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FIRST QUARTERLY PROGRESS REPORT
Covering the Period October 9 to December 9, 1975

on

STUDIES OF ENCAPSULANT MATERIALS FOR TERRESTRIAL SOLAR-CELL ARRAYS

JPL Contract No. 954328

Encapsulation Task
Low-Cost Silicon Solar Array Project

to

JET PROPULSION LABORATORY
CALIFORNIA INSTITUTE OF TECHNOLOGY

Compiled by

D. C. Carmichael

December 22, 1975

This work was performed for the Jet Propulsion Laboratory, California Institute of Technology, sponsored by the National Aeronautics and Space Administration under Contract NAS7-100.

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Columbus Laboratories
505 King Avenue
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ABSTRACT

This, the First Quarterly Progress Report on JPL Contract No. 954328, covers work conducted from October 9 through December 9, 1975. The research is part of a five-task development project, the Low-Cost Silicon Solar Array Project (LCSSAP), being managed by the Jet Propulsion Laboratory for the Energy Research and Development Administration. The Encapsulation Task of this project includes four studies assigned to Battelle. Progress made in the two studies active during this initial reporting period is summarized in this report.

Study 1 of this contract is entitled "Evaluation of World Experience and Properties of Materials for Encapsulation of Terrestrial Solar-Cell Arrays". The approach of this study is to review and analyze world experience and to compile data on properties of encapsulants for photovoltaic cells and for related applications. The objective of the effort is to recommend candidate materials and processes for encapsulating terrestrial photovoltaic arrays at low cost for a service life greater than 20 years. Progress reported for this period includes consideration of the requirements of various potential encapsulant designs, identification of some of the most-used encapsulant materials, establishment of identification and documentation procedures, and interrogation of numerous data banks and other information sources for relevant information. Approximately 500 documents have thus far been selected for review by the materials researchers; these reviews are currently being conducted.

The objectives of Study 2, "Definition of Encapsulant Service Environments and Test Conditions", are to develop the climatic/environmental data required to define the frequency and duration of detrimental environmental conditions in a 20-year array lifetime and to develop a corresponding test schedule for encapsulant systems. Progress reported this period includes selection of nine geographic regions to be characterized, compilation of primary data sources, ordering of appropriate climatic and environmental data, development of methodology for statistical data analyses, and development of a numerical example to evaluate the methodology. Progress on both Study 1 and Study 2 is on schedule.

RESULTS OF WORK DURING QUARTER

Study 1. Evaluation of World Experience and Properties of Materials for Encapsulation of Terrestrial Solar-Cell Arrays

D. C. Carmichael, G. B. Gaines, R. B. Bennett,
J. A. Sliemers, and R. D. Igou

Introduction

Achievement of acceptable low-cost, silicon solar-cell arrays with a life of 20 years requires the selection and/or development of encapsulant materials and processes compatible with the photovoltaic array under terrestrial climatic conditions and which afford the required encapsulant life. The final process for producing the active silicon arrays and the engineering design of the array are yet to be evolved. The output of Study 1 is formulated to make a contribution to the design evolvement and materials and process selections through a review and analysis of world experience in the area of encapsulants and protective covers for solar cells and related devices. Out of the analysis will come a list of the most promising candidate materials and processes for encapsulating terrestrial solar arrays and a compilation of the properties of the candidate materials. Such criteria as cost, known and potentially achievable properties, availability, and ease of automation will govern the selection of candidate materials and processes. World experience and materials properties will be drawn from published and unpublished literature, personal contacts, and site visits.

Since the early 1950's when serious attention began to be directed to design of potential power systems based on the photovoltaic cell, development has continued at an increasing rate, with most emphasis being put on cells and arrays for space use. Primary concerns quite naturally fell on power-to-weight ratios and on radiation-damage resistance, owing to possible high fluxes of energetic electrons and protons. Choices of encapsulant materials, as well as substrates, were based heavily on these concerns. The literature and experience dealing with the problems of space arrays are rather extensive. However, since the system requirements for terrestrial arrays will be significantly different, the literature dealing with encapsulants for space applications can furnish only limited information. Accordingly, the scope of the world experience to be reviewed in this study has been broadened to include experience with protective covers, adhesives, encapsulants, pottants, windows, etc., for related applications. To cover the vast literature of possible relevance, considerable use is being made in this program of the large number of data banks to which we have access, as well as the available bibliographic literature.

To accomplish the review of world experience, the procedure being followed entails (1) identifying relevant articles and documents in the data banks, in the Battelle holdings, and in the bibliographic literature, (2) procuring those documents, (3) reviewing the documents for relevant information, (4) adding information from manufacturers and other unpublished sources, and (5) assembling and analyzing the information to reveal the materials and processes which might serve specific functions required by the total encapsulant system. Based on this analysis, candidate materials and processes will be recommended. For materials in the candidate list, property data which have not been revealed earlier in the search and which are considered to be of possible importance from total system considerations will be sought from engineering and related reference sources. If relevant property data are not available over important ranges of environmental parameters, this study will identify these needs for measurements in subsequent studies of the task. Since the start of the program in October, 1975, progress has been made in three major areas:

(1) The initial review of possible encapsulation requirements

(2) The establishment of informational sources and procedures

(3) The initation of information collection and review activities.

In summary, the requirements of possible encapsulant systems have been considered, along with several functional roles the encapsulant might play in the total system. Some of the most-used encapsulant materials have been identified. Procedures for identifying, reviewing and storage of documents have been set up. Many data banks and bibliographic sources have been identified and interrogated for relevant information. Approximately 400 documents and articles have been procured to date, and approximately one-third of these have been reviewed thus far. More details about the progress in these areas are given in the following paragraphs.

Technical Discussion

Initial Review of Possible Encapsulant Requirements. As noted, a primary output of this study is to be a list of materials and processes which potentially might be employed to encapsulate the cell array. Critical to establishing such a list is knowledge about the total system to be encapsulated. At present, the final array system has not evolved. That is, the structure of the array, the crystalline form of the silicon, and the processes used to fabricate the array cannot now be defined. To achieve technically acceptable arrays, clearly the processes and materials used for encapsulation must be compatible with the materials and processes of the basic cell array. These considerations weigh heavily in establishing the scope and approach to meeting the goals of Study 1.

As an aide to establishing the study scope and approach, initial effort was directed toward bracketing the possible range of requirements for encapsulant materials. Such requirements were studied by briefly reviewing available information concerning various programs now in progress throughout the world directed toward development of materials and arrays. Some of the observations made are given below:

(1) Although the total precise functions of the encapsulant cannot yet be defined, they may range from only a canopy covering the array to an integral part of the antireflecting (AR) coating, while serving at the same time as a barrier to the outside environment. In some possible designs, the encapsulant may also serve as a critical structural element: in others, it will not.

(2) The encapsulant, or some element of the encapsulant "system", may have to be chemically, electronically, and/or structurally compatible with many materials, including silicon, an AR coating (to be identified), structural metal, plastics, glasses, and materials used for the current conductors (silver, copper, gold, aluminum, and several possible alloys). Interactions with these materials could be controlling in determining the life of the encapsulant.

(3) The encapsulant could be a multimaterial system. For example, the silicon "window" exposed to the sun could be "covered" by one material; the remainder of the system could be "potted" by another. Clearly, the material requirements could be vastly different.

These considerations dictate that the study encompass a wide range of materials, as well as a wide range of processes by which the encapsulant is applied.

As an additional initial effort to help set the scope and approach, a list was made of the materials most used as encapsulants or array windows. Since much of the recent literature deals with space arrays, the materials identified strongly reflect service requirements that are different in some important respects from those of interest in this study, as previously noted. Moreover, the space-use influence leads to a strong concern for lightweight materials for substrates. Nevertheless, this experience furnishes information on the performance of these materials in some environmental conditions that will be important to terrestrial arrays.

Tables 1, 2, and 3 present the materials identified in the review, along with some information concerning processing methods and some comments regarding their use. Note that the selection of glasses used as "windows" is made not only for good transparency, but also for radiation-damage resistance. In some cases, transparency has not been a principal criterion for the selection of organic materials. Again, the requirements for encapsulants for terrestrial arrays will differ and the final listing will take on additional materials, especially when the critical cost factors for the raw materials and processing are factored in.

Informational Sources and Procedures. World experience with encapsulants for solar arrays and related applications is being drawn from both published and unpublished literature, communications with fabricators and material suppliers, BCL experience, and visits to appropriate organizations and existing array installations. So as to instigate early the review and analysis of the available experience, the program has emphasized, to date, the selection of data banks and bibliographic sources that may be interrogated quickly. Other sources will be addressed for those areas where insufficient information has been obtained. Since the experience with actual terrestrial arrays is rather limited to date, the current state of technology regarding encapsulants of possible interest will also have to be drawn extensively from the literature concerning related applications. The initially selected data bases interrogated are listed in Table 4, and the bibliographic and conference-proceedings sources searched to date are shown in Table 5.

For the study, procedures have been set up for identifying appropriate articles and documents, ordering, logging, and storage. Articles are tagged for review by appropriate researchers.

Tentative data formats have been set up to collect information from basically two kinds of documents. The first kind reveals information about performance of systems and components, not necessarily about encapsulants. However, such documents can reveal information about, for instance, the minimum life of an encapsulant in a particular environment, even though only system parameters may have been measured. The second kind reveals specific property data about a potential encapsulant material. Of course, information from the two kinds of review formats will be combined later to yield the selected list of candidate material and processes, and to reveal spots where important information is missing. Based on the work experience to date, the procedures and formats appear to be functioning well.

Information Collection and Review. Consistent with the initial aim to start the review and analysis process as soon as possible, interrogation of the data banks was initiated. These banks are listed in Table 4. All of these banks have now been interrogated, and the printouts have been received. Column 2 of Table 4 indicates the number of references identified. The references identified by the search were then screened by the materials researchers to select those of direct

TABLE 1. SOME GLASS COATINGS WHICH HAVE BEEN APPLIED TO SILICON SOLAR CELLS

Material	Processing Method	Organization	Comments
Corning 7070	Electrostatic sealing, ~400 C	Simulation physics (AFAPL funding)	• α match to silicon • Electron-radiation darkening can be bleached out with UV • Cover cost projected to be 10¢/cm^2 • Resists 300 cycles, -150 to +150 C
Cerium-stabilized microsheet (composition/supplier unknown)	Silicone adhesive	European Space Research and Technology Center (Noordwijk, Holland)	• Resists 100 cycles, -180 to +130 C • Resists electron-radiation darkening as well as fused-silica covers • Absorption below 0.36 µm, eliminating need for UV filter on cover
Corning 7070 Corning 7740 Schott 8830	RF sputtering (automatic system operated reliably several years)	Electrical Research Association (ESTEC funding)	• Residual stress negligible with 7070 covers 300 µm thick • 7070 coatings resist boiling water and 100 cycles, -180 to +130 C • 7070 resists electron-radiation darkening better than 7740 or 8330 • Cover thickness 40 percent less at cell edges • Cover costs estimated at 25¢/cm^2
Corning 1720 (alumino-silicate)	Electron-beam evaporation (200-300 A/sec for total thickness of 2-4 mils)	Heliotek (NASA Goddard and AF funding)	• Source premelting and deposition rates affect transmission and humidity resistance of coatings from 1720 • Deposited 1720 glass composition completely different than source • Residual stress in 1720 covers inversely related to deposition rate • Humidity resistance inferior to glue on covers • Good resistance to electron-radiation darkening and UV exposure • Cover cost estimated at 65¢/cell
TiO_2-SiO_2 glass	Unclear, but probably sintering of glass powder (250 C firing temperature)	Spectrolab	• Nonvacuum process AR coating • Environmental durability not established
Germanoborate	Fusion of glass powders near 500 C	GE Space Science Laboratories (AFAPL funding)	• Expansion coefficients of 6×10^{-6}/C still higher than silicon at 4×10^{-6}/C • 50-µm coatings have been applied • Costs not discussed by authors but glass processing costs would probably make process uneconomical for terrestrial cells
Fused-silica (quartz) and Corning 7070 Glasses	Electron-beam sputtering, radio-frequency sputtering, and ion-beam sputtering for fused silica, fusion of powder for 7070	AFAPL and NRL cooperative program which evaluated vendor-supplied cells	• Integral covers 1 to 2 mils thick suitable for space applications • Integral covers permit annealing or high-temperature operation • Integral covers eliminate need for adhesives and UV filter layers

TABLE 2. SOME POLYMERIC MATERIALS WHICH HAVE BEEN APPLIED AS PROTECTIVE COVERS FOR SILICON SOLAR CELLS

Material Class	Material	Resin Manufacturer
Halocarbons	FEP	Du Pont
	Aclar	Allied Chemical
	Tedlar	Du Pont
Polycarbonates	Lexar	General Electric
Polyimides	Kapton	Du Pont
Acrylics	Plexiglass	Rohm & Haas
	S-224	-
Epoxies	Stycast 1266	Emerson & Cuming
Polyesters	Mylar	Du Pont
Silicones	QR-4-3117	Dow Corning
	808 Resin	Dow Corning
	Sylgard 182	Dow Corning
	Sylgard 184	Dow Corning

TABLE 3. SOME POLYMERIC MATERIALS THAT HAVE BEEN APPLIED AS ADHESIVES AND PRIMERS IN SILICON CELL CONSTRUCTION

Material Class	Material	Manufacturer
	Adhesives[a]	
Silicones	RTV-41 (dimethyl)[b]	General Electric
	RTV-560 (methyl phenyl)[b]	General Electric
	RTV-566 (methyl phenyl)[b]	General Electric
	RTV-602 (dimethyl)[b]	General Electric
	XR-63-489 (dimethyl, 5% vinyl)[b][c]	Dow Corning
	D.C. 93-500	Dow Corning
	D.C. 96-069[b]	Dow Corning
	D.C. 96-080	Dow Corning
	D.C. 96-083[b]	Dow Corning
	D.C. 732	Dow Corning
	D.C. 734	Dow Corning
	D.C. 3144	Dow Corning
	D.C. 3145	Dow Corning
Epoxies	3M 1751 B/A Scotch-Weld[b]	3M
	3M 1838 B/A Scotch-Weld[b]	3M
	3M 2214 Scotch-Weld (Reg.)	3M
	3M 2214 Scotch-Weld (Filled)	3M
	3M 2216 B/A Scotch-Weld	3M
	3M 2290 Scotch-Weld	3M
	Abletherm 511	Abletech
	Ablefilm ECF 518	Abletech
	Ablefilm ECF 535	Abletech
Elastomeric	3M 404 Weatherban	3M
	3M 415	3M
	3M 800 Scotch-Seal	3M
	3M 1202-T Weatherban	3M
	3M 2126 Scotch-Grip	3M
	Primers	
Silicones	D.C. 1200	Dow Corning
	D.C. 1203	Dow Corning
	D.C. 1204	Dow Corning
	D.C. A-4094	Dow Corning
	Sylgard Primer	Dow Corning
	SS-4044	General Electric

(a) Some of these materials have also been used as covers.
(b) These are two-part adhesives.
(c) Processed for optical clarity — a Sylgard.

TABLE 4. DATA BASES INTERROGATED ON STUDY 1

November 30, 1975

Data Base	Number of Items Identified	Years of Coverage
SSIE (Research in Progress)	14	(Not specified)
Chemcon	22	1972-1975
NTIS	181	1964-1975
Engineering Index	24	1970-1975
INSPEC (Science Abstracts)	67	1970-1975
DDC	84	1965-1975
NASA (Letter Request)	253	1968-1975
ERDA RECON - File 1	11	(Not specified)
ERDA RECON - File 9	81	(Not specified)
ERDA RECON - File 10	23	(Not specified)
CIRC (AIR FORCE)	319	1964-1975
CIRC (Air Force)	192	1964-1975
Reliability Analysis Center (RADC) (By Phone)	(In process)	1965-1975

TABLE 5. BIBLIOGRAPHIC, JOURNAL, AND CONFERENCE-PROCEEDINGS SOURCES INTERROGATED FOR STUDY 1

(To December 9, 1975)

- Conference Records of the Sixth, Seventh, Eighth, Ninth, Tenth, and Eleventh Photovoltaics Specialists Conferences
- International Congress, "The Sun in the Service of Mankind", Paris, 1973, Proceedings of the Section on "Photovoltaic Power and Its Applications in Space and on Earth"
- The University of Wisconsin Engineering Experiment Station Report No. 21, "World Distribution of Solar Radiation", July 1966
- "Proceedings of the First ERDA Semiannual Solar Photovoltaic Conversion Program Conference", University of California, Los Angeles, California, July 1975
- Geliotekhnika (Russian Applied Solar Energy Journal), Vol. 1 through Vol. 11, No. 1-2
- "Solar Energy, A Bibliography", December 1974, U.S.A.E.C.
- "Energy, A Special Bibliography with Indexes", NASA, April 1974
- "Solar Energy Technology, State of the Art, An Annotated Bibliography", Ocean Engineering Information Service, 1975
- 9th and 10th Intersociety Energy Conversion Engineering Conference Proceedings, 1974 and 1975
- "Optical Coatings for Solar Cells and Solar Collectors – A Bibliography with Abstracts, 1964-October 1974", NTIS
- "Silicon Solar Cells, A Bibliography with Abstracts, 1964-July 1975", NTIS
- "Cadmium Sulfide Solar Cells, A Bibliography with Abstracts 1964-August 1975", NTIS
- "Optical Coatings for Solar Cells and Solar Collectors – A Bibliography with Abstracts, 1964-August 1975", NTIS
- Ninth, Tenth, Eleventh, Twelfth, and Thirteenth Annual Proceedings, Reliability Physics, IEEE Electron Devices Group and the IEEE Reliability Group
- "Solar Energy Index", Arizona State University, December 1974.

interest to this study. Duplicates are identified and eliminated by our ordering procedures. So far, the number of relevant, separate documents selected for review is in excess of 500.

As the second step in the document-collection process, relevant articles have been identified in the bibliographic and conference-proceedings sources given in Table 5. Comparison with the results of the earlier searches suggests that the major portion of the published literature regarding world experience on photovoltaic arrays is now identified. Of course, additional sources will continue to be sought, especially in the areas of other related applications and basic property data. Searches for nonpublished information have yet to start in any substantial way. Of those documents identified so far, approximately 400 have been received and review of these documents has begun. To date, an initial review has been made of about 150 documents.

Conclusions and Recommendations

The program is in too early a stage to draw firm conclusions or to make recommendations. Certain reflections may be in order, however. After 2 months of the planned 9-month period, the program is on schedule and the procedures for collecting the world experience appear to be working satisfactorily. The collection process itself has yielded a sufficient quantity of significant articles so that the review process is not being delayed.

The review of documents to date has revealed the expected result in that literature on space applications predominates. Information from such literature will have to be drawn by inference rather than directly for terrestrial applications, and thus will have to be screened carefully. Only limited life data on encapsulant materials for terrestrial environments is available and the actual experience to date is much shorter than 20 years, with service experience for less than 2 years being typical.

Plans for Next Quarter

Presently scheduled plans for the next quarter include continued effort on identifying and collecting relevant information and an increased emphasis on review and analysis. Specifically, future plans include:

(1) The completion of the identification of information data sources and the procurement of relevant documents, especially on related experience and on basic property data

(2) Greatly increased emphasis on procurement of information from nonpublished sources, including system fabricators and material suppliers, and on site visits to appropriate organizations and array installations

(3) Increased emphasis on information review and analysis, leading toward the identification of candidate materials and processes

(4) A continued effort on identifying possible array system requirements so as to identify, in turn, the appropriate encapsulant material requirements.

Study 2. Definition of Encapsulant Service Environments and Test Conditions

R. E. Thomas, R. M. Cote, J. L. Gemma, R. C. Behn, P. R. Sticksel, S. G. Talbert, H. B. Shirley, F. A. Sliemers, J. A. Hassell, R. B. Bennett, G. B. Gaines, and D. C. Carmichael

Introduction

The objectives of this study are to develop climatic/environmental data requisite to specifying test conditions that can be used to determine whether solar-array encapsulant materials will yield a minimum service life of 20 years in terrestrial environments and to develop a corresponding test schedule. The methodology for accomplishing these objectives involves compiling data characterizing the service environments representative of various regions of the United States. Climatic data (temperature, relative humidity, wind speed, etc.), solar-radiation data (direct, diffuse, ultraviolet, etc.), air-pollution data (particulates, sulfur dioxide, oxides of nitrogen, etc.), biological data (fungi, bacteria, etc.), and data related to miscellaneous hazards (salt, tornadoes, earthquakes, hail, etc.) are included in this compilation. These data are then to be analyzed statistically to quantify past environmental conditions and to develop a 20-year projection of the ambient environmental conditions likely to be encountered at selected geographic regions. Trends and/or irregularities in past environmental conditions are to be considered in developing these projections. Special attention is being focused on the frequency and duration of those combinations of environmental conditions that are likely to initiate and/or promote material degradation. These projected environmental conditions will furnish the basis for specifying the schedule of test conditions required for evaluating candidate encapsulant materials.

For Study 2, the progress this quarter included the following:

(1) A detailed technical plan and a baseline cost plan for the conduct of Study 2 were prepared and were presented to JPL representatives at Battelle on October 31, 1975.

(2) A tentative set of geographic regions for environmental characterization was jointly determined by representatives of JPL and Battelle on October 30, 1975.

(3) A list of primary data sources has been compiled.

(4) Data gathering was initiated. Climatic, radiation, and air-pollution data have been ordered.

(5) A numerical example, based on data for Columbus, Ohio, was developed in order to evolve and evaluate Battelle's proposed methodology. Preliminary results obtained from this example were presented to JPL representatives on November 21-22, 1975.

(6) A review of the selected regions and the data-processing procedures and methodology which have been developed are currently under way. It is expected that all procedures initially required will be established during December, 1975.

Technical Discussion

Selection of Geographic Regions. Representatives from JPL and Battelle jointly selected 9 sites for initial use. Substitutions for some of these sites may be warranted if major deficiencies in the available data are found. Moreover, it is expected that the data related to some of the sites will be analyzed in more detail than those obtained for other sites. In general, those sites which yield the most suitable data and which best serve to define important environmental conditions for encapsulant materials will be selected for the most detailed analysis. Each site is labeled by the name of a principal city in the area. It is understood, however, that such a label identifies a general geographical and climatic region centered around the city. The intent of Study 2 is to define environmental test conditions that characterize different environments, the environment of particular cities. On this basis, deficiencies in data may be supplemented, if necessary, by secondary data sources associated with surrounding cities or regions.

A summary of the current list of sites and some of their associated attributes follows:

(1) Phoenix, Arizona (semiarid, some pollution, high insolation, moderate altitude, high temperature)

(2) Albuquerque, New Mexico (semiarid, high altitude, high insolation, dust)

(3) Miami, Florida (semitropical, marine, high humidity, moderate insolation, high rainfall, high average temperatures)

(4) Bismarck, North Dakota (moderate humidity, low winter temperatures, large seasonal temperature variations)

(5) Cleveland, Ohio (pollution, high humidity, heavy snow, climatic mixtures)

(6) Los Angeles/Riverside, California (pollution, high diurnal temperature variation, moderate seasonal variation, extreme local conditions)

(7) Fairbanks, Alaska (low average temperature, large diurnal temperature variation, extreme low temperatures, low rainfall)

(8) San Antonio or Brownsville, Texas (warm climate, high insolation)

(9) Boston/Blue Hill, Massachusetts (humid, seacoast climate, fog).

It is expected that, depending on the quality of the available data, either San Antonio or Brownsville (but not both) will be retained as a study site. In general, the above sites are currently believed to be centered in geographic regions having favorable environments for photovoltaic installations (Phoenix, Albuquerque, San Antonio/Brownsville), or in regions having possibly abusive environmental factors affecting the encapsulant/arrays (Miami, Bismarck, Cleveland, Fairbanks, Los Angeles/Riverside, Boston/Blue Hill).

List of Primary Data Sources. The primary data sources selected for use in the conduct of Study 2 are listed in Table 6.

Data Requested. Climatic and solar radiation data for the selected geographic regions have been requested from NOAA, Environmental Data Service, National Climatic Center, Asheville, North Carolina. Air quality data have been requested for Phoenix, Arizona, and Cleveland, Ohio, from the National Aerometric Data Bank, Environmental Protection Agency, Research Triangle Park, North Carolina.

In the initial work, primary emphasis will be placed on the following variables: ambient temperature, relative humidity, wind speed, solar radiation, and time of day. Subsequently, data on other environmental factors will be added. Data on miscellaneous hazards (e.g., hail storms, tornadoes) will be gathered on a national basis and will be appropriately superimposed on the basic climatic data for the various site regions.

Methodology. Preliminary data-processing procedures involve the use of the Statistical Package for the Social Services (SPSS) to edit data, to obtain descriptive statistics for the edited data, and to classify the edited data into cells defined by selected ranges (class intervals) for each of the variables. The frequencies of occurrence and durations for various cells (combinations of variables) are then tabulated. For the climatic variables, initial attention has been focused on combinations of four variables: ambient temperature, humidity, wind speed, and insolation. The output of the descriptive statistical analyses includes the mean,

TABLE 6. PRIMARY DATA SOURCES TO BE EMPLOYED IN DEVELOPING ENVIRONMENTAL DATA FOR STUDY 2

Agencies related to the U.S. National Oceanic and Atmospheric Administration (NOAA)
Agencies related to the U.S. Environmental Protection Agency (EPA)
National Weather Service, Silver Spring, Maryland
National Severe Storm Laboratory, Norman, Oklahoma
Smithsonian Institution, Washington, D.C.
National Hurricane Research Laboratory, Coral Gables, Florida
Earthquake Engineering Research Center, Richmond, California
Polar Information Service, Washington, D.C.
National Academy of Sciences, Washington, D.C.
U.S. Air Force Air Weather Service, Washington, D.C.
Bureau of Air Pollution Control, Phoenix, Arizona
Maricopa County Department of Health Services, Phoenix, Arizona
Department of Environmental Conservation, Juneau, Alaska
Fairbanks North Star Borough, Fairbanks, Alaska
Department of Health, Bismarck, North Dakota
Environmental Protection Agency, Columbus, Ohio
Cleveland Division of Air Pollution Control, Cleveland, Ohio
Bureau of Air Quality Control, Boston, Massachusetts
Metropolitan Boston Air Pollution Control, Boston, Massachusetts
Environmental Improvement Agency, Santa Fe, New Mexico
Albuquerque Department of Environmental Health, Albuquerque, New Mexico
Texas Air Control Board, Austin, Texas
San Antonio Metropolitan Health District, San Antonio, Texas
Texas Air Control Board, Brownsville, Texas
Department of Pollution Control, Tallahassee, Florida
Metropolitan Dade County Pollution Control Department, Miami, Florida
Air Resources Board, Sacramento, California
Los Angeles County Air Pollution Control District, Los Angeles, California
Riverside County Air Pollution Control District, Riverside, California

standard deviation, maximum, and minimum for each of the appropriate variables. Resulting from the cell-classification methodology, histograms showing frequency and duration of various combinations of these four variables are generated. That is, the number of occurrences and time spent in a particular temperature range at a specific range of humidity, wind speed, and solar insolation are being tabulated. After classification of the climatic data into cells, the frequencies of transition from cell to cell may also be tabulated. These transition frequencies permit the exploration of techniques based on Markov chains, and may serve to define a suitable sequence of test conditions for each geographic region.

Tentative methods based on the Poisson distribution have been explored for possible application to the generation of 20-year forecasts of the expected number of occurrences of events associated with climatic variables, air-quality variables, and miscellaneous hazards, such as hail storms, freezing rains, etc.

Illustrative Numerical Results. Pending the arrival of data for the selected sites, the Study 2 team focussed attention on developing the methodology for the required analysis. To do this it was most effective to exercise the methodology using real data. It was found possible to obtain immediately the 1972 data for Columbus, Ohio, involving four variables: wet-bulb temperature, dry-bulb temperature, wind speed, and total radiation. The validity, amount of prior processing, editing, etc., for these data are virtually unknown. Consequently, the numerical results shown below are to be interpreted solely as a vehicle to illustrate developing the method of approach; the validity of the individual numerical results is not known.

Table 7 shows examples of the annual descriptive statistics obtained using SPSS for Columbus, Ohio, 1972. Daily, monthly, and 3-month seasonal statistics were also obtained.

TABLE 7. SOME 1972 CLIMATIC DATA FOR COLUMBUS, OHIO

Statistic[a]	Temperature, F Dry Bulb	Temperature, F Wet Bulb	Wind Speed, mph	Total Radiation, Btu/ft^2-hr
Minimum	3.	3.	<4.	2.
Maximum	95.	85.	30.	305.
Mean	52.7	48.5	7.07	46.1
Standard deviation	18.6	16.6	2.55	65.9

(a) Based on 2927 measurements taken at 3-hr intervals.

The annual maximum and minimum values from Table 7 were then used to define class intervals for each variable (Table 8).

TABLE 8. CLASS INTERVALS DEFINED FROM DATA IN TABLE 7

Coded Value	Temperature, F		Wind Speed, mph	Total Radiation, Btu/ft^2-hr
	Dry Bulb	Wet Bulb		
0	(3,26)	(3,23.5)	(4,10.5)	(2,78)
1	(26,72)	(23.5,64.5)	(10.5,23.5)	(78,229)
2	(72,95)	(64.5,85.0)	(23.5,30)	(229,305)

Table 8 shows, for example, that the dry-bulb temperature is coded 0 if it is greater than 3 F but is less than, or equal to, 26 F; the coded value is 1 if the dry-bulb temperature is between 26 and 72 F; and the coded value is 2 if the dry-bulb temperature is between 72 through 95 F. Corresponding codes hold for the other variables for their indicated ranges. An ordered set of codes then specifies a particular cell, or combination of variables. For example, a cell with an ID of 2101 indicates the simultaneous occurrence of:

(1) A dry-bulb temperature in the range 72 to 95 F

(2) A wet-bulb temperature in the range 23.5 to 64.5 F

(3) A wind speed in the range 4 to 10.5 mph

(4) A total radiation in the range 78 to 229 Btu/ft^2-hr.

For this example, each variable has three coded levels, 0, 1, and 2, and with four variables this gives a total of 81 possible cells with code ID's ranging between 0000 (all four variables at their low levels), to 2222 (all four variables at their high levels). As the variables change over time, the cell ID associated with the combination of variables may also change. Thus, transitions from cell to cell occur in accord with the changing variables. Such transitions may be used to "track" the successive changes in several variables simultaneously.

Table 9 shows a portion of the observed sequence of cell transitions for Columbus, Ohio, for 1972. The table shows, for example, that at the beginning of the year, the variables were in the ranges associated with Cell 1100 (intermediate-range dry- and wet-bulb temperatures, low range of wind speed, and low range of total radiation). Table 9 also shows that these four variables remained in Cell 1100 for four successive measurements taken a 3-hr intervals. At noon on January 1 the total radiation was in the intermediate range so a cell transition from 1100 to 1101 occurred. The next measurement time shows a return to Cell 1100 where the variables remain for the next 14 measurements, etc. A total of 1022 transitions from cell to cell occurred for the year. The year ended in Cell 1111.

TABLE 9. PORTION OF OBSERVED SEQUENCE OF CELL TRANSITIONS FOR COLUMBUS, OHIO, 1972

Date/Time, hr:min	Cell ID	Number of Successive Measurements[a]
1 Jan/00:01	1100	4
	1101	1
	1100	14
	1000	1
	1101	2
	1100	11
	0000	4
	0001	1
31 Dec/24:00	1111	1

(a) Measurements taken at 3-hr intervals.

Figure 1 is a histogram constructed from the cell-transition data for Cell 0000 (all four variables in their low ranges) for Columbus, Ohio, 1972. The

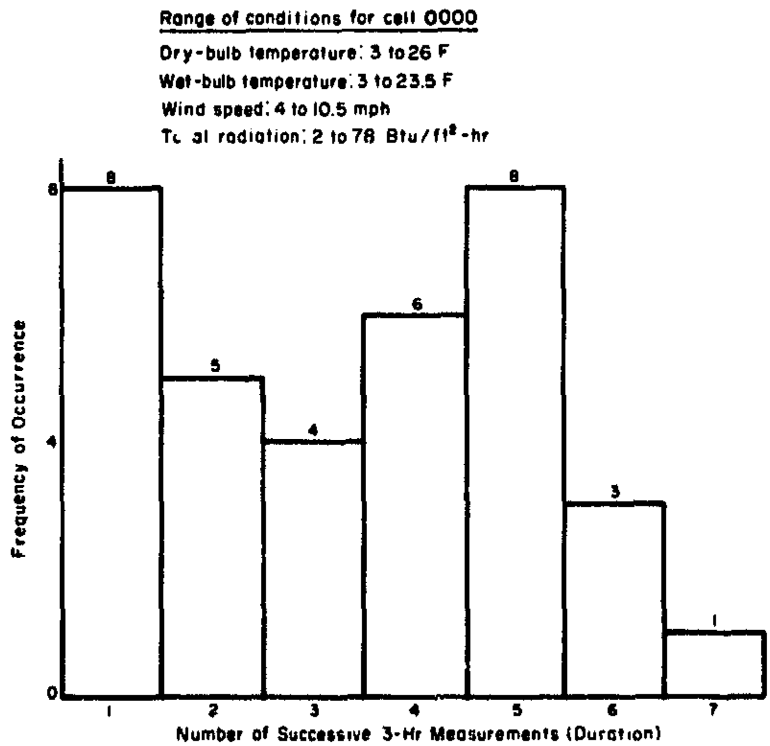

FIGURE 1. HISTOGRAM SHOWING FREQUENCY OF OCCURRENCE AND DURATION FOR CELL 0000 FOR COLUMBUS, OHIO, 1972

left bar of the histogram shows, for example, that during 1972 there were eight occurrences of Cell 0000 for a single 3-hr measurement; the next bar shows that there were five occurrences of Cell 0000 for two successive 3-hr measurements; and the last bar shows that there was one occurrence of Cell 0000 for seven successive measurements. Such histograms were constructed for the 31 cells found to occur in 1972 for Columbus.

In addition to the frequency of occurrence and duration (number of successive 3-hr measurements), the observed cell-to-cell transitions are used to define the transition frequencies. For example, for Columbus, Ohio, for 1972, it is found that Cell 1101 made 3 transitions to Cell 1102; 2 transitions to Cell 1110; 1 transition to Cell 1111; etc. In general, it is found, as would be expected, that most transitions occur among "adjacent" cells in which the ID numbers differ by one unit in one of the components as a result of a change in one variable.

The methodology for analyzing the frequency and duration of combinations of climatic conditions, as illustrated by the Columbus data, involves a general approach that may be stated as follows: (1) classify the environmental data into appropriate cells, and (2) count the frequency of occurrence of these cells over the historical time period associated with the observed data. In the absence of trends, an observed frequency of occurrence for a particular cell over a historical time base of 10 years would simply be doubled to obtain the expected frequency of occurrence of the cell over the next 20 years. The Poisson distribution is the simplest distribution for predicting such frequencies of occurrence. Consequently, this distribution is currently selected for use in the methodology for generating 20-year forecasts. When possible, the validity of this distribution will be checked against actual data, and if found deficient, appropriate modifications will be made. Because of a limited historical time base for some data, especially air-quality data, it is important to provide forecasts that can indicate the possible future occurrence of events, even though such events may not have been observed in the historical past. The Poisson distribution provides a method for making such forecasts.

Figure 2 shows the upper 95 percent bounds for the expected number of events in the next 20 years given the observed number and the historical time base. The figure is based on the Poisson distribution and shows, for example, that if no occurrences of an event E have been observed ($X_o = 0$) in the past 10 years, then the probability is less than 5 percent that more than six occurrences will be observed in the next 20 years. Similarly, if event E was not observed in the past 20 years, then E would not be expected to occur more than three times in the next 20 years. As a final example, if event E occurred three times in the past 20 years, then E would not be expected to occur more than eight times in the next 20 years. Such results may be useful to give conservative bounds for design purposes, but must, of course, be used with caution. Not all events are physically possible, so that predicted occurrences of impossible events are to be ruled out. In general, it appears desirable to restrict the application of this method to cells where data have actually been observed ($X_o > 0$) and to empty cells ($X_o = 0$) which are adjacent to occupied cells for which the occurrence of the event E is not judged to be impossible.

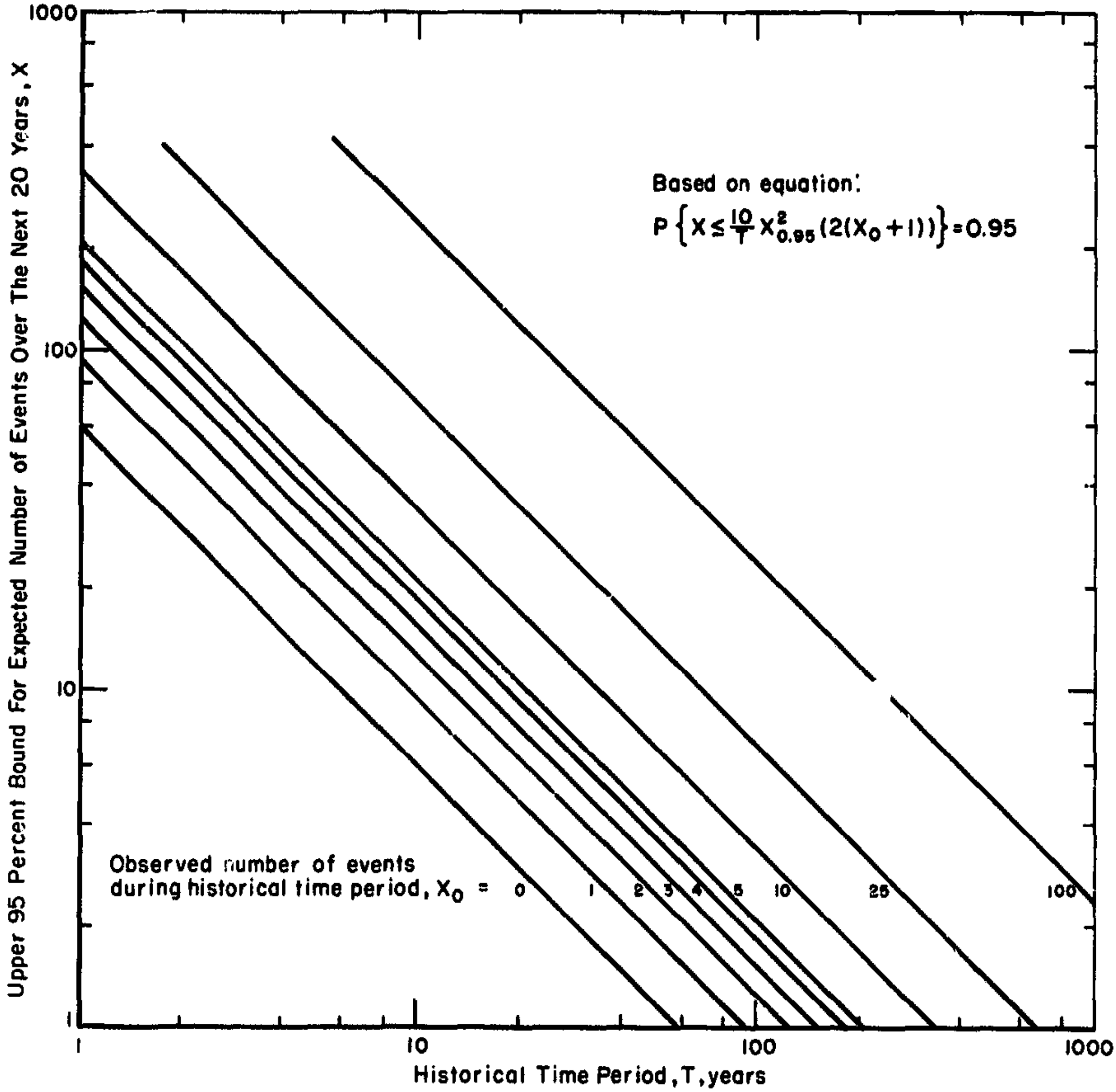

FIGURE 2. UPPER 95 PERCENT BOUNDS FOR THE EXPECTED NUMBER OF EVENTS IN THE NEXT 20 YEARS GIVEN THE OBSERVED NUMBER AND THE HISTORICAL TIME BASE

Conclusions and Recommendations

Based on the results obtained to date using the data for Columbus, Ohio, it is concluded that the methodology which has been developed as described above for characterizing terrestrial environments will provide a suitable basis for specifying test conditions for encapsulant materials to determine whether such materials will yield a minimum service life of 20 years.

Plans for the Next Quarter

The collection of data, statistical analyses, preparation of 20-year forecasts, and specifications of test conditions for encapsulant materials for selected geographic regions will be completed next quarter.

NEW TECHNOLOGY

In the initial 2-month period covered by this report, the technology is not sufficiently established to permit reporting of specific New Technology areas.