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S.J. Larsen
Vice President

June 15, 1998

Mr. Ken Kalman, Project Manager
Facilities Decommissioning Section
Low Level Waste & Decom. Project Branch Div. Of Waste Management
Office of Nuclear Mat'l Safety & Safeguards
U.S. Nuclear Regulatory Commission
Washington, D.C. 20555-0001

RE: Docket No. 70-925; License No. SNM-928
Response to NRC Comments on the Final Status Survey Report for Concrete Rubble in Sub-Area "F"

Dear Mr. Kalman:

Attached please find our responses to NRC Comments on the FSSR for concrete rubble in sub-area "F", that were transmitted to us via your letter dated May 20, 1998. The other issues raised in your May 20th letter will be addressed via separate submittals. I trust that our responses are satisfactory and that you will be able to approve the release of the concrete rubble shortly after review of the attached responses.

Please feel free to contact me if there are any additional questions or concerns.

Sincerely,

Jess Larsen

Jess Larsen
Vice President

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A SUBSIDIARY OF ***KERR-McGEE CORPORATION***

CIMARRON CORPORATION LETTER OF TRANSMITTAL

DATE: 06/16/98

TO: **M r. Ken Kalman, Project Manager**
Low Level Waste & Decommissioning Project Branch
Division of Waste Management
Office of Nuclear Material Safety and Safeguards
U.S. Nuclear Regulatory Commission
Washington, DC 20555-0001
MAIL DROP T2F27

FROM: **Mickey Hodo, Quality Assurance Manager**
Cimarron Corporation
P.O. Box 315
Crescent, OK 73028

☐ First Class Mail ☐ Internal ☐ Overnight--UPS
☐ Overnight--Fed Ex ☐ UniShippers ☐ Second Day Air--UPS
■ Second Day--Fed Ex ☐ Other________

COPY NO.	DATE	DESCRIPTION
1	6/15/98	Response to NRC Comments on the Final Status Survey Report for Concrete Rubble in Sub-Area "F"

These are transmitted as checked below:

☐ **For Approval** ☐ **Approved as submitted** ■ **For your use**
☐ **As requested** ☐ **Returned for corrections** ☐ **Return ____ corrected prints**
☐ **Disapproved** ☐ **For review and comment** ☐ **Controlled Copy**

REMARKS The above items are for your use. Please sign and return transmittal letter to me.

NOTE:

SIGNATURE Mickey W. Hodo

ACKNOWLEDGEMENT OF RECEIPT **PLEASE RETURN ONE SIGNED COPY TO SENDER**

I HAVE RECEIVED THE DOCUMENTS IDENTIFIED ABOVE AND THE PRIOR REVISIONS OF THESE HAVE BEEN
- DESTROYED N/A **VOIDED** N/A

PRINTED NAME OF RECIPIENT: Ken KALMAN

SIGNATURE OF RECIPIENT: Ken Kalman

DATE RECEIVED: 6/18/98

If enclosures are not noted, kindly notify Cimarron Corporation

Responses to Questions Raised by the U.S. NRC in Telephone Conversations with Cimarron Corporation

Staff Questions Regarding the FSSR for Concrete Rubble in Sub-Area "F" (April 16, 1998)

Introduction
Cimarron submitted the "Final Status Survey Report for Concrete Rubble in Sub-Area 'F'" to the NRC on March 10, 1998. NRC staff reviewed the Report and a telephone conference was held between Cimarron and NRC staff on April 16, 1998 to address questions pertaining to the Report. By letter dated May 20, 1998, the NRC sent Cimarron the seven questions concerning the Report, as well as questions pertaining to other submittals, and asked for a written response. The seven NRC comments concerning the Report are presented below with Cimarron's responses.

NRC Comment No. 1:
The last paragraph of page 11 states: "The random sample plan also contained those accessible areas known or suspected to have the highest gross beta-gamma surface contamination." How were the known or suspected sampling locations incorporated into the random sampling plan?

Cimarron Response:
Special efforts were not made to include known or suspected elevated areas in the random sample plan. Cimarron had already completed the non-random survey of the supplemental grids (i.e., grids #1 through #29 and grids #31 through #35) prior to performance of the random survey.

Preliminary surveys indicated that the concrete rubble with the highest gross beta-gamma surface contamination were in the areas below the spillway and near Burial Area #1. Based on this information, random samples were collected from those areas below the spillway and near Burial Area #1 in 5m x 5m grid areas that contained greater than or equal to 85% accessible concrete surface area. With this initial bias,, no other special efforts were incorporated to include specific elevated areas of rubble in the random sample. The statement in the report that the random sample plan includes locations "known or suspected to have the highest beta-gamma surface contamination" stems from the preliminary survey information available at the time that the random sample design was developed. Cimarron is confident that any similar random sample taken from the concrete would result in calculated total uranium concentrations that are similar or less than those indicated by the random sampling data presented in Appendix II, Table 3.

Drawing No. 98FCONC-0 shows that supplemental non-random samples were collected from grids #1 through #29 and grids #31 through 35. The data from these supplemental samples are included, along with the random sample data, in Appendix II, Table 4. Comparison of the data indicates that the supplemental grids contain lower total uranium concentrations. This additional information provides some quantitative basis for our statement that the random sampling data represents, on average, a conservative upper bound for calculated total uranium activity.

NRC Comment No. 2:
Please present an explanation of the headings in Table 3 of Appendix II, and a discussion of the data used to generate the "Average Concentration" columns (i.e., whether "weighted average or "average" data were utilized).

Cimarron Response:
The following explanations are provided for the headings (from left to right) in Table 3 of Appendix II:

"GRID #": Designates the 5m x 5 meter grid as shown on Drawing No. 98CONC-0.

REPRESENTATIVE AREA NET READING (dpm/100cm^2)
"AVE": Average gross beta-gamma reading (dpm/100cm^2) for the 1m x 1m representative area. Instrument background has been subtracted, but not concrete background.

"MAX": Maximum gross beta-gamma reading (dpm/100cm^2) in the 1m x 1m representative area. Instrument background has been subtracted, but not concrete background.

"% CONCRETE": Estimated percentage of the accessible concrete surface area within the 5m x 5m grid.

"TOTAL # OF HOT SPOTS": Number of 1m x 1m areas within the applicable 5m x 5m grid that contained elevated gross beta-gamma activity at or exceeding 5,000 dpm/100cm^2 (with instrument background subtracted).

HOT SPOT DATA (net reading)
"#": Hot Spot number (as recorded on Cimarron survey forms).

"AVE": Average gross beta-gamma reading (dpm/100cm^2) for the 1m x 1m area surrounding the hot spot. Instrument background has been subtracted, but not concrete background.

"MAX": Maximum gross beta-gamma reading (dpm/100cm^2) within the 1m x 1m area surrounding the hot spot. Instrument background has been subtracted, but not concrete background.

HOT SPOT DATA (background subtracted)

"#": Hot Spot number (as recorded on Cimarron survey forms).

"AVE": Average gross beta-gamma reading (dpm/100cm^2) for the 1m x 1m area surrounding the hot spot. Instrument background and concrete background has been subtracted.

"MAX": Maximum gross beta-gamma reading (dpm/100cm^2) within the 1m x 1m area surrounding the hot spot. Instrument background and concrete background has been subtracted.

5m x 5m GRID (dpm/100cm^2)

"AVE": Average gross beta gamma surface activity within each 5m x 5m grid. The calculation to determine the average was performed as follows:

Using Grid # 105 as an example:

1. Calculate the average hot spot activity (background subtracted) for the grid.

   Example: 4,200 + 2,277 + 3,382 + 3,450 + 4,200 + 2,343 + 8,121 + 7,129 + 5,015 + 3,117 + 3,561 + 4,283 + 4,200 + 4,800 = 60,078.

   60,078 ÷ 14 = 4291.3 dpm/100cm^2

2. Calculate the background subtracted representative area activity for the grid.

   Example: 1,129 – 800 = 329 dpm/100cm^2

   Note: Concrete background = 800 dpm/100cm^2.

3. Calculate the area of the concrete within the grid by multiplying the "% CONCRETE" by the grid area (25m^2).

   Example: 25m^2 x 0.97 = 24.25m^2

4. Weight the averages by their respective areas and sum.

   Example: 329 dpm/100cm^2 x (24.25 – 14) = 3,372 dpm/100cm^2

$4,291.3 \text{ dpm/100cm}^2 \times 14 = 60,078 \text{ dpm/100cm}^2$

$3,372 + 60,078 = 63,450 \text{ dpm/100cm}^2$

5. Calculate the average gross beta-gamma surface activity within the grid by dividing by the total surface area of the concrete in the 5m x 5m grid.

   Example: 63,450 dpm/100cm^2 ÷ 24.25m^2 = **2,617 dpm/100cm^2**

"MAX": Maximum gross beta-gamma surface activity within each 5m x 5m grid.

"WT. AVG.": This value is presented for informational purposes only and represents the "5m x 5m GRID, AVE" multiplied by the "% CONCRETE". The "WT. AVG." calculation was not utilized to determine average concentrations.

AVE. CONC (pCi/g)
"3"": Average concentration of total uranium in the concrete over a 3 inch depth. This calculation was determined as follows, using Grid #105 as an example:

Example: 2,617 dpm/100cm^2 ÷ 350 dpm/100cm^2 per pCi/g total U = **7.5 pCi/g**

Note: the conversion factor for a 3 inch concrete depth is 350 dpm/100cm^2 per pCi/g total U. This conversion factor was calculated in the same manner as the conversion factor for 6 inch concrete depth, except that only 24, ⅛ inch layers were used in the calculations. The reader is directed to Section 8.6.2 of the Report (page 27) for additional explanation.

"6"": Average concentration of total uranium in the concrete over a 6 inch depth.

Example: 2,617 dpm/100cm^2 ÷ 661 dpm/100cm^2 per pCi/g total U = **4.0 pCi/g**

Note: the conversion factor for a 6 inch concrete depth is 661 dpm/100cm^2 per pCi/g total U.

"Data Summary" Section

Note: This section contains data showing the beta-gamma surface activity (dpm/100cm^2) and the total uranium concentration (pCi/g).

Representative Areas (background subtracted)

"1 m2 Minimum": The lowest background subtracted gross beta-gamma activity and associated 6 inch average concentration for all representative areas in grids within the sample.

"Maximum": The maximum background subtracted gross beta-gamma activity and associated 6 inch average concentration for all representative areas in grids within the sample.

"Overall Ave.": The average gross beta-gamma activity and associated 6 inch average concentration for all representative areas in grids within the sample.

Hot Spots (background Subtracted)

"Total #": The total number of hot spots in the sample.

"Ave. #/grid": The average number of hot spots per grid area.

"1 m2 Ave. Min.": The lowest average gross beta-gamma surface activity and 6 inch average concentration calculated for any 1m x 1m hot spot.

"1 m2 Ave. Max.": The maximum average gross beta-gamma surface activity and 6 inch average concentration found within any 1m x 1m hot spot.

"1 m2 Ave.": The average gross beta-gamma surface activity and 6 inch average concentration for all hot spots in the random sample.

Maximum pCi/g

"3"": Maximum concentration of total uranium calculated for any 3 inch thick layer of concrete.

"6"": Maximum concentration of total uranium calculated for any 6 inch thick layer of concrete.

5m x 5m Grids (background subtracted)

"# of Grids": The total number of 5m x 5m grid areas in the sample.

"Area(m^2)": The total surface area of the concrete in the sample.

"Ave. Minimum": The lowest gross beta-gamma surface activity and total uranium concentration calculated for any 5m x 5m grid area.

"Ave. Maximum": The maximum gross beta-gamma surface activity and total uranium concentration calculated for any 5m x 5m grid area.

"Overall Ave.": The average gross beta-gamma surface activity and total uranium concentration calculated for all grids in the sample.

NRC Comment No. 3:
Is the 5,000 dpm/100cm^2 "cut-off value" noted in the first paragraph of page 12 the proposed release criteria for the concrete? Please explain why this value was chosen.

Cimarron Response:
The release criterion which is appropriate for the concrete is the BTP Option #1 volumetric concentration limit for enriched uranium (i.e., 30 pCi/g average). The 5,000 dpm/100cm^2 gross beta surface activity criteria was used only as a "cut-off" value for documentation of elevated surface activity on field survey forms to denote areas for additional surveys. The 5,000 dpm/100cm^2 value was selected based upon health physics considerations due to the fact that it represents the upper limit for enriched uranium surface activity (average) that can be unconditionally released in accordance with the USNRC "Guidelines for Decontamination of Facilities and Equipment Prior to Release for Unrestricted Use or Termination of License for By-Product, Source, or Special Nuclear Material." This "cut-off" value was considered to be reasonably conservative due to the fact that the NRC Guidelines apply to the release of buildings and equipment (averaged over 1m^2), and are not applicable as a release criteria for the concrete removed and placed in open land areas. No averaging was performed by Cimarron prior to documentation of the areas exceeding 5,000 dpm/100cm^2, gross beta-gamma activity.

NRC Comment No. 4:
Why is the data in Appendix II, Table 3, "HOT SPOT DATA MAX" presented in some cases using 5 significant places, while in other cases, only 2 significant places are used? For example, grid #11 has up to 5 significant places, while the data presented for grid #57 appears to have been rounded to two significant places.

Cimarron Response:
Cimarron used a conservative approach and rounded some of the survey data presented in the report upwards. When a fixed measurement was taken, at times the documented data was rounded upwards to reflect a conservative number. For example, a maximum reading of 14,723 dpm/100cm^2 can be recorded as 15,000 dpm/100cm^2. This practice of rounding upwards is commonly used throughout the nuclear industry.

NRC Comment No. 5:
How was the data in Appendix III developed and where did it originate?

Cimarron Response:
Cimarron staff used site construction drawings and staff knowledge of decommissioning history to estimate concrete volumes. The volume estimate includes all concrete rubble

removed from the Uranium Plant, and includes upward volume revisions that were made based upon "as-found" conditions during the decommissioning process. The volume estimate also includes all concrete rubble that was removed from the MOFF facility, even though much of this material left the facility as waste or was released for unconditional use. The volume estimate does not include any of the concrete that was placed into the drainage area by the State of Oklahoma during Highway #74 reconstruction.

NRC Comment No. 6:
There appears to be a typographical error in the first paragraph, second sentence of Section 8.6.3. Should the reference to Tables 5 and 6 be changed to Tables 3 and 4?

Cimarron Response:
This was a typographical error. The sentence is corrected to read as follows:

"These calculations, which are summarized in Appendix II (Tables 3 and 4), resulted in average total uranium concentrations (after background subtraction) ranging from –0.8 pCi/g to 7.4 pCi/g."

NRC Comment No. 7:
Please provide information and calculations to indicate the potential dose from inhalation of re-suspended materials from the concrete.

Cimarron Response:
Cimarron investigated available literature to determine appropriate resuspension factors for concrete and was unable to find specific citations. When determining potential exposures due to building occupancy, the resuspension of airborne particulates from concrete surfaces is normally dealt with from the standpoint of non-fixed materials which are suspended due to mechanical or physical interactions such as scraping. In the case of the concrete rubble in the drainage areas, the residual activity is known to be fixed and mechanical scraping is not applicable. Therefore, resuspension of the concrete would be the result of environmental factors such as wind and water acting upon the concrete. Since our review did not reveal any data relating to physical means of resuspension for our scenario, Cimarron investigated the deterioration of concrete and similar materials by weathering. The amount of material that is removed by weathering will include materials removed by the actions of water, wind, chemical interactions, pH, temperature, and other factors acting upon the surfaces. Much of the weathered materials will not be available for resuspension in the immediate area of the concrete due to the washing effects of rain that will carry the materials to other locations, as well as other factors such as particle sizes that are not easily suspended. Therefore, the use of the weathering estimate as an indicator of material that is resuspended is very conservative and should greatly overestimate the actual amount of resuspension that occurs.

Seymour and Wonneberger[1] (Attachment 1) performed evaluations of building stone weathering and reported data for the natural weathering of granite, marble, limestone, and sandstone. Of the stones studied, limestone is most likely to share its characteristics with concrete, and would be expected to have similar or greater weathering characteristics. Table 1 of Seymour and Wonnebergers' paper indicates that the mean lifetime of 1 mm (1/32 inch) of unweathered stone ranges from decades to hundreds of years[2]. Seymour and Wonneberger also cite work performed by Winkler[2] indicating that 10 mm (13/32 inch) of a limestone surface has been lost over a 300 year period of natural weathering, with about the same loss of a marble surface over a 150 year period.

For purposes of our analysis, we assumed that the concrete has a resuspension rate that is equal to the weathering rate for marble (i.e., 10 mm is lost from the surface every 150 years). This weathering rate is the highest reported in the referenced document for any of the materials investigated. This highest weathering rate will significantly overestimate the airborne concentrations of concrete particulates, since a significant portion of the weathering will occur as the result of forces that would not cause airborne particulates. In addition to assuming that all of the weathered material is resuspended, the analysis further assumes that all of the airborne material is respirable. Several other conservative factors have also been incorporated into the analysis as described later.

With the surface loss factors set, Cimarron evaluated two scenarios: a resident farmer (Scenario #1, and a Trespasser (Scenario #2). Scenario #1, the resident farmer scenario, assumes that reference man breathes airborne radioactive materials resuspended from the concrete. This scenario further assumed that the individual is in the plume centerline 25 percent of the time, and that the wind constantly blows toward the individual during the given time period.

<u>Assumptions</u>

1. The average concentration of total uranium in the uppermost 1/8 inch layer of concrete is 140 pCi/g. This is equivalent to the average concentration previously calculated for the 6 inch layer of concrete rubble based upon the random sample results (i.e., 2.9 pCi/g) multiplied by a factor of 48 to account for the fact that all of the activity is being concentrated in the uppermost layer.
2. The concrete weathers at a rate equivalent to marble, or 10 mm in 150 years. The weathering rate is assumed to be independent of time.
3. The estimated surface area of the concrete in Sub-Area "F" is 3,350 m^2, based upon 134 grid areas with 25 m^2 of surface area.
4. All of the weathered material is respirable and becomes airborne.
5. The density of the concrete rubble is assumed to be 1.8 g/cm^3.
6. The Stability Class is Class D, based upon given average weather conditions.
7. The average wind speed, u, is 5.6 m/s based upon Cimarron wind rose data from Oklahoma City WSFO Airport, Station ID 723530, 1945-1990 (Attachment 2).
8. The farmer is assumed to be in the plume centerline, directly downwind of the point source, with an occupancy of 25 percent.

9. Farmer occupancy is at 100 m downwind from the point source in the plume centerline.
10. The emission is from a point source. This is more conservative than the actual conditions, which would be multiple point sources, thus resulting in additional plume dispersion.
11. Dose Conversion Factor (DCF) for total uranium $\approx DCF_{238} \approx DCF_{235} \approx DCF_{234}$ = 3.58 E-05 Sv/Bq (Class Y).[3]
12. The breathing rate is assumed at 9.6 m^3/day for the resident farmer and for the trespasser.

The volume of concrete that is removed by weathering from the surface of the rubble, each year, is estimated as:

$$3{,}350\ m^2\ (10mm/150y)\ (m/1000mm) = 0.22\ m^3/y.$$

The total uranium source term activity that is assumed to become airborne each second, due to resuspension from weathering, is:

$$Q = 0.22\ m^3/y\ (1.8 g/cm^3)\ (10^6\ cm^3/m^3)\ (140\ pCi/g)\ (y/365d)\ (d/24h)\ (h/3600s)$$

$$= 1.8\ pCi/s, \text{ or } 1.8\ E\text{-}12\ Ci/s.$$

<u>Scenario #1: Resident Farmer Dose Calculation</u>

The basic atmospheric dispersion equation for a ground level source at the plume centerline is:

$$\chi = Q \div (2\pi)(\sigma_y)(\sigma_z)(u).$$

Sigma y and sigma z were picked from Figures 3-2 and 3-3 in Turner[4] (Attachments 3 and 4), using Class D atmospheric stability curves.

The concentration of airborne total uranium, χ, is calculated:

$$\chi = 1.8\ E\text{-}12\ Ci/s \div (2\pi)(6m)(4.6m)(5.6m) = 1.9\ E\text{-}15\ Ci/m^3$$

The effective dose can be calculated using the dose conversion factors from EPA Federal Radiation Guidance Report No. 11[3]. The dose conversion factors for U-234, U-235, and U-238 are similar. Therefore, simplification of the problem can be achieved through the use of the dose conversion factor for U-234, which is the most conservative. Inhalation

Class Y is assumed for the resuspended material. The breathing rate is assumed to be 9.6 m^3/day.

Effective Dose to the Resident Farmer = (1.9 E-15 Ci/m^3) (9.6 m^3/d) (365 d/y) (0.25)

(3.58 E-05 Sv/Bq) (3.7 E9 mrem/μCi per Sv/Bq) (10^6 μCi/Ci)

= **0.2 mrem/y**.

The upper estimate of dose to the resident farmer is 0.2 mrem/y, which is insignificant.

__Scenario #2: Trespasser Dose Calculation__

The trespasser scenario assumes a shorter period of time is spent per year in the vicinity of the concrete. The trespasser, however, is closer to the point source emission. The trespasser is assumed to spend one 8-hour day per month (or 96 hours per year) directly downwind of the point source emission in the plume centerline. This has the effect of minimizing the atmospheric dispersion, which is represented by the denominator in the basic atmospheric dispersion equation given for the resident farmer scenario.

Under normal circumstances, the concentration of total uranium due to the resuspension of material from the concrete rubble will increase up to a certain distance from the source, followed by a decrease. The resuspension forces (e.g., wind, etc.) will cause the respirable material to be carried from the surface of the concrete rubble to the breathing zone of the trespasser. This movement of residual activity requires that the individual be situated at a far enough distance from the source so that the resuspension forces can significantly affect the airborne concentrations in the individuals' breathing zone.

The model selected for this evaluation utilizes a single point source. In reality, the concrete rubble can be thought of as an infinite number of point sources, each with its' own applicable atmospheric dispersion factors. One can readily see that the dose estimates performed using the single point source model will result in extremely conservative estimates.

Estimates of σ_y and σ_z were obtained using the equations from Table 11.3.4 of "The Health Physics and Radiological Health Handbook"[5]. The power functions given in the table were used to provide estimates using neutral stability at distances of 10 to 100 meters from the assumed point source. The dose equations are identical to those given for the resident farmer. Attachment 5 provides a summary of the calculations for various point source to trespasser distances. **The single point source model estimated a maximum effective dose of 0.7 mrem per year at a distance of 10 meters from the**

single point source, and a maximum effective dose of 0.02 mrem at a distance of 100 meters from the point source. The dose to the trespasser under this scenario is therefore negligible.

In summary, the potential for inhalation dose from the concrete rubble placed in Sub-Area "F" drainage areas is negligible.

References

1. Seymour, A. B., and Wonneberger, B., "Laboratory Evaluation of Building Stone Weathering," Journal of the American Society of Civil Engineers, 1977, pages 85-104.
2. Winkler, E. M., "Important Agents of Weathering for Building and Monumental Stone," Engineering Geology I, 1966, pages 381-400.
3. Environmental Protection Agency, "Limiting Values of Radionuclide Intake and Air Concentration and Dose Conversion Factors for Inhalation, Submersion, and Ingestion," EPA-520/1-88-020, Federal Guidance Report No. 11, September, 1988.
4. Turner, D. B., "Workbook of Atmospheric Dispersion Estimates," U. S. Department of Health, Education, and Welfare, Cincinnati, OH, 1969.
5. Schlein, B. (Editor), "The Health Physics and Radiological Health Handbook," Scinta, Inc., 1992.

ATTACHMENT 1

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Laboratory Evaluation of Building Stone Weathering

Seymour A. Bortz,[1] Bernhard Wonneberger[2]

Abstract

Dimension stone is among the most durable materials, but the process of weathering has shown that some types of stone, even of the same variety, are more durable than others. At present there is little information available about the durability of dimension stone on a building facade. Designers generally select a particular stone for its aesthetic qualities, with casual reference to basic parameters such as porosity, pore size, moisture absorption, and other critical physical and chemical parameters. Generally, when there is reference to weathering, the recommendation is to inspect another building with the same variety of stone. The recommendation does not consider the fact that stone, being a natural material, can vary considerably, even from one place in a quarry to another. Thus, in addition to observing weathering history in the field, we must determine how rock weathering can be recreated in the laboratory.

This paper attempts to provide background regarding the environmental processes that cause stone weathering in the field, such as acid rain (chemical), thermal (temperature changes), and freeze-thaw of absorbed water. We compare laboratory to field data that indicates accelerated durability testing can provide reliable information to long-term behavior of dimension stone.

Introduction

Natural building stones are subjected to a variety of weathering conditions, both natural and man-made. Under these conditions, durability depends upon the stone's physical and chemical nature. Weathering of natural building stone consists of the reaction to environmental conditions within the body of the stone. It is the surface of

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the stone that is subjected to water and atmospheric gases. Weathering reactions are controlled by water and the natural gases dissolved in it (mainly O_2 and CO_2 and the human produced gases SO_2 and NO) that may penetrate the stone under various conditions. Weathering rates are influenced by temperature, moisture, organic acids, and dissolved carbon dioxide. The average rainfall is a major controlling factor of the weathering rate. The rain presents the dynamic for attack of the structure of the stone. This factor, in combination with the effects of our contemporary industrial society, accelerates natural weathering processes through elevated pollutant concentrations on the stone surface. Acid pollutants, in both air and rainfall, are recognized as serious hazards to carbonate rocks, such as limestone and marble, that are used in construction of major buildings. Silicate rocks and granite are affected by these acid pollutants to a lesser degree. However, even silicate rocks may be seriously affected by some acids and by alkalis. Elevated temperatures, or rapid temperature cycles, not necessarily cyclic freezing, affect differential volume changes of mineral grains. Temperature will accelerate solution of the carbonate minerals, while frost will cause damage to both carbonate and silicate stones.

Damage from frost is due to expansion of the freezing water. The structure of stone contains connected pores that can transfer water through the stone unit. Water entering the structure of the stone is an important consideration in this process. Rain, high humidity, and condensation are important factors in this weathering process. The water-filled pores exert forces against the pore walls by expanding water from ice crystallization during freezing. These pores may also contain clays, some of which may expand when wet. The swelling of expansive clay minerals when wet or by osmotic forces due to differential concentrations of dissolved material will put pressure against the pore walls. The outward forces of the expansion produce tensile stresses in the stone structure. Therefore, the tensile strength of the stone is of greater importance than the compressive strength with regard to freeze-thaw durability. For brittle material such as stone, the compressive strength is generally 10 to 15 times greater than the tensile strength.

Variation of Dimension Stone Used for Building Facades

This section will give some background regarding the natural weathering of granite, marble, limestone, and sandstone. It is important to understand the differing characteristics of the various types of stone that are available. These characteristics affect the behavior of the stone material under natural weathering conditions.

Limestone is a rock of sedimentary origin, composed principally of calcium carbonate (calcite) or the double carbonate of calcium and magnesium (dolomite). Many limestones are formed of shells or altered shell fragments. Oolitic limestone, a popular building stone, consists of cemented rounded grains of calcite, generally less than 2 mm (5/64 in.) in diameter. Some limestones have varying amounts of other material, such as quartz sand or clay. These materials are mixed with the carbonate

minerals. The carbonate materials will dissolve when exposed to acidic water or to water undersaturated with calcium.

Travertine is a variety of limestone usually precipitated from solution in ground waters and surface waters. When travertine occurs in hard, compact, extensive beds, it can be quarried and used as an attractive building stone. It is generally variegated gray, white, or buff, with irregularly-shaped pores distributed throughout.

Geologically, marble is a metamorphic rock formed by the recrystallization of the limestone or dolomite when subjected to high heat and pressure. Commercial marble includes all crystalline rocks composed predominantly of calcite and dolomite that can be polished to a reflective surface. It also includes serpentinite, which is not a carbonate rock. Thus, in addition to geological marble, commercial marble includes many crystalline limestones, travertine and serpentinite. In the metamorphic process, original sedimentary features, such as fossils, are usually destroyed, and the bedding planes are replaced by compositional layering (veins). The original calcite is recrystallized in an interlocking mosaic texture that provides the beauty a designer seeks for interior or exterior finishes.

Sandstone is a consolidated cemented sand sedimentary rock deposit. It has a distinctly granular texture with various cementing materials, including silica, iron oxides, and calcite. Enough voids generally remain in the rock to give it considerable permeability and porosity. (Commercially used sandstone is usually a sediment consisting almost entirely of quartz grains, 1 to 2 mm (1/32 to 5/64 in.) in diameter with various types of cementing material.) This allows the stone to readily absorb and confine water where it can freeze in colder weather.

Slate is a metamorphosed rock derived from argillaceous (clay) sediments consisting of extremely fine-grained quartz, mica, and other platy minerals. Slate possesses an excellent parallel cleavage that allows the rock to be split into thin, smooth-surfaced slabs with relative ease. The color of slate is generally determined by the oxidation state of pyrite (iron) or the presence of graphite. The cleavage planes are relatively weak in tension parallel to the planes. Water can enter and travel along these planes and later freeze in colder weather.

Commercial granite includes most rocks of igneous origin formed by solidification from molten rock beneath the earth's crust. True granites consist of feldspars and quartz, with varying amounts of other minerals such as mica and hornblende. These minerals are in an interlocking and granular texture with locked-in stresses. Each variety of mineral behaves differently when subjected to the same environmental conditions i.e. differential thermal stresses.

Role of Chemical Weathering

Rainfall which enters the pores in the rock is a controlling factor of the weathering rate. Material can be dissolved by percolating water solutions or by the chemical decomposition of the stone. The amount of CO_2 in the water causes the aggressiveness of the water that can dissolve the stone. Weathering reactions also depend on temperature. Higher temperatures increase thermal agitation. Hence, such reactions are more magnified in the tropical areas than in colder temperature zones. In desert areas, the stone is hot but not subject to the intense action of liquid water weathering, so chemical weathering does not develop.

Table 1 shows the mean lifetime of 1 mm (1/32 in.) of unweathered stone when it is subjected to environmental weathering. These results show that in a cold, temperate, or tropical humid climate, the average rainfall (i.e., water rising) probably controls the rate of weathering.

Table 1. Mean lifetime of 1 mm (1/32 in.) of unweathered stone [1]

Stone Type	Climate	Lifetime
Acid (Light-colored igneous granite)	tropical semi-arid tropical humid temperate humid cold humid	65 to 200 years 20 to 70 years 41 to 250 years 35 years
Metamorphic (Marble, slate, etc.)	temperate humid	33 years
Basic (Dark-colored igneous granite)	temperate humid tropical humid	68 years 40 years
Ultrabasic	tropical humid	21 to 35 years
Sedimentary	arid-semiarid all others	50 to 100 years highly variable

Rates of silicate weathering are more difficult to evaluate because too many factors are involved which may influence the process. Stone exposed to polluted air may show signs of incipient weathering by undesirable discoloring, loss of polish and hardness of feldspars and ferro-magnesium silicates. There are estimates that there is a 2 to 2 ½ times increase of the weathering rate by solubilization and hydrolysis with each temperature increase of 10°C (50°F). The weathering rate can increase nearly 20 to 40 times in tropical moist areas.[2]

There have been observations that 10 mm (13/32 in.) of a limestone surface has been lost over a 300-year period of natural weathering, with about the same loss of a marble surface over a 150-year period. Sandstone with feldspar and mica as impurities will lose about 2.5 mm (5/64 in.) over 200 years, while almost pure quartz sandstone will remain sharp and clear over the same period.[3]

Temperature Effects on Weathering

Weathering can also be caused by the difference of thermal expansion of the minerals that constitute the various stones. Volumetric or linear expansion of the different mineral materials that comprise the same stone mass can cause microcracking of the stone when heated in direct sunlight. Temperatures as high as 82°C to 88°C (180°F to 190°F) have been measured on dark stone surfaces. All minerals expand with increasing temperature, however, they expand to different degrees. Quartz expands about four times more than feldspars and twice as much as hornblende. Quartz is considered the most critical mineral under conditions of heating of granites and quartzitic sandstones. When quartz expands during heating, it exerts pressure against the surrounding crystals. These stresses can cause microcracking in the granite, lowering the strength and allowing other weathering phenomena, both chemical and freezing, to accelerate the disintegration processes. Figure 1 indicates the loss in compressive strength of granite when heated up to a temperature of 93°C (200°F).

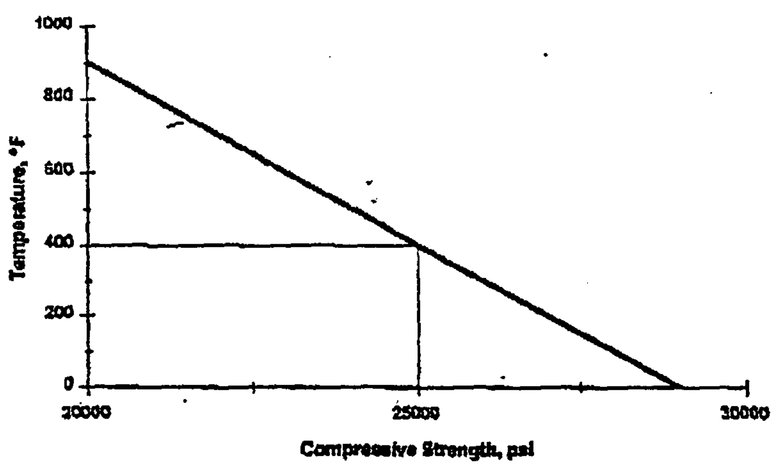

Figure 1. Loss in compressive strength of granite when heated.[4]

Individual stone crystals will have different expansion properties for each axis orientation, as shown in Figure 2. Calcite exhibits linear thermal expansion parallel to the C-axis of about 0.2 percent, but contracts about 0.1 percent perpendicular to the C-axis. The differing expansive rates of calcite cause microcracking in the structure of the stone. This disruption is manifested as increased volume and absorption of the stone during heating and cooling phases plus loss in strength. Stone that is low in quartz and carbonate minerals will expand very little with increases in temperature.

Another cause of stone disruption due to temperature changes is the differential expansion of trapped salts in the pores of the stone. Trapped salt can result from natural exposure due to high salt content in precipitation along coastal regions or from dissolved materials, (pollutants) in the environment. Figure 3 presents the thermal expansion of calcite, quartz, granite, and "rock" salt (halite). As the temperature increases from 0°C to 70°C (32° to 180°F), halite expands 0.5 percent compared with 0.2 percent for granite and about 0.1 percent for calcite. Small as these differences may appear, it is believed that expansion of absorbed salts combined with other factors can lead to stone decay.

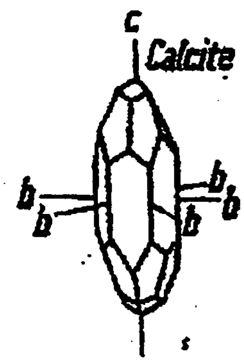

Figure 2. Calcite crystal.

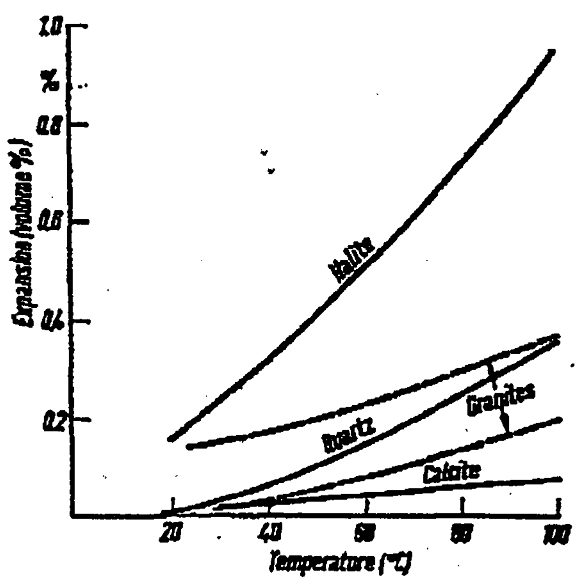

Figure 3. Thermal expansion of calcite, quartz, granite, and "rock" salt (halite).(5)

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Effect of Freezing on Stone

Damage to stone results when temperatures are below freezing and any absorbed water forms ice crystals. The expansive crystallization pressure is very important as it produces tensile forces on the stone structure.

In addition to the expansion of the ice crystals, water itself expands just before it reaches a solid state. The ice volume is at a maximum and the density at a minimum of 4 °C (39 °F) (from 1,000 kg/m^3 (62.4 lb/ft^3) in an unfrozen state to 916 kg/m^3 (57.2 lb/ft^3) in a frozen state). However, the density of water also increases with increasing outward pressure when it is in a confined space. This increase in density is similar to that of unconfined ice, but somewhat greater.

Need for Laboratory Evaluation

The introductory sections of this paper were presented to provide a background for the design of a durability test procedure. This laboratory procedure has been used to develop information presented in the latter sections of this paper.

In the past, people have claimed that stone is "as hard as rock" and, therefore, durability testing is not necessary. However, as we have already shown, different types of stone will have varied behavioral characteristics when subjected to natural weathering. The long-term behavior can also be determined by using an accelerated test. The designer needs to know whether large blocks or thin slabs are to be used. Structural considerations for large blocks are mainly compressive strength. Because of the large mass of the stone units, minor loses of thickness and property changes due to weathering have a negligible effect on the structural capabilities of massive stone. However, structural considerations for thin stone include panel size, flexural strength, and weatherability. Loss of strength and small changes in thickness can have a major effect on the long-term behavior of thin stone facades.

A good laboratory test must consider environmental factors, such as temperature, air pollution, and rain. In addition, the designer must consider not only wind loads, but the fact that the stone can vary from quarry to quarry, from one area within a single quarry to another, and possibly within a single quarry block. Therefore, it is important to test the specific supply of stone for a large building project. Stone used successfully on a similar project in the past may not have the same physical or mechanical properties for the current project.

Based on previously discussed environmental effects on the properties of stone, we have developed a procedure that considers the following environmental factors: acid rain, temperature change, and freeze-thaw cycling. The test procedure consists of placing a stone specimen with minimum dimensions of 32 mm (1 1/4 in.) thick, 102 mm (4 in.) wide and 381 mm (15 in.) long in a 4 pH sulfurous acid solution. The specimens

are immersed 6 mm (1/4 in.) to 10 mm (3/8 in.) deep in the solution in a stainless steel pan. Each specimen is also set on 6 mm (1/4 in.) diameter rollers to assure the stone face is subjected to the action of the bath solution. A fresh solution is used after each 25 cycle interval. The specimens are then subjected to 100 cycles between -23°C to +77°C (-10°F to +170°F). Before the test procedure is started, the test specimens are evaluated for dynamic Young's Modulus of Elasticity (sonic modulus) using ASTM Procedure C 215, "Test Method for Fundamental Transverse, Longitudinal and Torsional Frequencies of Concrete Specimens." The sonic modulus testing is repeated after every 25 freeze-thaw cycles to provide a nondestructive method of monitoring the changes in strength of the specimens. Figure 4 shows the relationship of sonic modulus to flexural strength developed from marble specimens. There is a good correlation at each measured cycle between strength and sonic modulus.

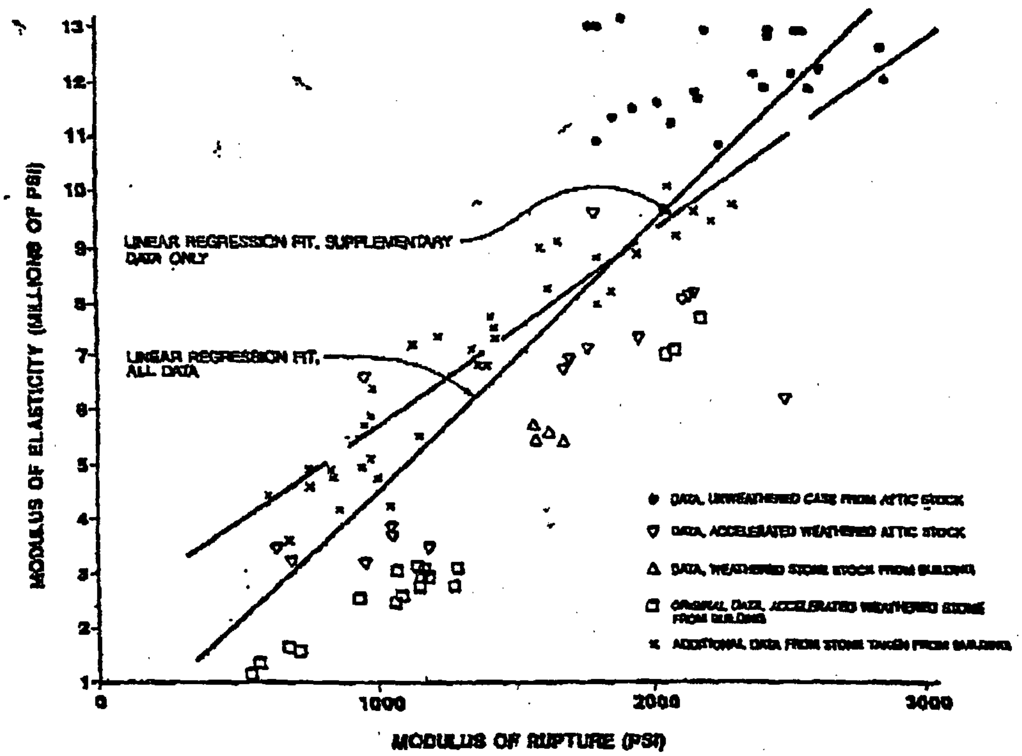

Figure 4. Relationship of sonic modulus to flexural strength developed from marble specimens.[6]

Laboratory Data

Table 2 provides stone durability test data obtained using the test procedure described above at the Wiss, Janney, Elstner Associates, Inc. (WJE) test laboratory over a period of ten years. Results from granite, marble, and limestone are presented. Note how stone types of the same classification vary, including stones of the same area and

name. Most of the stones indicate strength changes during the durability testing. Table 3 shows how stones from different blocks of the same quarry can vary. Material from one quarry block withstands the duration of the test while material from another block does not. These results show the need for testing several different blocks of the same quarry for use on a single building project.

Table 2. Summary of Durability Test Results of Various Dimension Stones

STONE	FINISH AND THICKNESS	INITIAL FLEXURAL STRENGTH kg/cm² (psi)	FLEXURAL STRENGTH AFTER TESTING kg/cm² (psi)	PERCENT LOSS OF STRENGTH
Spanish Pink Granite	30 mm (1 3/16 in.) Thermal Finish	94.6 wet (1,345)	Samples Fractured	100%
Unidentified Granite		115.3 (1,640)	88.6 (1,260)	23%
		115.3 (1,640)	109.1 (1,552)	5%
Moonlight Granite	33 mm (1 5/16 in.) Thermal Finish	74.5 wet (1,060)	66.0 wet (939)	11.4%
		80.5 dry (1,145)	70.4 dry (1,001)	12.6%
		74.5 wet (1,060)	58.6 wet (834)	21.3%
Stoney Creek Granite (Pink Granite from Bramford, CT)	30 mm (1 3/16 in.) Light Thermal Finish	79.4 wet (1,130)	44.6 wet (635)	43.8%
Mount Airy Granite (Fine-grained, white domestic granite)	51 mm (2 in.) roughened finish	98.4 wet (1,400)	81.1 wet (1,154)	17.3%
			86.0 wet (1,223)	12.3%
			89.3 wet (1,270)	9.0%
Venetian Gold Granite	30 mm (1 3/16 in.) honed	68.4 dry ∥ (973) 102.8 dry ⊥ (1,462)	54.1 dry ∥ (770) 100.7 dry ⊥ (1,433)	21% 2%
Baltic Brown Granite	30 mm (1 3/16 in.) honed	95.4 dry ∥ (1,357) 112.2 dry ⊥ (1,596)	76.3 dry ∥ (1,086) 98.9 dry ⊥ (1,407)	20% 12%

Table 2. Summary of Durability Test Results of Various Dimension Stones (Continued...)

STONE	FINISH AND THICKNESS	INITIAL FLEXURAL STRENGTH kg/cm² (psi)	FLEXURAL STRENGTH AFTER TESTING kg/cm² (psi)	PERCENT LOSS OF STRENGTH
Rockville Beige Granite	30 mm (1 3/16 in.) honed	105.2 dry ∥ (1,496) 98.4 dry ⊥ (1,399)	a. 88.4 dry ∥ (1,257) b. 84.4 dry ∥ (1,201) a. 83.8 dry ⊥ (1,192) b. 76.6 dry ⊥ (1,089)	a. 16% b. 20% a. 15% b. 22%
Calibri Granite	30 mm (1 3/16 in.) Polished Thermal	128.3 dry ∥ (1,825) 190.3 dry ⊥ (2,707) 133.0 dry ∥ (1,891) 176.5 dry ⊥ (2,510)	112.5 dry ∥ (1,600) 184.1 dry ⊥ (2,619) 136.8 dry ∥ (1,946) 173.1 dry ⊥ (2,462)	12% 3% 3% gain 2%
Massangis Limestone	51 mm (2 in.)	112.0 dry (1,593) 79.0 dry ⊥ (1,124) 69.7 dry ∥ (992)	95.5 dry (1,359) 71.1 dry ⊥ (1,012) 54.3 dry ∥ (773)	15% 10% 22%
Chandore Limestone	51 mm (2 in.)	149.1 dry ⊥ (2,121)	125.8 dry ⊥ (1,790)	16%
Valdenot Limestone	51 mm (2 in.)	68.8 dry ⊥ (979) 81.0 dry ∥ (1,152)	51.9 dry ⊥ (738) 83.7 dry ∥ (1,190)	25% 3% gain
Luget Limestone	51 mm (2 in.)	65.9 dry ⊥ (938) 58.1 dry ∥ (826)	0 dry ⊥ 0 dry ∥	100% 100%
Rosal Limestone	51 mm (2 in.)	81.5 dry ⊥ (1,159)	0 dry ⊥	100%
Valders Buff Limestone	51 mm (2 in.)	109.0 dry ⊥ (1,551) 126.7 dry ∥ (1,802)	122.8 dry ⊥ (1,746) 108.1 dry ∥ (1,537)	13% gain 15%
Valders Dove White Limestone	51 mm (2 in.)	147.2 dry ⊥ (2,094) 125.4 dry ∥ (1,783)	126.4 dry ⊥ (1,798) 100.2 dry ∥ (1,426)	14% 20%
Valders Gray Limestone	51 mm (2 in.)	178.2 dry ⊥ (2,535) 147.6 dry ∥ (2,100)	162.8 dry ⊥ (2,315) 115.9 dry ∥ (1,648)	9% 22%

Table 2. Summary of Durability Test Results of Various Dimension Stones (Continued...)

STONE	FINISH AND THICKNESS	INITIAL FLEXURAL STRENGTH kg/cm² (psi)	FLEXURAL STRENGTH AFTER TESTING kg/cm² (psi)	PERCENT LOSS OF STRENGTH
Dolomitic Limestone from France	32 mm (1 1/4 in.)	156.3 (2,223)	120.9 (1,719)	23%
		61.2 (870)	38.8 (552)	37%
Indiana Limestone	64 mm (2 ½ in.)	65.6 (933)	59.3 (843)	9.6%
Valders Dolomitic Limestone	30 mm (1 3/16 in.)	148.0 (2,105)	153.3 (2,180)	4% gain
Pierre De Lens Limestone	51 mm (2 in.)	89.5 dry ⊥ (1,273) 59.3 dry ∥ (843)	68.1 dry ⊥ (969) 45.5 dry ∥ (647)	24% 23%
White Marble from Carrara, Italy after 15 years of exterior exposure	32 mm (1 1/4 in.) polished	64.0 wet (911)	38.0 wet (540)	41%
			41.4 wet (589)	35%
			59.7 wet (849)	7%
Georgia Golden Vein Marble	25 mm (1 in.) honed	79.0 dry ∥ (1,124) 104.3 dry ⊥ (1,484)	a. 74.6 dry ∥ (1,061) b. 76.4 dry ∥ (1,087) a. 96.6 dry ⊥ (1,374) b. 97.3 dry ⊥ (1,384)	a. 6% b. 3% a. 7% b. 7%
Marquis Gray Danby Vermont Marble	30 mm (1 3/16 in.) honed	60.5 dry ∥ (861) 99.5 dry ⊥ (1,415)	54.1 dry ∥ (769) 46.1 dry ⊥ (656)	11% 5%
White Carrara Marble	25 mm (1 in.) honed	154.4 dry (2,196)	112.0 dry (1,593) 90.6 dry (1,289)	27% 41%

∥ Tested parallel to the bedding plane or rift

⊥ Tested perpendicular to the bedding plane or rift

Table 3. Summary of Durability Test Results for Limestone Removed from the Same Quarry

Block A Tested Perpendicular to Bedding Plane			
Cycles	0	100	Change
Dry Wet	81.5 kg/cm² 43.2 kg/cm²	Unable to test Unable to test	-100% -100%
Block B Tested Perpendicular to Bedding Plane			
Dry Wet	178.2 kg/cm² 172.4 kg/cm²	162.8 kg/cm² 147.5 kg/cm²	-9% -14%

Figure 5 shows the change in sonic modulus that occurred when granite was subjected to the 4 pH sulfurous acid bath. Exposure to acid bath cycles apparently has little or no effect on the granite. However, the temperature change does appear to cause differential expansion that breaks the bond between the mineral crystals and, by that, lowers the strength. Figure 6 is a similar curve for marble. The change in property is due to differential expansion and contraction of the individual calcite crystals, and some dissolving of the calcite. Although some calcite dissolves in the acid solution, this essentially neutralizes the acid. Figure 7 consists of curves for different limestones. The Massangi and Valders dolomitic limestones show no basic effect while the Indiana Limestone has a slight downturn at the end of 100 cycles indicating dissolving of the calcite.

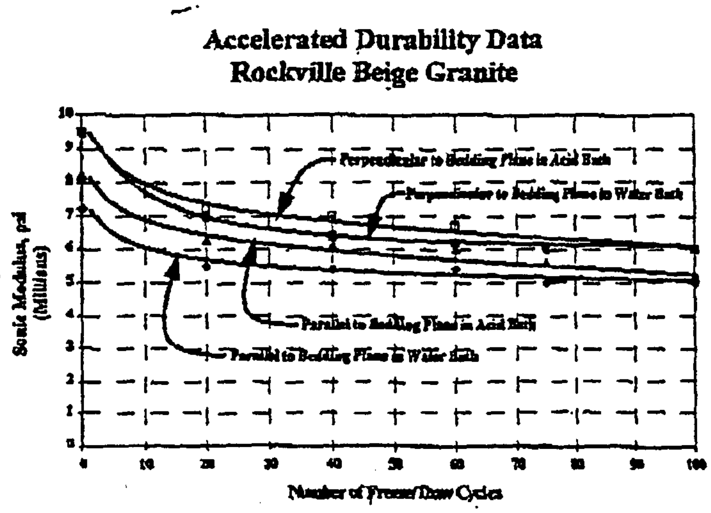

Figure 5. Accelerated durability test results for Rockville Beige Granite.

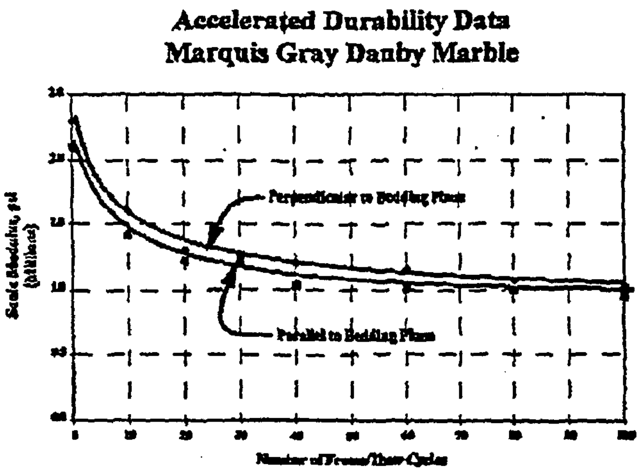

Figure 6. Accelerated durability test results for Marquis Gray Danby Marble.

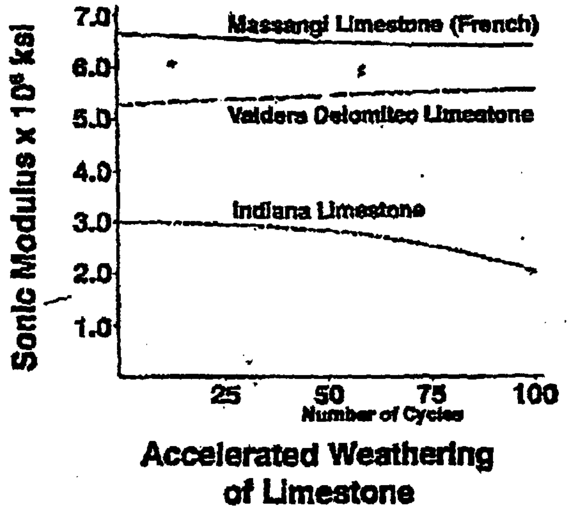

Figure 7. Accelerated durability test results for three different types of limestone.

Natural Weathering Studies

The durability test allows one to make comparisons between stones. However, there has been criticism that the durability test procedure has no relationship to natural weathering. Arguments also state that the test has no meaning for building projects that are in warmer climates. To counteract these comments, we have compared sonic modulus test results from stone subjected to natural weathering to sonic modulus test results determined from stone subjected to the durability test procedure. For warmer climates, the test procedure can be modified to cycle between +5°C and +77°C (+41°F and +170°F).

Thirty-five years ago, twelve domestic marbles were placed on the roof of a building located immediately south of the main business district in Chicago. The marbles were monitored quarterly over 8 years using sonic modulus testing. Figure 8 is a chart showing the results of this work, including the results for Danby marble, indicated as "I" on the chart. Recently, we had an opportunity to perform durability tests on a second set of Danby marble. The previously shown Figure 6 presents the change in sonic modulus determined during these tests. Figure 9 presents the natural weathering and durability test curves shown in Figs. 6 and 8. These curves show 100 freeze-thaw cycles of durability testing can be considered equivalent to 6 or 8 years of natural weathering. Therefore, 12 to 16 freeze-thaw cycles would be equivalent to one year of natural weathering in a northern temperature environment. Our data from this work and similar additional work using naturally weathered stone from a building was compared with data obtained from durability testing of attic stock stone, (stone kept in reserve, but not exposed to weathering). This work indicated that real-time effects could be estimated from laboratory tests.

Field Studies

Evaluation of a 10-year-old marble-clad high-rise office building in Rochester, New York, permitted evaluation of actual strength degradation from natural weathering. Many panels from the building facade, and panels that had not been exposed to natural weathering, were provided for durability tests. This provided a large statistical population for data analysis. The data is summarized in the chart previously shown in Figure 4. The chart shows a correlation between modulus of elasticity and flexural strength. A weathering chart was plotted using the modulus of elasticity and flexural strength data, Figure 10. In this figure, the flexural strength chart has been superimposed over the elastic modulus chart.

The process of obtaining the curves shown is empirical. To provide guidance regarding the meaning of accelerated weathering, the data from weathered and unweathered stone had to be related in some manner. Data was plotted for elastic modulus vs. accelerated aging cycles for both the unweathered and weathered stone. They were analyzed such that the original elastic modulus and strength for the building weathered stone are close to being a tangent to the curve for elastic modulus and strength of attic stock subjected to the durability test. This occurred at approximately 160 cycles. Using these relationships, the conclusion was drawn that 160 cycles of accelerated weathering appear to be equivalent to 10 years of natural weathering on the building. Thus, 16 cycles were determined to be equivalent to one year of service life in upper state New York. While this cannot be considered a rigorous proof of the time relation of natural aging to accelerated aging, the empirical data from the laboratory and field observations indicate this is a reasonable approximation of what the designer can expect regarding changes in strength properties from natural weathering.

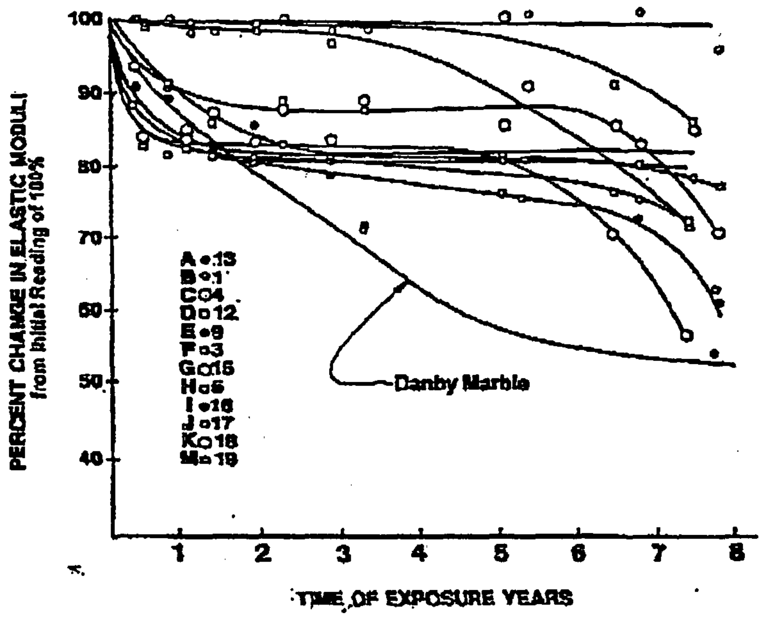

Figure 8. Chart showing natural weathering test results for twelve different domestic marbles.

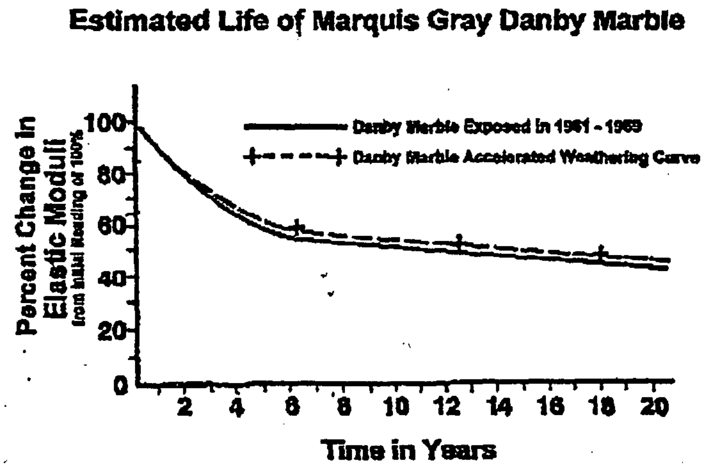

Figure 9. Natural weathering test results for Marquis Gray Danby Marble.

Using this technique, two other marble-clad buildings were also studied. A correlation between elastic modulus and strength was also determined, Figure 11. Composite curves for building weathered and attic stock were developed, Figs. 12 and 13. For the marble in Figure 12, 12 ½ cycles of accelerated weathering were found equivalent to one year of natural weathering on a building in Kansas City. For the marble in Figure 13, 13 cycles of accelerated weathering were seen to be equivalent to one year of natural weathering. The plot in Figure 13 is based on actual flexural

strength of the stone, not sonic modulus. Note the curves for sonic modulus are similar to the curves for flexural strength.

The three marbles tested indicate approximately 15 cycles of accelerated weathering is equal to one year of natural weathering on the buildings. All the data correlates with the rooftop test and laboratory accelerated weathering of the Danby marble previously discussed. The Danby data showed that changes in properties due to natural weathering and accelerated weathering are similar. Curves from testing stone from the buildings and laboratory accelerated weathering can be tied together so as to predict the number of cycles that will constitute one year of weathering.

Limited data has also been obtained for granite and limestone. The results of these tests have been similar to those obtained from the more extensive marble data. Figure 14 presents a summary of all the data we have for granite, marble, and limestone. In this figure, changes in properties of granite were plotted for 300 cycles, 500 cycles for marble and 200 cycles for limestone. Based on the data, approximately 13 cycles represent one year of natural weathering for granite, 12 ½ cycles represent one year for marble, and 12 cycles represent one year for limestone.

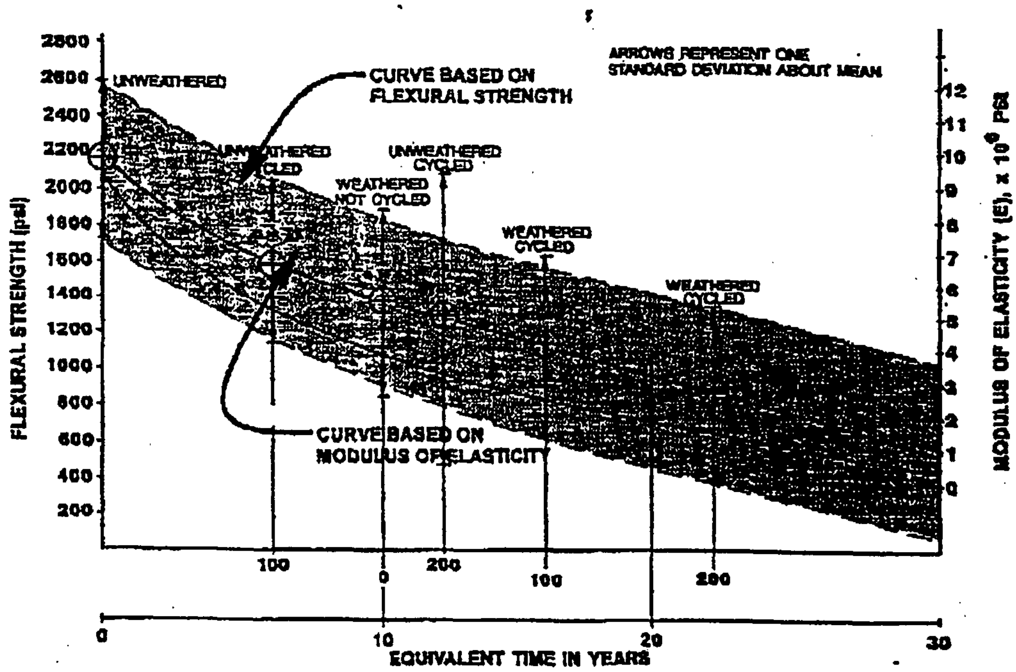

Figure 10. Relation of number of durability test cycles to years of natural weathering for Bianca White Carrara marble. n=number of specimens.

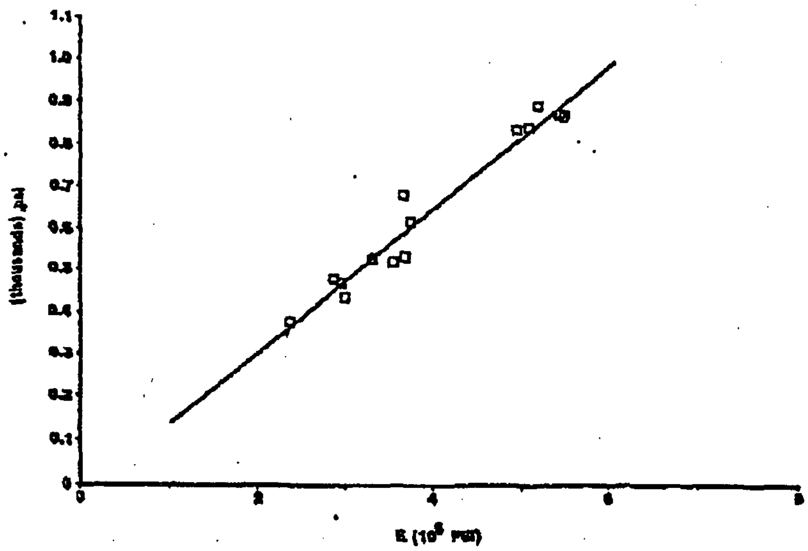

Figure 11. Modulus of elasticity (E) vs. flexural strength determined from marble specimens.

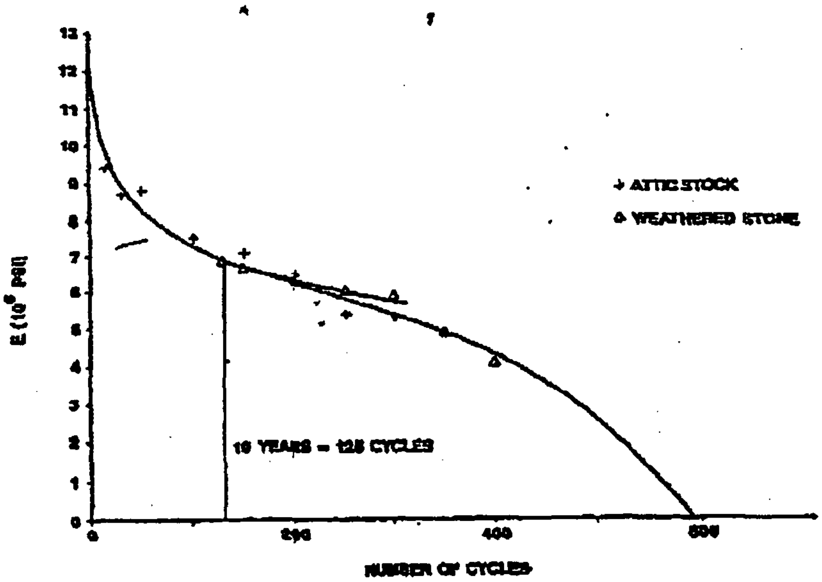

Figure 12. Number of durability test cycles vs. modulus of elasticity (E) determined from Georgia Golden Vein marble specimens.

We are currently exposing granite, marble and limestone specimens to natural weathering on the roof of a WJE building in Northbrook, Illinois, Figure 15. Figure 16 shows the sonic modulus curves determined after 1 ½ years of exposure. The curves can be compared with the data plotted in Figs. 5 through 7 for accelerated weathering. Note the similarity of the curves obtained during earlier accelerated weathering and the naturally weathered stone. These tests will be extended over a ten-year period.

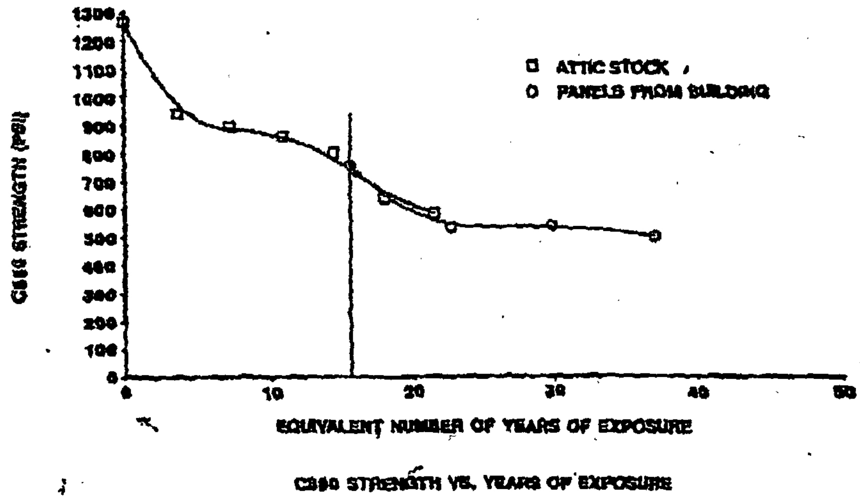

Figure 13. Comparison of durability test cycles to years of natural weathering determined from White Carrara marble specimens.

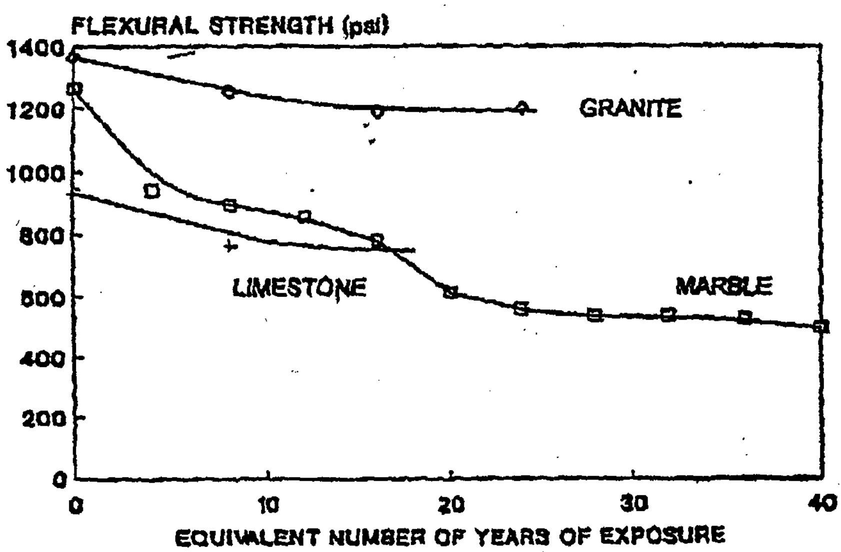

Figure 14. Flexural strength vs. years of natural weathering for marble, granite, and limestone.

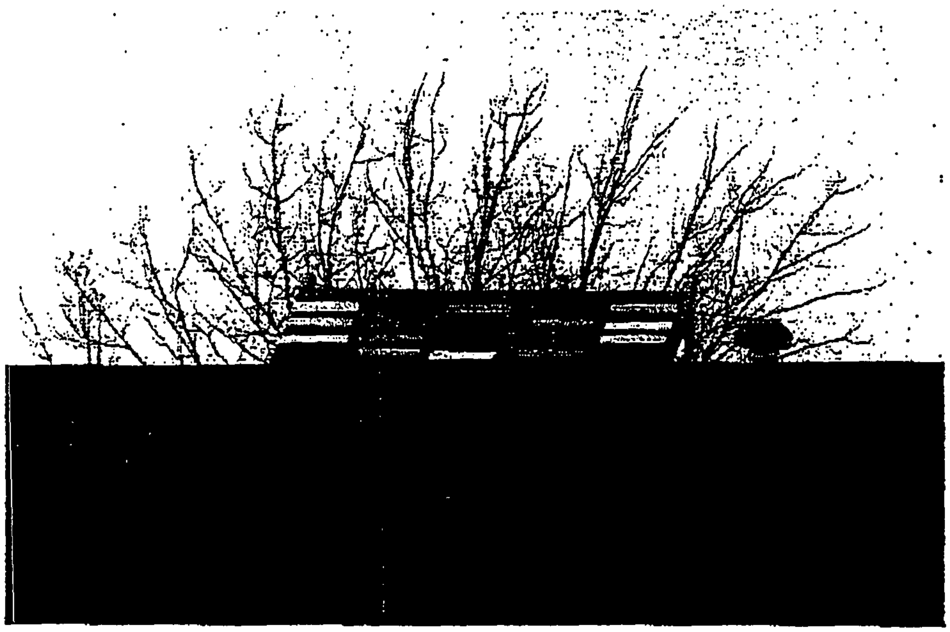

Figure 15. Stone test specimens exposed to natural weathering on roof.

Conclusions

The efforts described in this paper include the results from several years of durability (accelerated weathering) testing. These tests were performed to determine the long-term durability of thin stone to natural weathering. The accelerated weathering test procedure described in this paper will distinguish between a durable and less durable stone under natural weathering conditions. The procedure will also provide an indication of strength loss due to weathering. This data can affect the structural design for long-term reliability of thin stone panels on high-rise buildings.

The data obtained showed useful information can be obtained from thin stone specimens less than 50 mm (2 in.) subjected to the described accelerated aging test for at least 100 cycles. If comparison tests can be made using naturally weathered stone and unweathered stone, a relationship can be determined between number of cycles and time. The design can then be optimized by either increasing the thickness of the panel or reducing the unsupported span. These options will reduce load stresses and increase the service life of the stone.

Natural Weathering Study Test Results

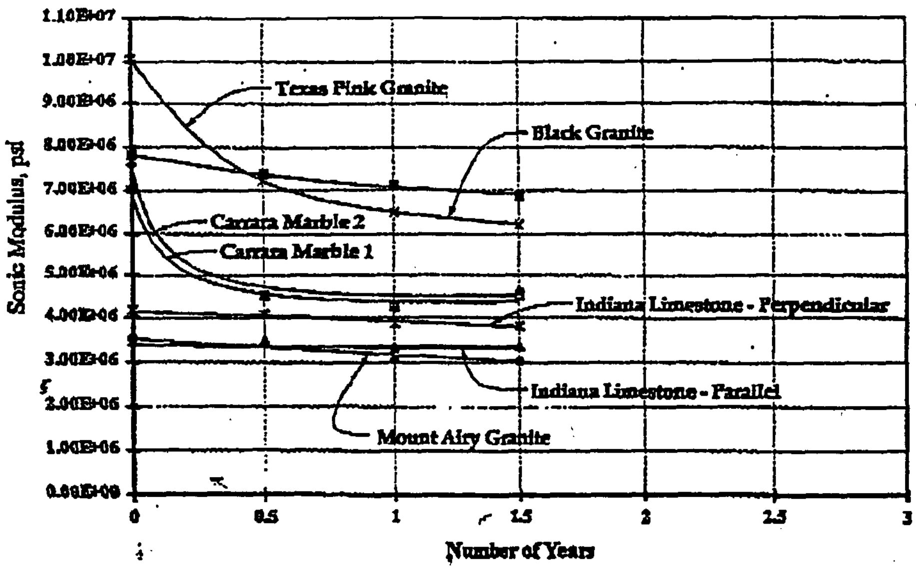

Figure 16. Number of years of natural weathering vs. modulus of elasticity (E) determined from various stone specimens on roof.

The weathering curves provided can be used for design by determining where the allowable working stress crosses the strength loss curve for the stone. When data for naturally weathered stone is not available, an estimated cycle per year can be used from the data in this paper. Assume 12 to 15 freeze-thaw cycles of the durability test procedure is equivalent to one year of natural weathering in a temperate climate.

We would like to acknowledge Mr. William G. Hime, Senior Consultant with Erlin, Hime Associates, (EHA) and Mr. Ross A. Martinek, Senior Petrographer with EHA, for their helpful review and comments in the preparation of this paper.

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ATTACHMENT 2

FREQUENCY DISTRIBUTION

	SPEED						Total	Mean Wind Speed (m/s)
	1-3	4-6	7-10	11-16	17-21	> 21		
N	.2	1.3	2.9	3.5	1.6	.9	9.9	6.3
NNE	.1	.6	1.7	1.9	.5	.2	5.3	5.9
NE	.1	.8	1.6	1.1	.2	0	3.9	5.2
ENE	.1	.7	1.3	.6	.1	0	2.9	4.5
E	.2	.8	1.3	.6	.1	0	2.8	3.9
ESE	.1	1.0	1.5	.7	.1	0	3.5	4.3
SE	.2	1.8	3.5	2.1	.4	.1	8.6	4.8
SSE	.2	2.4	6.5	8.5	1.6	.5	18.1	5.7
S	.3	2.3	5.4	6.5	2.4	1.0	17.3	6.1
SSW	.2	.9	1.8	2.7	1.2	.6	7.7	6.6
SW	.2	.6	1.0	1.0	.3	.1	3.3	5.9
WSW	.1	.4	.5	.4	.1	.1	1.8	5.0
W	.1	.5	.4	.3	.1	0	1.4	4.1
WNW	.1	.5	.6	.4	.1	.1	1.8	5.2
NW	.2	.8	1.1	.9	.5	.4	3.7	6.1
NNW	.1	.9	1.6	1.9	1.0	.6	6.5	6.6
VA	0	0	0	0	0	0	0	
CLM	0	0	0	0	0	0	1.7	
ALL	2.6	16.4	33.1	31.1	10.4	4.7	100	5.6
FREQUENCY OF CALMS .017 = 1.7%								

STATION ID: 723530 WIND ROSE-OKLAHOMA CITY WSFO AP, OK, US
YEARS: 1945-1990

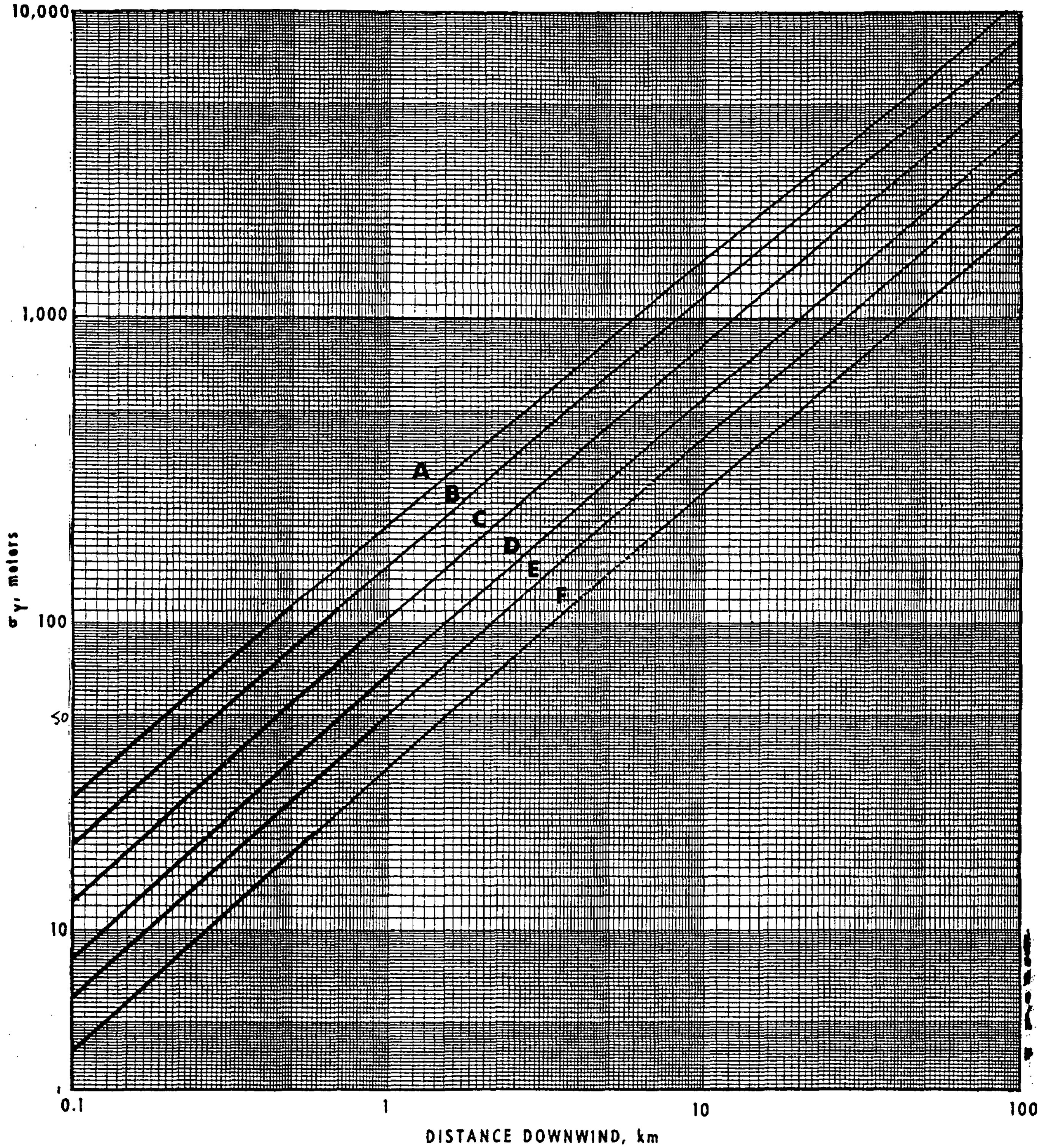

Figure 3-2. Horizontal dispersion coefficient as a function of downwind distance from the source.

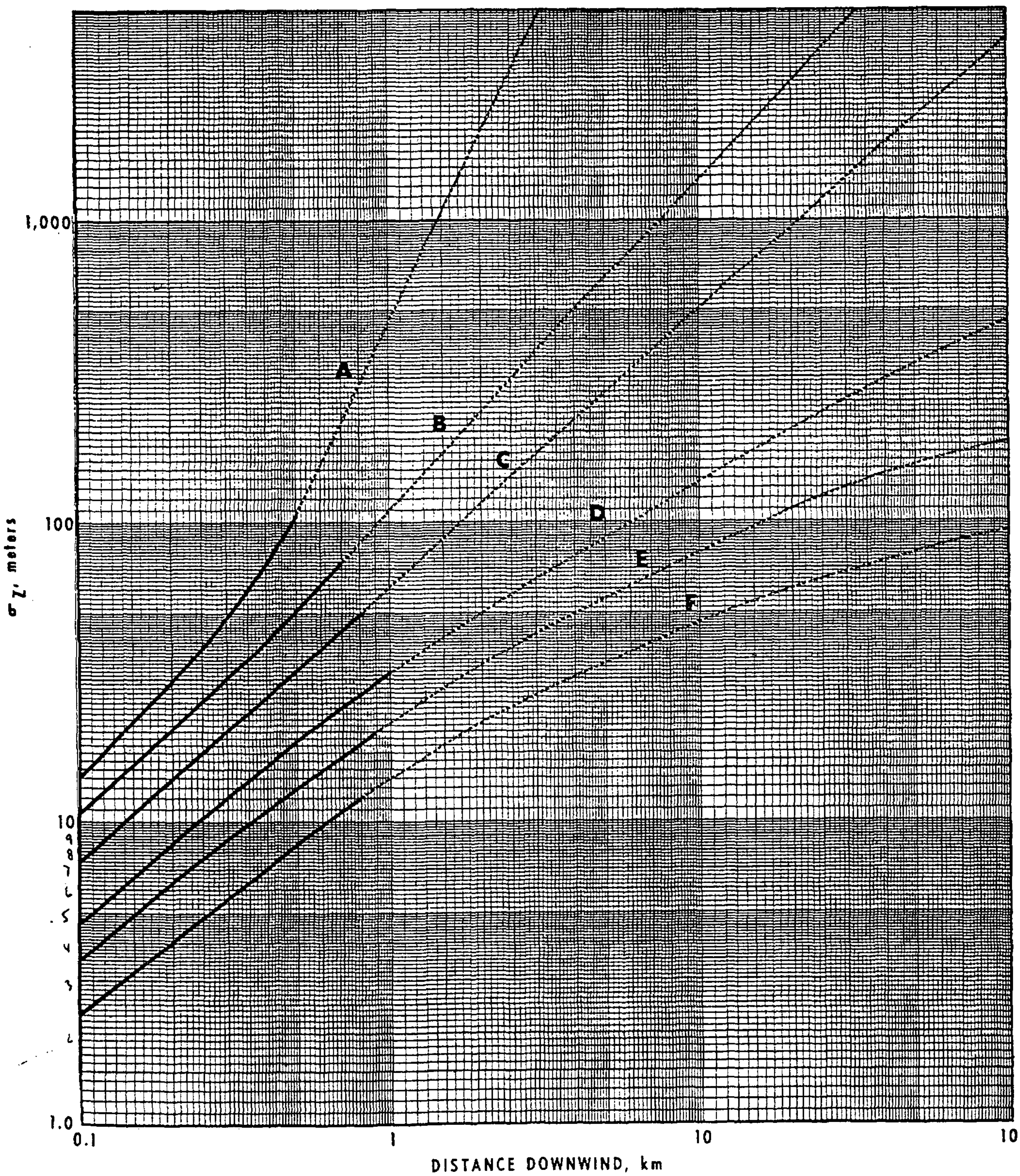

Figure 3-3. Vertical dispersion coefficient as a function of downwind distance from the source.

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ATTACHMENT 5

Distance (meters)	sigma y (meters)	sigma z (meters)	Q (Ci/s)	Chi (Ci/m^3)	Dose (mrem/y)
10	0.50	0.75	1.8E-12	1.36E-13	0.656742
20	0.94	1.22	1.8E-12	4.44E-14	0.213661
30	1.37	1.62	1.8E-12	2.30E-14	0.110779
40	1.79	1.98	1.8E-12	1.44E-14	0.069512
50	2.19	2.32	1.8E-12	1.01E-14	0.048424
60	2.59	2.64	1.8E-12	7.48E-15	0.03604
70	2.99	2.94	1.8E-12	5.83E-15	0.028076
80	3.38	3.22	1.8E-12	4.70E-15	0.022615
90	3.77	3.50	1.8E-12	3.88E-15	0.018686
100	4.15	3.77	1.8E-12	3.27E-15	0.015754

Notes:

1) Sigma y = 0.06x^(0.92) per "The Health Physics and Radiological Health Handbook", page 440.
2) Sigma z = 0.15x^(0.70) per "The Health Physics and Radiological Health Handbook", page 440.
3) Dose = Trespasser dose per year, assumes trespasser spends 12 8-hour days per year in the plume centerline.
4) Q is assumed to be a point source.
5) Distance is downwind from the point souce in plume centerline.