the literature. The second effect is aesthetic, that is, discoloration of the surface apart from any other enhanced damaging effects. In this case, soiling does not normally affect the structural functioning of the material. A soiled coat of paint will continue to protect the substrate, but soiling does detract from the amenity of the living and working environment.

The soiling of surfaces is a continuous function of time. Immediately after corrective action is taken, such as cleaning to restore a surface to its original appearance, soiling begins again.

In a study in Birmingham, Alabama, Beloin and Haynie (1975) exposed several materials (painted cedar siding, concrete block, zinc, limestone, asphalt shingle and window glass) at five sites. Total suspended particulate matter measured using high-volume samplers at these sites ranged from 60 $\mu g/m^3$ to 250 $\mu g/m^3$. Observed TSP values in the SCAB range from 52 to 156 $\mu g/m^3$. The degree of soiling was measured by reflectance and was found to be proportional to the square root of the dose for all substrates except for the white asphalt shingles where the reflectance was directly proportional. A linear regression of the data resulted in the following damage functions for acrylic emulsion paint:

$$\ln (92.5 - Y) = -0.311 + 0.345 \ln (TSP) + 0.612 \ln (t) \qquad (4\text{-}19)$$

where: Y is the percent reflectance
TSP is the average concentration of total suspended particulate matter
t is the time in months

For white asphalt shingles the damage function is:

$$\ln (41.8 - Y) = - 4.881 + 1.007 \ln (TSP) + 0.595 \ln(t) \qquad (4\text{-}20)$$

Although these damage functions pertain to specific effects on certain types of very susceptible materials, these damage functions can be more generally applied. Watson and Jaksch (1978) used these damage functions to calculate household cleaning costs due to soiling. McCarthy et al. (1981) used these functions to develop the potential benefits due to reduced soiling of building materials in the Boston area.

4.2.5 Elastomers

Damage to elastomers is caused primarily by ozone and other oxidants. Sulfur dioxide and nitrogen dioxide have been implicated by several researchers as causative factors in elastomeric degradation, as has sunlight (UV spectrum), but oxidant damage is typically the limiting factor in the use-life of the material.

Ozone can cause cracks in rubber under stress through attack on the chemical structure of the rubber. Automobile tires are the major rubber product in wide use outdoors and thus dominate the potential damage costs to this pollutant. Modern formulation of plasticizers and antiozonants reduces the susceptibility of tires to attack by ozone to a point where tread wear is usually the dominant factor in product lifetime. However, the recent development of the long-lasting radial steel-belted tires might reestablish the importance of ozone as a limiting factor on the lifetime of tires. Damage functions directly relating tire life to ozone concentration were derived by McCarthy et al. (1981) based on general information on rubber damage in the literature. The work of Edwards and Storey (1959) provides a framework for making an initial assessment of ozone concentrations and rubber. They determined the effects of ozone on certain elastomeric formulations used in tire sidewalls containing various amounts of antiozonants under 100 percent strain. The results show that increasing the amount of antiozonants produced significant reductions in the rate of cracking, with increasing amounts of ozone necessary to initiate visible cracks. An exponential relationship between the dose, expressed in ppm multiplied by exposure time in minutes, and the percentage of antiozonant, was found:

$$\text{Critical Dose (ppm min)} = ae^{bz} \qquad (4\text{-}21)$$

where: a and b are constants dependent on the elastomeric mix
z is the percentage of antiozonant

Haynie (1980) has suggested the following damage function to relate the rate of cracking (depth) with ozone concentration and antiozonant:

$$R = 75.3\ e^{-1.55x}\ [O_3] \qquad (4\text{-}22)$$

where: R is the rate of cracking (mm/yr)

x is the amount of antiozonant expressed as a percentage of tire weight

$[O_3]$ is the ozone concentration in parts per million, volume (ppm)

Substituting design worst case ozone concentrations of 0.05 ppm and the typical antiozonant concentrations used by tire manufacturers (about 1.5 percent), the formula predicts design lifetimes in good agreement with observations if the critical damage level for crack depth is assumed to be 5 mm. This yields lifetimes in excess of 13-1/2 years. Tread life for a good tire rarely exceeds 60,000 miles. If a car is driven only 5,000 miles per year, the tires' useful life will be limited by its tread wear, not ozone induced cracking.

4.2.6 Fabrics

Nitrogen dioxide and ozone are two pollutants which significantly affect the use-life of fabrics. Particulate matter is thought to affect deterioration of fabrics through abrasive actions but the controlling factor for particulate matter damage is usually soiling.

Nitrogen dioxide and ozone affect the use-life of fabrics, primarily through their influence on dye fading. Ozone, due to its high solubility in water, is thought to attack some fabrics, notably cotton. However, according to Bogarty, Campbell and Appel (1952), the effects of ozone on fabrics are minor compared to the effects of sunlight, heat, wetting and drying, and biological attack.

While the effects of nitrogen dioxides on fabric dyes was first noted prior to World War I, it wasn't until 1955 that Salvin and Walker (1955) showed that ambient levels of ozone were also capable of fading dyes. Ozone fading of dyes, which affects primarily the blue and red disperse dyes applied to nylon, is characterized by a bleached or washed out appearance rather than the reddening which is characteristic of the effects of NO_2. The ozone fading of sensitive dyes is accelerated by moisture. Studies performed in the last 10 years have indicated that long exposures of sensitive dyes to ambient levels of atmospheric ozone in the presence of relative humidities greater than 65 percent leads to accelerated fading.

Although many controlled exposure studies have been conducted to measure the effects of these two pollutants (O_3, NO_2) on dye fading, Haynie et al. (1976) appears to be the only researcher to develop and publish a damage function relating pollutant exposure to measurable damage. Based on a chamber study and resultant fading of a drapery fabric (manually employed indoors) exposed to NO_2 exposures of 262 $\mu g/m^3$ and 940 $\mu g/m^3$, Haynie developed the following:

$$\Delta E = 30\,(1 - e^{-(0.75 + 0.01\,M + 2.9 \times 10^{-5} \times NO_2 \times M)\,t}) \qquad (4\text{-}23)$$

where:
- ΔE = amount of fading (fading units)
- M = amount of moisture ($\mu g/m^3$)
- NO_2 = concentration of NO_2, ($\mu g/m^3$)
- t = exposure time (years)

According to the regression analysis used to develop this relationship, this function accounts for nearly 78 percent of the variability. Alternatively, Haynie has also used the data derived in the chamber study to develop an equation relating the NO_2 concentration to the percentage of life lost due to pollutant exposure:

$$\text{Percentage Life Lost} = \frac{2.9 \times 10^{-3} \times NO_2 \times M}{0.75 \times 0.01\ M + 2.9 \times 10^{-5} \times NO_2 \times M} \qquad (4\text{-}24)$$

4.2.7 Building Stone, Concrete, and Masonry

Apart from the aesthetic effects to building materials through soiling due to particulate matter, gaseous SO_2 and sulfates and nitrates dissolved in precipitation are involved in the deterioration of several types of stone, most notably marble and limestone. The natural weathering process, the effects of moisture, freezing and thawing, and impurities present in the materials themselves, tend to dominate the deterioration of the material.

For marble, the typical damage due to air pollution is manifested as sooty encrustations of gypsum in areas protected from rainfall (Yocom, 1979). The gypsum is the end product of the reaction of marble and gaseous SO_2. These encrustations slowly develop with time, obliterating details of the structure. For limestone, SO_2 reacts with the calcite present in the stone and the resulting product, gypsum, is readily washed away during precipitation events. This also results in the pronounced loss of surface detail, most noticeable on monuments and statuary. New information indicates that carbonaceous particles may also play an important role in deterioration of marble.

Few quantitive studies of air pollution damage to stone have been reported although the increased rate of erosion for marble tombstones in the urban environment of Edinburgh was observed as early as 1880 (Geike, 1880). A study of tombstomes in U.S. National Cemeteries (Baer and Berman, 1981) has developed a methodology for measuring damage to marble headstones exposed to the environment for 1 to 100 years. Their data base consists of measurements of some 3,900 stones in 21 cemeteries distributed throughout the United States. The factors affecting damage rates include grain size, total precipitation, and local air quality.

In the United States, measured rates of marble deterioration have generally been small, on the order of 2.0 mm per 100 years (Winkler 1982). This is substantially below values reported for stones exposed in urban areas in Europe although direct comparison is difficult because the stones exposed in Europe are generally more reactive.

Comparing the condition of similar samples of sandstone exposed in different areas of Germany for about 100 years, Luckat associated large differences in observed deterioration with trends in local air quality (Luckat, 1981; Schreiber, 1982). These results presented in Table 4-2 describe stones openly exposed to the environment. For similarly reactive stones protected from the direct action of rain and placed at 20 locations in West Germany, the following functions correlating reaction with SO_2 emission rate were obtained:

Baumberg sandstone $U = 0.54\ D;\ r^2 = 0.92.$ (4-25)

Krensheim shell limestone $U = 0.22\ D;\ r^2 = 0.72.$ (4-26)

When similar test samples were exposed to the rain the following damage functions were obtained:

Baumberg sandstone $L = 0.03\ D + 0.5;\ r^2 = 0.36.$ (4-27)

Krensheim shell limestone $L = 0.018\ D + 0.6;\ r^2 = 0.80.$ (4-28)

where:

U = SO_2 emission rate (uptake rate) of the stone in $(mg/m^{-2}d)\ \ d^{-1}$

D = SO_2 emission rate, IRMA measured valued $(mg/m^{-2}d)\ \ d^{-1}$

L = Loss in weight

r = Correlation coefficient

TABLE 4-2

DETERIORATION OF SCHLAITDORF SANDSTONE EXPOSED FOR 100 YEARS IN WEST GERMANY (AFTER SCHREIBER 1982)

Monument	Location	Relative SO_2 Emission Rate,* mg m^{-2}-day	Deterioration
Neuschwanstein Castle	Fussen	6	Practically none
Ulm Cathedral	Ulm	48	Moderate
Cologne Cathedral	Cologne	111	Very severe

*Relative emission or uptake rate of SO_2, annual average (August 1973 - July 1974).

A series of measurements made at St. Paul's Cathedral, London on the Portland stone (biosparite limestone) balustrade, demonstrate a high rate of weathering (Sharp, et al. 1982). Using lead plugs filled in 1718 in openings in the stone as base level references, a mean rate of lowering of 0.078 mm yr^{-1} was obtained for the period 1718-1980. The balustrade represent conditions of exposed rain flow. Similarly, by use of a micro-erosion meter (dial micrometer gauge mounted on reference studs) a current erosion rate of 0.139 mm/yr^{-1} was obtained for six sites on the cathedral. These sites represented drip erosion zones. Though the two sets of data are not strictly comparable, both represent substantially higher rate of loss than observed for marble in the United States.

Haynie (1982) conducted controlled chamber experiments to calculate the effects of SO_2 on cement and marble. For white Cherokee marble, a damage function relating erosion to pollutant concentrations was calculated:

$$E = -3.31 + 0.078 \times RH + 2.95 \times 10^{-3} \times SO_2 + 3.33 \times 10^{-3} \times O_3 \qquad (4\text{-}29)$$

where:
- E = erosion rate, μm/yr
- RH = relative humidity, %
- SO_2 = concentration of SO_2, $\mu g/m^3$
- O_3 = concentration of O_3, $\mu g/m^3$

The calculated erosion rates were very low. Using 80 percent RH, SO_2 levels of 80 $\mu g/m^3$, and ozone levels of 60 $\mu g/m^3$, the equation predicts that marble will erode only 1 mm in about 300 years. The pollutant effects on cement could not be determined due to effects of moisture and temperature on the weight of the samples.

Haynie has also analyzed the erosion of white Georgia marble exposed for 3 years in the St. Louis area as part of the EPA study performed by Mansfield (1980). He found that erosion of marble was strongly related to the time of wetness and developed a stoichiometric erosion rate for a marble surface taking into account the presumed effects of acid rain and sulfur oxides:

$$Em = Er + (17.6 + 5.34\ SO_2)f \qquad (4\text{-}30)$$

where: Em = marble erosion rate (µm/yr)

Er = erosion rate from rain, defined as 171 x R x exp(-2.3 pH)

where: R = annual rainfall (cm)
pH = pH of rain

SO_2 = flux of sulfur oxides ($mg/cm^2/yr$)

f = fraction of time when wet

These damage functions relate sulfur oxides and moisture to SO_2 but do not address the more pronounced and potentially more serious effect of encrustation.

4.3 Uncertainties with the Physical Damage Function Approach

Most material damage functions currently available in the literature are based on two different methods of study: outdoor field tests and laboratory chamber tests. Field tests of materials are inherently representative of actual exposure. However, they are compromised by the fact that most types of damage are the result of a number of factors. Damage can be caused by unreported pollutants, moisture, CO_2, natural particulate matter, sunlight, and other features of the test environment. Determining the isolated influence of a single pollutant or class of pollutants in an ambient exposure study is not a simple matter and spurious correlations can easily lead to erroneous conclusions.

Chamber studies, where individual pollutants are introduced to sensitive materials independent of other influences, have tended to be conducted at unrealistically high concentrations or otherwise are not representative of actual exposure situations. These types of studies are typically designed to demonstrate cause and effect relationships in a reasonable period of time, not to mirror real-world conditions. Attempts to extrapolate these results to ambient concentrations can produce damage estimates of questionable value.

A major source of uncertainty in the application of damage functions is associated with the variations in types of materials or exposures tested compared with those used or experienced in real-world applications. That is, seemingly minor variations in surface treatments, in the composition of alloys or mixtures used for determining corrosion damage functions, or in the manner in which the sample is prepared for damage assessment can have a profound effect upon the nature and extent of air pollution-induced damage to materials indicated by the tests. General functions based on such data may not apply to the specific situation being assessed.

In addition, there is uncertainty in the use of material damage functions because of disagreements in the literature on the form of the functions themselves. If separate studies yield results which are significantly different yet nothing disqualifies one of them on technical grounds, the potential user is uncertain as to which author's function to apply. A user may have a preference for one function or another, but it is often difficult to show that it is clearly superior on completely objective grounds.

One can summarize as follows the applicability and reliability of damage functions:

- The damage functions for steel and zinc damage by gaseous pollutants are well developed and documented.

- The present damage functions for paint are not adequate to characterize damage definitively. Peeling and cracking as well as erosion of the painted surface are the primary forms of damage that are experienced in the real-world. These types of damage are not adequately treated in existing calculations. The equations typically lack climatic data such as heat, cold, sunlight, wind and temperature which have an impact on the use life of a painted surface. In addition, the damage functions do not address many of the new types of coatings currently available in the marketplace.

- For the effects of gaseous and particulate acidic pollutants on building stone (marble, limestone) and concrete, available material damage functions are of limited usefulness either because they do not address the full range of variations in materials or because they are based on data of questionable applicability to conditions in places other than where they were derived.

- The current damage function for the impact of ozone on rubber appears to fit the existing data well.

- Available damage functions for soiling by TSP do not address the effects of soiling on the range of colored materials of interest and do not account for the range of self-cleansing mechanisms (e.g., rain) that operate in real environments. However, as with damage to paints, the existing soiling functions can be used to provide approximate estimates.

For other demonstrative effects of pollutants on materials such as NO_2 and dye fading, ozone and dye fading, and ozone and fabric deterioration, available material damage functions are of limited usefulness either because they do not address the full range of variations in materials or because they are based on data of questionable applicability to conditions in the South Coast Air Basin.

4.4 Acid Deposition and Material Damage

Acid precipitation, sulfate deposition, and acid fog represent relatively "new pollutants" for material damage. There is only one published damage function relating these parameters to material erosion or corrosion. The low volume and intermittent nature of such damage agents make it difficult to apply engineering studies of materials response to acid solutions directly to ambient atmospheric conditions.

Yocom and Baer (1983) have reviewed the state of knowledge about the effects of acid deposition on materials and cultural resources. Haagenrud, Kucera, and Gullman (1982) reported on the results of a chamber study where carbon steel and zinc specimens were exposed to simulated precipitation pH values of 5.7, 4.2, 3.4, 3.2 and 2.7. Over the course of a chamber study of a few week's duration which featured six simulated rain periods (2.5 hours at 2 mm/hr) each week followed by intervening dry periods (10°C, 50% RH), weight loss was monitored. For the carbon steel samples, there was no effect, defined as no increase in the corrosion rate, with decreasing pH in the range 5.7 to 4.2. Below 4.2 at pH values of 3.2 and 3.4, the corrosion rate rose sharply. At a pH of 2.7, the corrosion rate increased to a value 7 times higher than at a pH of 5.7 or 4.2.

For zinc, the corrosion rate for pH exposure values of 3.2, 3.7, 4.2, and 5.7 were essentially equivalent. Corrosion rates for the zinc, calculated using the weight loss method, were four times greater at a pH of 2.7 than a pH of 3.2.

Harker et al (1982) conducted a dynamic chamber study of the effects of SO_2 and H_2SO_4 (aerosol) pollutant induced corrosion of zinc. The results of the study indicated the principal factors affecting sulfur pollutant-induced corrosion to be surface wetness, pollutant flux to the surface of the material, and the chemical form of the pollutant.

Harker found that with typical urban ambient pollution levels for SO_2 and H_2SO_4 (27 $\mu g/m^3$ and 15 $\mu g/m^3$), SO_2 deposition was 30 times greater than the deposition of H_2SO_4 aerosol. In addition, it was found that SO_2 induced corrosion of zinc proceeds at a rate approximately a factor of two greater than that for the equivalent amount of deposited sulfuric acid aerosol.

The work of Ateraas and Haagenrud (1982) on corrosion of metals in Norway represents an attempt to propose a damage function to differentiate between the effects of gaseous SO_2 and acidic deposition. However, it is uncertain if the results can be applied directly to an analysis of damage elsewhere. In the U.S., the Acid Deposition Task Force as part of the National Acid Rain Assessment Program is currently conducting outdoor exposure tests for a wide variety of materials but the results are not yet available.

4.5 The Application of Damage Functions Applied to Economic Estimates

A summary of the known air pollution damage to materials, various causative agents, and the recommended damage functions for assessing the damage are presented in Table 4-3.

In all cases except for the metals only one material damage function exists. For zinc and steel, a number of damage functions exists for specific material types, such as zinc, carbon steel, and weathering steel.

For zinc, Haynie's 1982 damage function is selected because it incorporates moisture variables, SO_2 concentration, and a pollutant deposition term keyed to the type of material application. Conceptually, this approach is superior to those incorporating only pollution concentration and moisture.

For other types of steel, the damage functions of Haynie and Uphan (1970a) are selected. This selection is based on TRC's prior use of these functions in a previous study for EPA.

For building stone, the only damage function available is for pollutant effects (SO_2) on marble. At the present time, damage functions do not exist for limestone, concrete, masonry, or brick.

The evaluation of painted surfaces and subsequent economic analysis of damage presents a special problem. Paint is widely distributed and commonly used. The effects of the ambient environment on paint is a strong function of the paint formulation and application (i.e., surface preparation and thickness). The formulations vary from residentially used latex and oil based types to aluminum and vinyl top coat systems used in the commercial/industrial sector to the lead-silico chromate-linseed oil alkyds, vinyl-lead silico chromate, and inorganic zinc rich systems for highway and transportation systems. As part of the survey in SCAB, paint retailers, industrial/ commercial maintenance groups and public works departments were contacted to

TABLE 4-3

AIR POLLUTION DAMAGE TO MATERIALS
AND APPROPRIATE DAMAGE FUNCTIONS

Materials	Type of Impact	Principal Air Pollutants	Other Environmental Factors	Recommended Damage Function	Comments
Metals	Corrosion, tarnishing	Sulfur oxides and other acid gases	Moisture, air, salt, particulate matter	Carbon Steel: $y = 9.013\ e^{0.00161\ SO_2}\ (4.768t)^{(0.7512\ -\ 0.00528\ OX)}$ Copper Steel: $y = 8.341\ e^{(0.00171 SO_2)}(4.351t)^{(0.8151\ -\ 0.00642\ OX)}$ Weathering Steel: $y = 8.876\ e^{0.0045 SO_2}\ (3.389t)^{(0.6695-0.00544\ OX)}$ Galvanized Steel: $y = (A + B\ SO_2)t$	Other metals such as copper and aluminium are not significantly affected by air pollutants. Bare steel is rarely exposed to environmental conditions (except weathering steel). Steel will be protected by paint.
Building Stone	Surface erosion, soiling, black crust formation	Sulfur oxides and other acid gases	Mechanical erosion, particulate matter, moisture, temperature fluctuations, salt, vibration, CO_2, microorganisms	Marble: $Em = Er + (17.6 + 5.34 SO_2)f$	Limestone is greatly affected by acidic pol-lutants, however, no damage function exists Cement, masonry, andother stone are unaffected.
Ceramics and Glass	Surface erosion, surface crust formation	Acid gases, especially fluoride-containing	Moisture	None	Damage to glass and ceramics is not considered important. Soiling may be a problem.
Paints and Organic Coatings	Surface erosion, discoloration, soiling	Sulfur oxides, hydrogen sulfide	Moisture, sunlight, ozone, particulate matter, mechanical erosion, microorganisms	Oil: $E = 14.3 + 0.0151\ (SO_2) + 0.388RH$ Vinyl: $E = 2.51 + 1.60 \times 10^{-5} \times RH \times SO_2$ Latex-Acrylic: $E = 0.159 + 0.000714 O_3$ Soiling on wood: $\ln(92.5 - Y) = -0.311 + 0.345 \ln(TSP) + 0.612 \ln(t)$ Soiling on stucco: $\ln(41.8 - Y) = -4.881 + 1.007 \ln(TSP) + 0.595 \ln(t)$	Damage functions do not include primary erosion factors (sunlight time of wetness, & temperature). Soiling may be a problem.
Paper	Embrittlement, discoloration	Sulfur oxides	Moisture, physical wear, acidic materials introduced in manufacture	None	Not considered important due to exposure at typical ambient levels. An indoor air pollution problem.

TABLE 4-3
(Continued)
AIR POLLUTION DAMAGE TO MATERIALS
AND APPROPRIATE DAMAGE FUNCTIONS

Materials	Type of Impact	Principal Air Pollutants	Other Environmental Factors	Recommended Damage Function	Comments
Photographic Materials	Microblemishes	Sulfur oxides	Particulate matter, moisture	None	Not considered important due to exposure at typical ambient levels. An indoor air pollution problem.
Textiles	Reduced tensile strength, soiling	Sulfur and nitrogen oxides	Particulate matter, moisture, light, physical wear, washing	None	Textiles have limited outdoor exposure. Sunlight and temperature are key causative decay factors.
Textile Dyes	Fading, color change	Nitrogen oxides	Ozone, light temperature	$\% \text{ Life Lost} = \dfrac{2.0 \times 10^{-31} \times NO_2 \times M}{0.75 \times 0.01M + 2.9 \times 10^{-5} \times NO_2 \times M}$	Dye fading due primarily to NO_2, moisture and sunlight. May no longer be an important damage mechanism.
Leather	Weakening, powdered surface	Sulfur oxides	Physical wear, residual acids introduced in manufacture	None	As with paper, not considered important. An indoor air pollution problem.
Rubber	Cracking		Ozone, sunlight, physical wear	$R = 75.3e^{-1.55X}(O_3)$	Damage model provides a good general fit considering the variety of batch ingredients and antiozonants used.

obtain information on paint sales, routine maintenance practices, and frequency of painting in various areas of SCAB. For the purposes of the economic estimates latex paints were assumed to erode in the same way as latex-acrylic paints, and the damage to all paint systems on metal substrates in the commercial sector was assumed to be represented by the vinyl coating system equation. Both of these systems are relatively pollutant resistant compared to paints in wide use at the time of the original damage studies. Recent paint formulations are likely to also be more damage resistant, and, therefore may be well represented by the choice of these two paint systems. Alternatively, if most paint systems are not as resistant as latex-acrylic and vinyl coil coatings, then the damage calculations may under-estimate the total pollutant induced damage.

Soiling of painted surfaces is another form of damage, however, it is not an additive impact to paint erosion. In fact, as the paint surface erodes, it sloughs off a portion of the soiling layer together with the paint surface. Damage functions explicitly combining these two effects are not available, however, damage functions for soiling alone are available. Two soiling damage functions are selected for use in estimating the damage. For painted wood, Haynie's damage function for soiling of acrylic emulsion paint is used. For painted stucco, with its rougher surface and lower initial reflectivity, the damage function for soiling of white asphalt shingles is used as an approximation.

For elastomers, only one material damage function is available to assess the effects of ozone. For ceramics and glass a damage function does exist to quantify the effects of particulate soiling on exposed surfaces.

5.0 COSTS OF AIR POLLUTION DAMAGE

5.1 Cost Estimate Basis

Several pieces of information are needed to estimate the incurred costs of air pollution damage to materials. The necessary information includes:

- the distribution and exposure of materials;
- the ambient pollutant levels to which the materials are exposed;
- the rate at which damage is incurred as a function of pollutant levels;
- the amount of damage that triggers remedial actions, or alternatively the actual frequency of maintenance in polluted atmosphere;
- the costs of remedial or preventative actions; and
- if remedial action is not possible, an estimate of the value associated with the loss.

The distribution of materials in the SCAB is discussed at length in Section 3. The pollutant levels in the basin are available from the California Air Quality Data Summaries, and have been included on the projects' data base as described in Section 2.2. Table 5-1 gives the pollutant concentration data used in deriving the damage estimates. Only those stations reporting two or more years of data for each pollutant were included in the data base and the concentrations used are averages of the reported annual average concentrations. Both the materials distributions and pollutant data are based on field measurements in the SCAB. Estimates of their reliability can be defined, and, because they have been measured in the SCAB, the data are representative of conditions in the SCAB. The remaining information categories required to compile cost estimates for materials damage are based on data of unknown representativeness. This section describes the remaining information categories and presents estimates of the damage costs for different classes of materials.

TABLE 5-1

POLLUTANT CONCENTRATION LEVELS USED FOR CALCULATION OF MATERIALS DAMAGE

The Three-Year Average of the Reported Annual
Average Pollutant Concentrations (1978-81)

Station Name	SO_2 (ppm)	O_3 (ppm)	TSP ($\mu g/m^3$)
L.A. Downtown	.008	.034	93.3
Azusa	.005	.041	156.3
Burbank	.008	.033	-
North Long Beach	.012	.014	101.4
Resida	.005	.038	109.0
Pomona	.007	.035	-
Lennox	.009	.026	87.4
Whittier	.009	.026	-
Newhall	.008	.043	-
Pasadena-Walnut	.009	.042	83.1
Lynwood	.010	.013	108.3
Pico Rivera	.006	.034	114.6
West L.A.-Robertson	.007	.058	83.5
Mt. Lee	.007	.058	83.5
Long Beach	.032	-	71.8
Mt. Wilson	-	.063	-
Dominguez-Cal. St.	.014	-	82.3
Harbor City	.017	-	82.0
Anaheim	.006	.019	88.8
La Habra	.007	.021	100.6
Costa Mesa Harbor	.004	.015	58.5
Santa Ana Police Sta.	-	-	82.5
El Toro	-	.025	75.1
Los Alamitos-Orange	.007	.023	92.7
Santa Ana-Weir Canyon Rd.	.003	.018	80.9
Norco Prado	-	.030	-
Riverside-Rubidoux	.006	.039	146.9
Riverside-Magnolia	.004	.030	111.3
Perris	-	.038	-
San Bernandino	.005	.041	103.5
Redlands	-	.026	63.0
Rialto Airport	.005	-	88.7
Ontario Airport	-	-	143.1
Upland Civic Center	-	-	97.5
Upland - ARB	.007	.037	-
Fontana-Foothill	.007	.048	113.4
Lake Gregory	-	.055	52.4
Yucaipa	-	.047	-
Upland-Post Office	-	-	101.6
Redlands-Univ. of Grove	-	.041	99.9
Fontana	.007	-	-
L.A.-North Main	.009	.024	118.4
Glendora-Laurel	.004	.042	98.3
Costa Mesa-Placentia	.004	.021	83.1
Riverside-UCR WTHR	-	.040	-

The rate at which damage is incurred is calculated from the materials damage functions discussed in Section 4. Damage functions are available for a limited number of materials which include:

- Bare steel
- Galvanized steel or iron
- Paints, erosion and soiling
- Marble
- Textile dyes
- Rubber

The application of some of these functions, however, is moot. Steel is nearly universally coated in some manner to prevent corrosion. Therefore, the use of damage functions for bare carbon steel or copper steel is not appropriate because the actual surface exposed to pollutants is normally painted. There are two notable exceptions where bare steel is exposed. The first is for railroad track. Railroad track is generally uncoated steel and is directly exposed to pollutant induced damage. The useful life of track, however, is limited by wear and stress from railway traffic use, and not by air pollution induced damage. Therefore, although it is possible to calculate pollutant damage to railroad tracks, it is inappropriate to assume that this damage leads to an economic disbenefit. The second exception to steel being coated is the use of "weathering steels". Weathering steel is formulated to rapidly produce a surface corrosion layer that offers significant protection from subsequent corrosion. Weathering steel has been used primarily for highway applications and as structural supports. Unfortunately, metal stains caused by rain water run-off from weathering steel surfaces have been an aesthetic problem, and continued use of weathering steel has not been widespread. While some weathering steel undoubtedly exists in SCAB, no examples were found by the field survey or the telephone survey. For this reason, no economic estimates are made for corrosion of weathering steel.

Elastomers are used primarily for automobile tires and for waterproofing. The inclusion of antiozonants in rubber formulations, discussed in Section 4.2.5, has effectively eliminated pollutant induced damage as a use-life limiting factor for tires. The cost of antiozonant compounds as a portion of the total product cost at the retail level has been indicated to be vanishingly small by tire distributors and manufacturers. The use-life of a tire, if calculated from ozone induced sidewall cracking, would be at least eleven years in the SCAB. Average treadlife of a tire is estimated to be 40,000 miles (based on distributor information) and, assuming that the vast majority of cars are driven more than 3,600 miles per year, the tire use-life will be determined by tread wear, not sidewall cracking. The primary construction use of elastomers is as waterproofing (normally for roofs) applied either as sheeting or trowelled in place. The most common types of waterproofing materials are polyvinyl chloride, polyethylene, neoprene, or tar extended polyurethane, all of which are very ozone resistant.

The sole use of marble found in the basin was for tombstones. The vast majority of cemetery markers in the basin are bronze or granite, however, in at least the small, older cemeteries a small percentage of the stones are marble. Approximately 750,000 markers are in place in the cemeteries contacted during the telephone survey. An estimated 500 of these markers (about 0.07 percent) are marble. Approximately half that number were cleaned periodically with a cleaning/fungicide solution. Assuming one man-year per year is expended basin-wide cleaning marble tombstones, a total estimated cleaning costs would be less than $50,000/year. Some fraction of this cost would be due to air pollution induced damage, the rest to fungus growth and soiling caused by lawn mowing, etc. These costs are minimal, and a more rigorous investigation of marble damage is not warranted with the current data set.

For galvanized steel, paint, textiles and soiling induced damage, the damage functions can be used to estimate either the rate at which pollutant induced damage occurs, or the portion of damage resulting from pollutant induced degradation. The damage functions, as discussed in Section 4, are from various studies, and represent different exposure modes and climatological conditions. Stankunas, et al. compared calculated repainting costs for SO_2 induced damage in metropolitan Boston based on two different damage functions. The estimated costs were \$31.6M and \$0.83M (a factor of 38 difference) depending upon the damage functions used. Although their example may be somewhat extreme, it does provide a quantitative illustration of the dependence of the final economic estimates on the selection of the damage functions.

Another crucial factor in determining the economic impact of pollutant induced damage is the frequency of maintenance. Critical damage levels are defined as the amount of damage that must be incurred for maintenance or repair activities to be triggered. For example, galvanized fencing has a zinc coating thickness of about 25μm. Because the zinc electrochemically protects the substrate steel, all 25μm of zinc must be removed before the steel begins to rust. Therefore, the critical damage level for galvanized steel is the removal of 25μm of zinc. The period required for this amount of zinc erosion to occur can be calculated from the galvanized steel damage functions, and thus the maintenance frequency can be estimated for various pollutant levels.

The critical damage level approach must be applied with caution, however. The "rule of thumb" for paint is that, when ninety percent of the thickness of paint has been eroded, repainting is performed. If the thickness of a typical residential paint system is assumed to be about 60μm (Haynie, et al., 1976) and the time to erode 54μm of paint is calculated using the damage function for oil based paint selected in Section 4, repaint frequencies on the order to two years are predicted for the basin. Clearly, this is not reasonable based upon common experience. The telephone survey results indicate that routine repainting frequencies in the basin are on the order of seven years for residential exteriors. The reason for this apparent gross discrepancy is not clear. However it is known that the paint damage functions were developed based upon chamber studies conducted at relatively high pollutant levels. The applicability of chamber studies, using unrealistically high pollutant levels, to real world exposure has always been somewhat questionable. In light of these difficulties, another approach is required. Since typical repaint frequencies are available from the telephone survey of paint distributors and painting contractors, it is possible to calculate the total costs for repainting in the basin, and then assign a portion of that cost to pollutant induced damage based on the damage function. This approach has been used for the economic estimates of paint damage.

Once the total area of each material type is known, and the frequency and portion maintenance activities assignable to air pollution damage are estimated, the final piece of information needed to make monetary estimates are the costs of maintenance on a square foot of materials basis. Costs for this project are estimated based on a maintenance strategy, rather than a replacement or neglect strategy. For example, once a galvanized fence has deteriorated to the point where it begins to show rust (i.e., the critical damage level has been reached), it is assumed that the fence is painted. The alternatives would be to either replace the fence (more expensive), or to allow the fence to continue to deteriorate (less expensive). Estimates of maintenance costs for this project are based on the Repair and Remodeling Cost Data, Commercial/Residential (R.S. Means Co., Inc., 1983). The Means Company provides cost estimating data for contractors and others interested in construction costs. Maintenance costs estimates from the Means Company have been adjusted to be 1979 dollars, based upon construction cost indices, and have been adjusted to reflect labor and material costs in the basin by applying the city cost indices for finishing work in Los Angeles. The values used in the current studies are shown in Table 5-2.

5.2 Costs of Pollutant Induced Damage and Soiling on Painted Surfaces

The largest quantity of exposed material in the South Coast Air Basin is paint on either stucco or wood and constitutes sixty-one percent of the total exposed material. The functions for paint erosion were described in Section 4.2.3 in equations 4-16 through 4-18 where the independent parameters include SO_2 and O_3 concentration, available from air quality monitoring stations, and relative humidity. The annual average relative humidity only ranges from about 60 to 70 percent across the basin (Keith, 1981). Countywide averages of relative humidity were developed as:

Los Angeles County	67%
Orange County	70%
Riverside County	60%
San Bernadino County	60%

These average relative humidities were used to calculate time of wetness based on equation 4-15.

The telephone survey indicated that the average exterior repainting interval in the basin for residential homes is approximately seven years.

TABLE 5-2

ESTIMATED COSTS OF MAINTENANCE PER SQUARE FOOT OF EXPOSED MATERIAL (R.S. Means Co., 1983)

Item	1983 Cost	1979 Adjustment
Painting Stucco (Primer +1 Coat)	.56	.467
Painting Metal Building (Remove existing paint, primer +2 coats)	4.03	3.365
Chain Link Fence (Paint both sides)	.92	.768

1979 cost = 1983 cost x I x C

where I = .743, Nationwide Construction Cost Inflation Factor
C = 1.124, Los Angeles Labor and Materials adjustment factor for finishing work.

Further, the survey found that paint sales for exterior residential use are divided about eighty percent for latex and twenty percent for oil based paints. The total cost for repainting due to pollution, T, is given by:

$$T = PC_AA \qquad (5-1)$$

where P is the ratio of the predicted erosion rate due to pollutant concentrations to the total erosion rate (based on equations 4-16 and 4-18), A is the painted area, and C_A is the annualized cost for repainting (i.e. the total repainting costs from the Mean's Co. cost data divided by the repainting interval). The annualized wall painting cost is about $0.067 per square foot. P, the ratio of the predicted pollution induced erosion rate to the total erosion rate, is calculated on a tract by tract basis. The lowest observed three-year average pollutant concentration levels (see Table 5-1) are used as background pollutant levels for this calculation. The background level for SO_2 is taken as .003 ppm; and the background level for O_3 is taken as .013 ppm. Equations 4-16 and 4-18 are then solved for pollutant induced damage using the anthropenqenically induced pollutant levels (assumed to be the three-year average pollutant level interpolated for each tract minus the background pollutant level) and setting the non-pollutant concentration containing terms in these equations equal to zero. These results are then divided by the total predicted damage using all terms in 4-16 and 4-18 equations and using the interpolated tract pollutant concentrations. This yields the proportion of damage due to anthropenquenically produced pollution, P. Both total cost estimates and the costs per housing unit based on solving equation 5-1 across the entire basin are shown in Table 5-3. Note that high ozone levels combine with high usage to make latex paint damage substantially more significant than damages to oil based paints.

TABLE 5-3

YEARLY COSTS (1979 DOLLARS) FOR AIR POLLUTION INDUCED DAMAGE TO PAINTS FOR RESIDENTIAL STRUCTURES IN THE SCAB

Paint Type	Total Cost (Million $)	Cost/Residential Unit (Single Family & Multi-Unit Dwellings)
Latex	38.2	13.40
Oil	2.2	0.75
Total	40.4	14.15

For all exposed steel, and iron or metal clad buildings in the commercial and public sectors, (excluding galvanized steel) it was assumed that vinyl top coat systems were used to protect the substrate. Equation 4-17 was used to develop damage estimates for the commercial sector. The telephone survey results indicated that the repainting interval ranged from four to more than twenty years for commercially exposed steel. The very short intervals seem to be for corporate signs, or other special uses where aesthetics are especially critical. The repaint interval selected for the economic analysis is fifteen years, and appears to be reasonable for most uses. For commercial structures, it was assumed that existing paint is removed, and a primer and two coat system is applied. Based on Mean's data, this process acts about $3.36 per square foot on an annualized cost of $0.24 per square foot to maintain commercial sector painted metal surfaces. Multiplying the figure by the portion of damage due to sulfur dioxide and the total exposed painted metal in the commercial sector yields a cost of $45,000 per year attributable to sulfur dioxide for maintaining these structures. The relatively low cost is because vinyl top coat systems are quite resistant to pollutant induced damage, and the total area at risk is far less than painted areas for residential structures.

The amount of soiling is computed from equations 4-19 and 4-20 to predict changes in reflectance. While many socio-economic factors control the ability and motivation to maintain clean surfaces, estimates of repainting costs have been made assuming reflectance of the surface is a criterion a houseowner uses to repaint.

In order to estimate the total cost of soiling damage to painted surfaces, a repainting interval of seven years was used, consistent with the previous analysis. Equation 4-19 is applied to painted wood surfaces (high initial reflectivity) and 4-20 is applied to painted stucco and brick (moderate initial reflectivity). TSP concentrations in the basin range from 52 to 156 $\mu g/m^3$ from Lake Gregory to Azusa, respectively. If 52 $\mu g/m^3$ is assumed to be the naturally occuring background particle loading, then levels above 52 $\mu g/m^3$ are taken to be anthropogenically induced loading, i.e., pollution. On a tract by tract basis, using the interpolated TSP levels for each tract, the portion of soiling over and above the background soiling can then be calculated. The total cost of soiling can then be evaluated is:

$$T = SC_A\ A \tag{5-2}$$

where S is the proportion of soiling predicted over and above the background induced soiling; C_A is the annualized reprinting cost per square foot based on the means data and the seven year repaint interval, and A is the area of painted material. The above equation is evaluated twice for each tract, once for painted wood and once for painted stucco and brick. The annualized cost of soiling is thus computed to be about $44 million, or comparable to the cost estimated for paint erosion damage.

There is no damage function that combines the effects of both soiling and the erosion of paint by pollutant gases. One would expect that damage from SO_2 and other acidic components that erode the paint's surface would tend to inhibit the build up of particulate matter that would decrease reflectance. Thus, the effects of soiling and erosion are not additive. However, one must remember that the soiling damage function was based on exposure of various materials in the area around Birmingham, Alabama in the early 1970's (Beloin and Haynie, 1975). Thus, the resulting soiling of material surfaces (decrease in reflectance) represented the integrated effect of particulate matter, SO_2 and other pollutants, and other environmental factors characteristic of that area at that time. If the presence of SO_2 caused some erosion of the soiled surface, this effect would be included as part of the damage function.

TABLE 5-4

RESIDENTIAL SURFACE AREA ($ft^2 \times 10^6$) FOR PAINTED STUCCO AND PAINTED WOOD

Pollutant Concentration	Painted Stucco	Painted Wood
NO_2 (PPM)		
.025 - .05	24.6	16.8
.05 - .075	31.2	20.3
.075 - .100	1798.5	886.8
.100 - .125	34.2	23.4
.125 - .150	293.7	176.2
NO_3 ($\mu g/m^3$)		
6 - 8.25	42.21	28.8
8.25 - 10.5	1846.50	918.6
10.5 - 12.75	293.58	176.4
O_3 (PPM)		
.013 - .023	114.6	76.3
.023 - .033	348.1	212.2
.033 - .043	1719.6	835.1
SO_2 (PPM)		
.003 - .006	1799.8	885.8
.006 - .009	375.8	232.8
.009 - .120	4.9	3.8
.120 - .150	1.7	1.2
SO_4 ($\mu g/m^3$)		
8.5 - 11	60.4	40.1
11 - 13.5	2120.2	1082.5
13.5 - 16	1.7	1.2
TSP ($\mu g/m^3$)		
52 - 73	74.3	51.0
73 - 94	369.2	224.2
94 - 115	1738.8	848.5

TABLE 5-5

DISTRIBUTION OF PAINTED STUCCO AND PAINTED WOOD BY COUNTY ($ft^2 \times 10^8$)

County	Stucco	Wood
Los Angeles	16.81	8.17
Orange	3.36	2.12
Riverside	0.72	0.61
San Bernadino	0.92	0.50

However, the relative importance of any such effect may not be characteristic of conditions in the SCAB. Large variations in predicted damage rates and economic impacts can arise as a result of selecting different materials damage functions.

Currently, CARB is sponsoring research to develop materials damage functions specific to California's environment. In order to facilitate recalculation of the damage estimates presented here, the amounts of residential painted surface exposed at different pollutant levels have been summarized. The results are seen in Table 5-4. The table shows that the majority of the painted material as exposed to high ozone and TSP concentrations and low sulfur dioxide levels. The distribution of stucco and wood by county is shown in Table 5-5 and can be used to develop gross estimates of damage if desired.

Commercial structures that are painted stucco or wood are assumed to have the same repaint frequency as residential structures. For the SCAB, the repaint cost estimates based on residential structures can be increased by about 2 to 3 percent for stucco and by 3 percent for painted wood to include the quantities from commercial structures.

In summary, the damage to paint in all sectors is estimated to be about $43 million per year as the result of the presence of ozone, and sulfur dioxide. Estimates of repainting due to soiling are about $44 million per year. These numbers are not additive. Using the larger figure and estimating the population in the basin as eleven million people, the cost can also be represented as approximately $4 per capita per year.

5.3 Costs of Pollutant Induced Damages to Galvanized Surfaces

There are approximately 2.00×10^8 square feet of galvanized fencing, mostly as chain link fence in highway and residential uses, in the SCAB.

Approximately one half this amount is along highways and has been estimated from the telephone survey results, the remaining area is residential and commercial usage. The telephone survey did not determine the geographical distribution of highway fencing, and for this reason, the distribution has been treated as uniform across the basin. In reality more galvanized fence may be used in densely populated areas, which also have higher sulfur dioxide levels. Thus the estimates of costs for damage to fences may be underestimated. An average sulfur dioxide level for the basin for the period 1978-1981 was 0.008 (about 21 $\mu g/m^3$) ppm and an average relative humidity of 65 percent (resulting in a time of wetness equal to about .31 years/year based on equation 4-15) were used for these calculations. The predicted erosion rate of galvanized coatings exposed at the background SO_2 concentration of .003 ppm is estimated as 0.85 μm/year, and in the actual environment as 1.04 μm/yr based on equation 4-14. If the thickness of galvanized coating of fencing is assumed to be 25 μm, then expected maintenance intervals are 29.4 years and 24.1 years at background SO_2 levels and in the actual environments, respectively. If painting both sides of the fence is the selected maintenance procedure, the costs are $0.77 square foot based on the Means costs data. Thus, on an annualized basis the costs are about $.032 per square foot ($0.77/24.1 years) for a total annual maintenance cost of $6,400,000. If 0.18 of the total damage to galvanized fencing [(1.04μm/yr - 0.85μm/yr)/1.04μm/yr] is induced by SO_2. Then the estimated annual cost of SO_2 damage to galvanized fences is approximately $1,169,000. It must be recognized, however, that not all galvanized fences have been in place for 24 years in the basin, and that these predicted maintenance costs have not actually been expended, although the damage has presumably been incurred.

Similarly, costs can be predicted for SO_2 induced damage to large galvanized surfaces, e.g. guard rails, electrical transmission towers, and roofing. There are about 0.64 x 10^8 square feet of these materials exposed in the basin. Predicted erosion rates for large surfaces are 0.79 µm/yr and 0.89 µm/yr in a background concentration level SO_2 environment and in the actual environment, respectively. Thus about 11 percent of the damage to these surfaces can be attributed to SO_2. If the original coating thickness is assumed to be equal to the ASTM standard for electric transmission lines, 88 µm, then the predicted maintenance interval is 99 years. This is a very long maintenance interval, and it may be reasonable to assume that the use-life of this type of galvanized is determined by economic factors (e.g., replacement due to new construction) rather than by surface erosion. Assuming maintenance involves removing rust, priming and two coats of paint ($3.36 per square foot) for the surfaces, the annualized maintenance cost is about $0.034 per square foot. This yields a total, annual SO_2 induced damage cost for large galvanized surfaces of $240,000. These expenditures will not have been made because the critical damage level will not have been reached (i.e., no galvanized steel has been in place for 99 years), however the damage has presumably been incurred.

5.4 Other Damage Costs

The painted surfaces represent about approximately 61 percent of the total exposed building material in the SCAB. Windows constitute an additional 20 percent. The remaining materials of significance are brick (5%), concrete or reinforced concrete (10%). Damage functions applicable to these materials are not available. However, the major damage to these materials appears to be soiling. In the case of glass, routine maintenance is generally undertaken by either the individual homeowner or by the owners of the commercial buildings.

The other materials are not normally cleaned on a routine basis. No damage function for window cleaning is available. Based on census data, there were 31 firms with 219 employees and a payroll of $1.1 million that clean windows in the SCAB. The total revenues (payroll, overhead, profit, etc.) would be higher. However, a portion of the soiling is also due to natural sources.

Soiling an automobile can be attributed to natural, airborne soiling, and transportation related soiling. In the SCAB, these are 297 car washes with 4,260 employees and an annual payroll of $28.3 million. Again, total revenues would be higher. In addition, a large number of automobile owners will wash their own cars.

The outdoor exposure of permanently placed fabrics is quite limited in the basin. Awnings tend to be painted metal, rather than cloth, and only one example of outdoor exposure of cloth was reported. Obviously, soiling of clothes occur. No estimate was made of these costs due to the lack of previous studies and to the large number of reasons that would require clothes to be cleaned. For this reason, no estimates of damage to fabric has been made, although it is probably safe to assume that the overall cost impacts are low.

Likewise, no examples of outdoor art work were found in the field survey. Telephone conversations with the Getty Museum indicated that they have a few, minor pieces exposed outdoors. In ongoing work for the National Park Service, as part of the National and Deposition Program, TRC has found that the average cost to clean a bronze statue is approximately $5,500, and that this typically occurs no more than every five years (or, for many pieces, never at all). If an annual cost of $1,100 per statue per year is assumed, and an estimated twenty-five statues per year are cleaned, the costs are only $27,500 per year. Most other pieces of art work are protected indoors, and no estimate has been made of pollution damage to materials located indoors.

6.0 SUMMARY AND CONCLUSIONS

A study of the South Coast Air Basin (SCAB) was made to estimate costs associated with air pollution induced materials damage during the period 1978-1980. The study developed an inventory of the exposed materials and an estimate of the additional maintenance costs of damage and soiling to selected materials. The following conclusions are the result of the study;

1. The materials inventory assembled for the South Coast Air Basin is based on a combination of readily available data, field surveys and telephone surveys. This multipronged approach makes efficient use of resources and permits reliable estimates of materials in place to be assembled. The methodology should be readily transferable to other locations.

2. Extrapolations of materials based on an exhaustive census of total housing units and businesses appear to be more reliable than estimates based on material densities (i.e., the square feet of exposed materials per square feet of land area). This is because there is greater variability in the density of buildings from urban to rural areas, than there is in the amount of exposed material per building. For example, both urban and rural areas may contain refineries in regions classified as industrial land-use. The total exposed materials for two refineries of similar capacity are likely to be similar, while the material densities for the refineries and their surrounding areas classified as industrial land-use will be significantly different. Therefore, to extrapolate materials in place beyond the immediate region of the survey, it is more reasonable to count the total number of refineries and extrapolate, than to extrapolate based on an estimate of the number of square feet of exposed material per refinery type land-use area. Fortunately, the U.S. Census Bureau and several private agencies maintain detailed records of the number of housing units and the numbers and types of business, farms, etc.

3. On a gross area basis, as well as for most types of materials, the residential sector dominates the commercial/industrial and public sectors. The notable exceptions are for masonry (brick and stone), concrete, and metals. Approximately seventy-two percent of the total exposed materials are in the residential sector in the basin.

4. Paint, as painted stucco and painted wood, dominates the exposed surface area, accounting for about sixty percent of the total exposed materials. Latex paint accounts for most of this area.

5. Damage functions are available for a limited number of materials, and their applicability to environmental conditions in the South Coast Air Basin has not been generally demonstrated. Common materials for which damage functions are not available include glass, brick, concrete and tile. The damage functions for paint selected for this project are based upon results of chamber studies performed at elevated concentrations. While they are useful for estimating the portion of damage due to pollutants, these functions cannot be used reliably to estimate total damage in the real world. The damage function selected for galvanized steel agreed reasonably well with the limited field measurements collected for loss of thickness of zinc on transmission towers.

6. Estimates of the incurred damage costs, based on a maintenance strategy, are presented below. The estimates have been made based on the survey of materials in place (presented in Section 3), materials damage functions (presented in Section 4) relating pollutant levels to rate of damage, and the observed pollutant levels and estimated costs of maintenance per square foot of material exposed (presented in Section 5). These estimated costs include the cost of the increased frequency of painting various building structures and fencing due to pollutant induced damage estimated from the damage function presented in Table 4-3 and the estimated costs for cleaning cemetary markers and statuary: other cleaning and maintenance costs have not been included. Other aspects of economic loss, such as preventative maintenance costs, substitution of more resistant materials, replacement costs, and aesthetic losses are not contained in these estimates. The figures are in 1979 dollars and are estimates for the damage to materials in place in the basin circa 1979. Further, inadequate data exists to quantify the potential errors associated with these estimates, and caution should be applied in using these figures for quantitative purposes.

Materials	Incurred Pollutant Induced Damage Costs	Comments
Elastomers	Minimal	Protected by addition of antiozonants.
Marble	< $50,000/yr	Cost of cleaning cemetery markers and incidental monuments.
Textiles	Minimal	Negligible use of textiles in permanent outdoor exposures, and most textiles use-life limited by non-pollution wear.
Latex Paint	$38.2 million/yr	Residential plus commercial/industrial, public sectors.

Materials	Incurred Pollutant Induced Damage Costs	Comments
Oil Paint	$2.2 million/yr	Residential plus commercial/industrial public sectors.
Vinyl Top Coat Paint	$45,000/yr	Commercial/industrial and public sectors.
Soiling (Stationary, Painted Surfaces)	$44 million/yr	Not additive to paint erosion damage as calculated for the above three items.
Galvanized Fence	$1,169,000/yr	
Other Galvanized	$240,000/yr	
Outdoor Statutory	$27,500/yr	
Total (approximate)	$42 million/yr	Excludes soiling to paint as distinct from erosion to paint.

There are approximately eleven million people in the South Coast Air Basin, therefore this is about $4 per person per year. Costs are dominated by the predicted erosion damage to latex paint and/or soiling of surfaces. The lack of preciseness in the damage functions precludes estimates of the variability of the costs.

7. Several assumptions and extrapolations have entered into this estimate and have been noted throughout this report. The quality of the information required to make the estimates is summarized below:

   - the distribution and exposure of materials was developed specifically for the SCAB and is representative of the basin.

   - the pollutant levels and climatological data for the basin have been subject to external quality assurance, and are of known high quality.

   - the applicability of damage functions to exposures in the basin is uncertain. Selection of different damage functions can lead to large differences (more than an order of magnitude) in the predicted damage rates. Further, no damage functions are available for several common materials, and estimates of damage to these materials have not been possible.

   - the critical damage levels are generally poorly defined. Surveys of actual maintenance frequencies appear to be more reliable for estimating maintenance costs.

- the costs of maintenance are available from survey data and from commercial estimating firms. These estimates, on average, are probably fairly reliable although costs for individual projects may vary widely.

- finally, costs of replacement where maintenance is not possible, have not been included for this estimate. All costs for this program have been based on a maintenance strategy and estimates for processes like textile dye fading (where maintenance cannot be done) have not been made.

In summary, the cost estimates presented are subject to wide error bands. Significant classes of materials have not been included in these estimates (such as damage to concrete and soiling of windows). Therefore, it is likely that the estimated costs represent a minimum of the increased costs of material damage from pollutants, and that the actual costs may be significantly higher.

7.0 RECOMMENDATIONS

Based on the work performed for this project, the following recommendations are presented for further studies:

1. The extrapolation of materials in place using land use data produces unreliable results. Future material surveys will produce better estimates if extrapolations are based on the absolute number of housing units and businesses in various census categories.

2. On a gross area basis, and an incurred damage cost basis, latex paints are the most significant material to which damage is incurred in the SCAB. Careful study of a variety of available formulations of latex paint should be undertaken to refine the potential range of costs associated with these materials in the SCAB. Further, it is recommended that these studies be done in the SCAB to ensure the representativeness of the results to the basin's environment.

3. Damage estimates for glass, concrete, brick and tile were not made because no damage functions or critical damage levels have been established for these materials. Research to develop these relationships should be initiated, and the results of the research combined with the estimates for total areas of these materials presented in this report to produce economic estimates.

4. No estimate has been made of pollutant induced damage to materials in the indoor environment. Research should be carried out to establish these estimates, such as:

   - Indoor pollutant levels attributable to outdoor concentrations and indoor sources.

   - Critical damage levels associated with pollutant induced damage for "indoor materials" (e.g., paper, electronic components, etc.)

5. No damage estimates were made for acid deposition due to the current lack of acid deposition damage functions. Damage functions applicable to acid deposition phenomina should be developed, and, if significant damage is expected, estimates of the costs of acid deposition induced damage should be compiled.

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APPENDIX

TELEPHONE SURVEY INSTRUCTIONS
AND
GROUPS CONTACTED

TELEPHONE SURVEY - Instructions to Surveyor

1) Contact highway and public works departments:

- information on:

  - amount of chainlink fencing (length and type of fence
  - amount and type of guardrails ("w" and cable)
  - types of materials and coatings

    → COR10 steel
    → galvanized
    → painted galvanized
    → aluminum
    → painted (baked on)

    *Any information of # of gallons of paint used each year.

- information on structures, signposts, poles

  - # of structures
  - types of materials and coatings
  - maintenance practices

2) Call California DOT

- obtain highway bridge inventory
- need location, type of bridge, length of bridge
- what are maintenance practices and maintenance schedule
- obtain info regarding Item #1 above
- maintenances practices (i.e., type of paint, surface preparation, etc.) vary in different parts of SCAB?

3) Contact electrical utilities

- find the number and type of electrical transmission towers (either poles or lattice), painted steel, bare steel, on galvanized steel; the size and number of switch yards and maintenance/replacement/repair practices)
- obtain information on the number, size, and maintenance practices for storage tanks (most California utilities have predominantly oil fired capacity)
- contact the phone company and radio/television stations (perhaps a trade organization)

4) Contact railroad companies

- obtain information on the number of miles of track (Class I & II)
- obtain information on the number and type of bridges and material of construction
- what are maintenance practices; what types of coatings are used

5) Contact water and oil (bulk storage) firms

- obtain information on the number, sizes of tanks, amount of chain link fence (length and height) amount of exposed piping
- obtain information on the material of construction, maintenance practices, types of coatings

6) Contact wholesalers, contractors (major), and distributors of fencing, paint, and building materials

- how much chainlink fencing is sold?
- how much chainlink fencing with vinyl coating is sold?
- how often do people paint (residential structures, commercial, industrial sectors)?
- how much and what types of paint are sold annually (alkyd, latex, oil, specialty coatings)?
- how much aluminum and vinyl siding is sold?
- any maintenance or replacement practices for these materials?
- what is perceived effect of air pollutants and their effect on the durability?
- are paints and other coatings specially formulated or blended for use in SCAB?

7) Contact motor vehicle department to find the total number of:

- trucks
- buses
- auto (private and otherwise)

registered in SCAB in 1978-79-80.

8) Contact tire distributors to determine

- the number and type of tires sold
- special autiozonaut protect (this may only be available from a trade organization on a national basis)

9) Contact cemeteries and cemetery association

- obtain information on the number of monuments, spacing
- most common monument size and material
- portion of monuments that are marble
- structures and chainlink fencing
- maintenance practices for materials and monuments

The following cities, agencies, and companies were contacted:

California Transportation Department, District 7
Long Beach
Los Angeles
Pasadena
Riverside

A A Pacific Fence Company
Alcan Siding Company
American Tire Warehouse
Atlantic Richfield Company
Benjamin Moore Paint Company
Built-rite Fence Company
Commercial Chemical Company
Edgington Oil
Griffith Company
Lechleiter Fence Company
Mark C. Bloome
Scotch Paint Company
Shell Oil Company
Southern Pacific Transportation Company
Spectrum Paints
United Steel Fence Company