Research Agenda for Test Methods and Models to Simulate the Accelerated Aging of Infrastructure Materials: Report of a Workshop

Board on Infrastructure and the Constructed Environment, National Research Council

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Board on Infrastructure and the Constructed Environment
National Materials Advisory Board
Commission on Engineering and Technical Systems
National Research Council

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In Memoriam

The committee dedicates this report to the memory of Ann Chidester Van Orden, friend and colleague, who passed away while the report was in preparation. She will be missed by all who knew her.

Acknowledgements

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and knowledge of the subject matter, in accordance with procedures approved by the NRC Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the NRC in making this report as sound as possible and to ensure that it meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their participation in the review of this report: Robert Eagan, Sandia National Laboratories; Richard Gangloff, University of Virginia; James Jirsa, University of Texas; Charles Kurkjian, Telcordia Technologies, Inc.; Alton Romig, Jr., Sandia National Laboratories; George Scherer, Princeton University. While these individuals provided constructive comments and suggestions, it must be emphasized that responsibility for the final content of the report rests with the authoring committee and the NRC.

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Executive Summary

In the next several decades, a significant percentage of the country's transportation, communications, environmental, and power system infrastructures, as well as public buildings and facilities, will have to be renewed or replaced. Next-generation infrastructure will have to meet very high expectations in terms of durability, constructability, performance, and life-cycle cost. One way of meeting future expectations will be through improved, high-performance materials, but before new materials can be confidently deployed in the field, a thorough and comprehensive understanding must be developed of their long-term performance in a variety of applications and physical environments.

The National Science Foundation (NSF) has launched an initiative to promote the development of innovative short-term laboratory or *in-situ* tests for making accurate, reliable predictions of the long-term performance of materials and requested that the National Research Council (NRC) conduct a workshop as a reconnaissance-level assessment of models and methods that are being used, or potentially could be used, to determine the long-term performance of infrastructure materials and components.

The objectives of the workshop were to:

- define the objectives for infrastructure-based research that would use accelerated testing and computational simulations to determine life-cycle performance
- assess the state of the knowledge base to identify gaps and overlaps in research activities
- establish outcome-oriented metrics for setting research priorities
- identify promising lines of research and collaborations

As a result of the discussions at the workshop and the committee's deliberations, the committee appointed by the NRC to conduct the workshop believes that NSF should develop mechanisms (1) to promote the materials-based issues associated with the life prediction and reliability of infrastructure in order to attract the interest of scientists at the forefront of the study of complexity in materials research and (2) to foster collaborations among scientists and engineers engaged in life prediction and accelerated testing to encourage the transfer of knowledge, methods, and techniques among various fields and applications.

The workshop discussions revealed a general agreement that the "root cause" of the deterioration and failure of any system is related to materials, and that fault trees, risk analysis, and other related methods should be used to identify the most important degradation mechanisms. Accelerated-testing methods could potentially be used to rank the performance of materials in a real-world system but are not, at present, sufficiently reliable to make system-life predictions.

The committee concluded that a reasonable objective for infrastructure-based research is to develop methodologies for predicting the total and remaining life of a structure and that NSF should support materials research directed toward understanding the combined effects of degradation mechanisms and applying that understanding to quantitative predictions of system life.

Life-prediction models and accelerated-testing procedures have the potential to increase the deployment of new materials in infrastructure applications and to improve traditional materials. The government and professional organizations will play major roles in encouraging the acceptance of new materials.

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Workshop Synopsis and Committee Findings and Recommendations

INTRODUCTION

The United States spends an enormous amount of money annually to replace or repair deteriorated equipment, machines, and other components of the infrastructure. In the next several decades, a significant percentage of the country's transportation, communications, environmental, and power system infrastructures, as well as public buildings and facilities, will have to be renewed or replaced. Next-generation infrastructure will have to meet very high expectations in terms of durability, constructability, performance, and life-cycle cost. Knowing when to replace facilities and systems or how to prolong their useful lifetimes will also become increasingly important.

One way of meeting future expectations will be through improved, high-performance materials, but many barriers to the use of new materials in infrastructure will have to be overcome. Because infrastructure materials must perform in a complex physical environment defined by nonlinear relationships between multiple variables, a thorough and comprehensive understanding must be developed of their long-term performance in a variety of applications and physical environments before they can be confidently deployed in the field. Engineers will be reluctant to apply empirically based design methods to materials used outside the range of their observed performance (assuming empirical data exists at all) until their rates of deterioration can be accurately predicted, measured, and ultimately controlled and their life-cycles determined. Developing design methodologies and/or inspection, monitoring, and replacement strategies that could significantly extend the life of a complete system would then be feasible and would yield corresponding savings to society.

BACKGROUND

The Civil and Mechanical Systems Division of the National Science Foundation (NSF), recognizing that a major barrier to the development and deployment of advanced infrastructure systems and materials has been the difficulty of simulating long-term service conditions or collecting and analyzing data over long periods of time, launched an initiative in December 1997 on the Long Term Durability of Materials and Structures: Modeling and Accelerated

Techniques (the Durability Initiative). The aim of this initiative was to promote the development of innovative short-term laboratory or *in-situ* tests for making accurate, reliable predictions of the long-term performance of materials, machines, and structures and provide engineers with reliable data for using and specifying new infrastructure materials. Because this knowledge base involves many disciplines at varying levels of maturity, NSF requested that the National Research Council (NRC) conduct a reconnaissance-level assessment of the simulation-modeling and accelerated-testing methods that are being used, or potentially could be used, to determine the long-term performance of infrastructure materials and components.

Under the joint auspices of the Board on Infrastructure and the Constructed Environment and the National Materials Advisory Board, the NRC established a committee of 10 renowned scientists and engineers to plan and organize a two-day workshop on the subject. The committee decided the focus of the workshop should be on computational modeling and accelerated physical testing, the two primary ways of simulating long-term service conditions. Extensive research in these areas that has been done in other fields (e.g., aerospace, biomedical devices, nuclear weapons) could also be applicable to the determination of the life-cycle performance of infrastructure materials.

The objectives of the workshop are listed below:

- define the objectives for infrastructure-based research that would use accelerated testing and computational simulations to determine life-cycle performance
- assess the state of the knowledge base to identify gaps and overlaps in research activities
- establish outcome-oriented metrics for setting research priorities
- identify promising lines of research and collaborations

ORGANIZATION OF THE WORKSHOP

The Workshop to Develop a Research Agenda for Test Methods and Models to Simulate Accelerated Aging of Infrastructure Materials was held on August 24 and 25, 1998, at the NRC in Washington, D.C. In addition to the committee, the workshop was attended by 25 experts from academia, government, and industry who were chosen for their familiarity with life-prediction and accelerated-testing methods and represented a broad range of disciplines and perspectives. The first morning of the workshop was devoted to five prefatory presentations. The first afternoon and second morning of the workshop were devoted to discussions of life-prediction methodologies and accelerated-testing techniques, respectively. To maximize the interaction among the diverse perspectives represented at the workshop, participants were divided into five subgroups of experts from a variety of material disciplines and application areas. Two members of the committee were assigned to each subgroup. Each subgroup was requested to define objectives for life prediction and accelerated testing, identify useful methods for applying these techniques to infrastructure systems, and identify potential barriers and limitations. The subgroups presented their findings regarding the state of knowledge and what needs to be done, and in the final, plenary session of the workshop, the committee chair summarized the results of the roundtable discussions. This report summarizes the information presented during the workshop, the summary results of the roundtable discussions, and includes the briefings presented during the workshop. Subsequent to the workshop, the committee developed the findings and conclusions, identified research areas that should be pursued, and recommended the framework for a research agenda that could be implemented by NSF.

The initial plan for the workshop included an exploration of metrics that could be developed to guide research funding, (i.e., funding priority would be given to activities with the highest probability of improving predictive capability). These metrics were envisioned as measures of the combined potential for improving the knowledge base and the likelihood of success, essentially an "expected value." However, during the course of the workshop it became apparent to the committee that there was not enough time to deal with the issues of metrics in a meaningful way. Rather than do so superficially, the committee chose not to address metrics in this report. However, the committee does believe that this is a potentially fruitful area that should be considered by NSF.

The observations, findings, and recommendations for further research that follow are based on discussions facilitated by the workshop and the knowledge and experience of committee members. This report does not purport to be a comprehensive state-of-the-art assessment; rather, it represents the consensus of the committee regarding what was learned at the workshop and is intended to guide NSF in setting research priorities and evaluating proposals received in response to its Durability Initiative. Although the knowledge and participation of the workshop attendees were invaluable for the preparation of this report, the findings and recommendations represent the opinion of the NRC committee that was appointed for this purpose. The responsibility for the final content of the report rests entirely with the committee.

COMMITTEE FINDINGS AND RECOMMENDATIONS

Rather than highlighting differences, the presentations and discussions at the workshop strongly reinforced the common elements of different applications. Although materials deterioration mechanisms (i.e., the "deterministic" aspect of the problem) may change with different materials, applications, environments, and systems, the computational and analytical tools that provide a basis for predicting performance, lifetimes, and reliability can be adapted to study numerous systems.

The presentations and discussions also showed that an understanding of the performance of materials has usually progressed fastest when the material is very well characterized and the relevant property is controlled by a small set of mechanisms (e.g., semiconductors for electronic devices). Most participants, however, agreed that infrastructure materials tend to be very difficult to characterize because of the large number of degradation mechanisms, the broad range of regional variations (e.g., environments, constituent materials, and construction techniques and quality), and the strong nonlinear interactions that occur between them. In spite of the great improvements that have been made in the fundamental understanding of complex material systems (e.g., concrete), the prognosis for dealing, on a fundamental level, with complexities such as life prediction in real environments are very limited if they are based solely on the capabilities of traditional materials science.

Many participants were optimistic about the future of infrastructure materials research because of significant advances in instrumentation and analytical capability on the experimental side and a dramatic improvement in the simulation of material properties on the theoretical side. For example, although still in its early days, an exciting advance on the experimental side that was discussed at the workshop is the potential application of synchrotron x-rays for the nondestructive evaluation (NDE) of engineering materials. Examples on the theoretical side are advances in computational methods and computer capabilities, which provide new opportunities in computational simulation.

The workshop participants agreed that the study of complexity has become one of the foremost challenges in materials science, but fundamental research focused on infrastructure appears to be lagging behind other application areas, such as aerospace or biomaterials. This discrepancy was considered more a reflection of resource availability in other fields than of the level of interest within the research community. As a result of the discussions at the workshop and the committee's subsequent deliberations, the committee agreed that NSF should develop mechanisms (1) to promote the materials-based issues associated with the life prediction and reliability of infrastructure in order to attract the interest of scientists at the forefront of the study of complexity in materials research and (2) to foster collaborations among scientists and engineers engaged in life prediction and accelerated testing to encourage the transfer of knowledge, methods, and techniques among various fields and applications. One potential mechanism would be for NSF to continue to sponsor multidisciplinary workshops on modeling and accelerated-aging testing. These workshops could either be independent events or part of larger conferences on materials science.

A corollary problem for the development and deployment of new infrastructure materials that was identified during the workshop is that infrastructure involves many different types of systems and, consequently, very different technical and regulatory communities. If an infrastructure sector is well organized institutionally, technological developments find their way more easily into practice. In some sectors, however, the community is so fragmented that poor communication between research and practice has seriously hindered the deployment of new technology. In some cases, fundamental research is completely disassociated from practice. The committee believes that NSF should evaluate each infrastructure sector and attempt to organize its research across communities and disciplines so that (1) practical needs can be formulated as research goals and objectives and (2) the results can be transferred smoothly into practice. NSF should investigate organizational strategies to maximize its funding, including the establishment of highly interactive, focused programs that span many physically and scientifically distinct laboratories. NSF should also investigate ways to improve coordination both within its own organization (e.g., between the Engineering Directorate and the Division of Materials Research) and among other federal agencies with similar concerns (e.g., Federal Highway Administration).

Life-Prediction Modeling

Based on the information collected during the workshop, the committee concluded that a reasonable objective for infrastructure-based research is to develop methodologies for predicting the total and remaining life of a structure. These predictions would enable engineers to construct, manage, and maintain infrastructure at the lowest life-cycle cost. Thus, a useful life-prediction model must be able to (1) narrow the field of acceptable candidate materials for an application; (2) provide a quantitative rationale for the adoption of new materials, processes, or procedures; and (3) provide a basis for formulating maintenance and rehabilitation schedules to increase the longevity of infrastructure systems.

Improved life-prediction models will require (1) a fundamental understanding of the physical behavior of the materials incorporated into infrastructure applications, (2) models of the processes associated with that behavior, (3) observables (e.g., field experience and accelerated-testing methods) that can be used to validate and refine the models, and (4) methodologies for combining and validating models to estimate the time remaining until a system or structure can no longer meet its performance objectives.

The workshop discussions revealed a general agreement that the "root cause" of the deterioration and failure of any system is related to materials and that fault trees, risk analyses, and other related methods should be used to identify the most important degradation mechanisms. Evidence was also presented showing that specific, detailed materials investigations have been (and are being) conducted to quantify the behavior of materials as a function of time, environment, and other factors. However, incorporation of the results of these studies into models that can quantitatively predict the future performance and reliability of complex systems has not been uniform. For example, in the field of light guide fibers, reliability studies have been used to predict fiber lifetimes. There was little evidence presented at the workshop, however, that this is being done in other areas. Many materials studies provide exquisite detail of how chemical and physical changes occur in specific *laboratory* environments, but these data cannot always be related directly to system behavior in a real-world environment.

Accelerated-testing methods can be used to rank the performance of materials in a real-world system but are not, at present, sufficiently reliable to be used for making system-life predictions. The committee identified this as an area for further research. The Electric Power Research Institute (EPRI) has reported considerable success in using life-prediction modeling systems to formulate maintenance and rehabilitation schedules and increase the longevity of infrastructure systems. EPRI's work, however, should be followed up by more traditional materials research on the long-term mechanisms for failure. Very often the failure mode is associated with fatigue, but this is not well understood (and thus difficult to predict) for many of the materials used in infrastructure systems. A better understanding of the relationships between the onset of fatigue and remaining system life would be extremely beneficial. The current trend of pushing the real-life limits of many aging systems clearly calls for research on all aspects of fatigue and its relationship to component or systems failure.

The initiation and propagation of other degradation mechanisms (e.g., corrosion, diffusion, erosion, and wear) can also be important. Synergetic interactions that are not well understood can (and do) occur between these mechanisms. NSF should support materials research directed toward understanding these combined effects and applying that understanding to quantitative predictions of system life.

The three main life-prediction modeling systems discussed at the workshop were mechanistic-based models (both empirical and analytical); constituent-based models; and predictive damage models that include interactions between materials and structures (e.g., the corrosion of coated and uncoated rebars). The workshop presentations and discussions showed that life-prediction capabilities could be improved by state-of-the-art tools in characterization and simulation. Analytical characterization tools are now available that allow the key changes in materials microstructure and composition to be determined at increasingly high levels of sensitivity and resolution. These tools have the capability to determine mechanisms and measure changes at lower levels of degradation (i.e., shorter times at ambient or accelerated conditions). In addition, as computing tools are improved, they should be able to simulate materials performance more accurately with respect to microstructural features, such as anisotropy (e.g., crystallography or grain orientation), nonhomogeneity (e.g., inclusions, phase structure, or grain size), and defect structure (e.g., solutes, dislocations, or grain boundaries).

Thus, it may be possible to include more microstructural effects in the performance simulations of systems and capture the effects of changes in microstructure due to deterioration (e.g., wear, corrosion, or loading). Properly constructed computational simulation models can account for the effects of uncertainty not only in materials behavior but also in environmental and other conditions. The workshop discussion revealed that selected "high-end" tools and associated support are available at university, government, and private laboratories and that using or adapting existing capabilities may be less costly and more efficient than acquiring or building new, dedicated facilities.

The development of useful and valid life-prediction models will thus require the following advances:

- a better fundamental understanding of infrastructure materials and systems, including interfaces and degradation modes
- the development of behavioral models of materials and systems that span the continuum from microstructural to total-system performance
- the development of a standardized database of the characteristics and properties of materials and infrastructure systems
- a better understanding and definition of the characteristics and effects of the operational environments of materials and systems
- the development of sensors and test methods for monitoring and testing infrastructure systems during construction and use
- the design of valid, standardized, accelerated-testing methods and test-bed demonstrations of materials and systems to provide data for the validation and refinement of life-prediction models (see next section)
- the incorporation of economic models as a basis for accurate trade-off assessments and the determination of total life-cycle costs of implementing a new material or process

The committee firmly believes that the successful development of life-prediction models will require an interdisciplinary approach that draws on expertise from a number of fields, including materials science and engineering, structural engineering, and end-user engineering applications. Materials studies should be closely coordinated with system applications, and continuous comparisons of field data with laboratory data should be used to validate results. One way of facilitating this comparison is by using analytical characterization tools to quantify relevant microstructural and compositional aspects of accelerated-testing results and field-returned material. Simulation is another tool for making comparisons; simulated responses (based on materials models) can be compared to measured system responses.

Accelerated-Testing Methods

Based on the information collected during the workshop, the objective of accelerated-testing methods is to accumulate data on the long-term performance and degradation of materials in a time period of, at most, 10 to 20 percent of the expected lifetime of the infrastructure system. For example, accelerated-testing methods must be able to produce reliable data for a one hundred-year period in five to ten years, but preferably in less than two years. The results of accelerated-testing methods could then be used to validate and refine life-prediction models and thus help (1) reveal the performance of new and traditional materials in various service conditions, (2) narrow the field of candidate materials for a particular application, (3) screen and characterize new materials and systems, (4) determine the residual service life of existing structures, (5) suggest directions for product improvements, and (6) reduce the legal risk to the design and construction communities of utilizing new materials that have not been fully characterized in practice. Accelerated-testing methods, combined with real-time data and life-prediction models, can also help determine the long-term residual properties of current infrastructure systems.

Accelerated-testing methodologies must have the following characteristics:

- faithful replication of the processes that occur in practice, based on a thorough understanding of all of the possible degradation mechanisms, their kinetics, and the effects of their interactions
- the flexibility to evaluate multiple factors and identify those that should be the focus of future research
- the ability to account for scaling effects to ensure that laboratory results reflect true environments
- the ability to account for the possible effects of the infrastructure application, design, and quality of construction, all of which can significantly affect lifetimes
- monitoring of all environmental variables (e.g., temperature, humidity, ultraviolet exposure) and other variables (e.g., age, history, composition, porosity, and crack size) so the sensitivity of different mechanisms to variations in parameters can be determined and competing theories and models can be tested
- the ability to identify and track the physical phenomena resulting from degradation (and their interactions), preferably using NDE methods

The development of useful, valid life-prediction models will require the following advances:

- the development of NDE methods for characterizing the microstructure of materials (e.g., fresh, in-place concrete), the development of microstructure over time, and the growth of any degradation phenomena
- the development and standardization of nationally available databases that span all levels of the product chain (e.g., from laboratory to construction)
- the development of sufficient fundamental understanding of the damage mechanism to enable the prediction of component life outside of the accelerated-test database

Real-time tests in real environments (e.g., outdoors, *in vivo)* cannot be eliminated, however, especially in the last stages of product development. Field tests will also be necessary for validating models and providing definitive data on failure modes that cannot be accelerated.

LIMITATIONS AND BARRIERS

Life-prediction models and accelerated-testing procedures have the potential to increase the deployment of new materials in infrastructure applications and to improve traditional materials. However, the workshop identified several barriers to using model output or accelerated-test data as surrogates for empirical field observations and experience.

Traditionally, the construction industry has been cautious about adopting new materials and practices and has not been a significant force in materials-based research. The discussions identified two related reasons for this: poor integration of the engineering community into materials-based infrastructure research, and concerns about risk and liability. Engineers who design and construct infrastructure are not generally involved with materials research, either in their university training or in practice. Thus, end-users have had little input into materials-based research programs, and the transfer of results to the user groups has been minimal. Practicing engineers have little opportunity or incentive to develop the same level of trust in simulation models and accelerated laboratory tests as they have in their many years of empirical field observations. Because of the consequences of construction failures (legal, financial, and professional) and the engineers' exposure to risk, the validity of models and test methods will have to be proven over a wide range of applications, materials, and environmental conditions before their results will be widely accepted in the engineering community. The government and professional organizations will play major roles in encouraging the acceptance of new materials through the use of life-prediction models and accelerated testing.

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Background Presentations

This section of the report summarizes the seven invited presentations that were given during the course of the workshop. Five presentations were given during the introductory session on the first morning. Two were given prior to the subgroup discussion sessions on life-prediction issues (on the first afternoon of the workshop) and accelerated-testing (on the second morning of the workshop). Materials used during the presentations are found at the end of this report.

FIVE OVERVIEW BRIEFINGS

The first morning of the workshop was devoted to five overview presentations that were intended to convey the breadth of applications for accelerated-testing and life-prediction modeling in predicting systems performance. The first presentation was by John M. Hanson of North Carolina State University, who reviewed the aging and deterioration issues associated with civil infrastructure in the United States and current life-prediction methodologies and accelerated-testing methods applied to these systems. To encourage discussion between members of the various application communities present and to review the state of practice in other fields that could potentially be applied to civil infrastructure, the next four presentations focused on materials durability, reliability, and degradation issues in other fields. Jack E. Lemons of the University of Alabama and John Anderson of Case Western Reserve University spoke on the durability, reliability, degradation, and life-prediction issues associated with surgical implant devices. Richard Wachnik of IBM Microelectronics Division gave a presentation on the reliability and testing of high-performance integrated circuits. Carol M. Jantzen of the Savannah River Technology Center discussed vitreous materials for the long-term storage of hazardous and radioactive waste. The final presentation of the morning session, given by John Stringer of the Electric Power Research Institute, focused on life-cycle performance in the electric utility industry.

Infrastructure Aging and Deterioration

John M. Hanson,
North Carolina State University

Professor Hanson began his presentation by stating that many people currently believe that practicing engineers and the construction industry in the United States have been slow to change and have failed to take advantage of innovations in technology that could improve the nation's infrastructure. He believes that this view should be put into proper perspective by acknowledging the significant advances that have been made in construction in the past two or three decades. For example, a review of the record height of concrete buildings in the past two decades shows how advances in technology have been translated into the construction of taller buildings. Professor Hanson pointed out that the buildings, bridges, and tunnels constructed in the United States are comparable to similar structures around the world and that U.S. engineers and contractors are frequently sought as consultants in large construction projects around the world.

Professor Hanson also reminded the group that problems have often resulted from infrastructure materials and products being introduced before adequate experience with them had been gained and before their responses to the environment were fully understood:

- Field welding led to many of the fatigue and fracture problems that plague steel bridges.
- The introduction of Sarabond, an additive in masonry mortar, caused so many problems that it was withdrawn from the market, and hundreds of buildings required recladding.
- The epoxy coating of embedded reinforcements for concrete was supposed to prevent corrosion, but extensive use revealed that corrosion still occurred at pinholes or where the coating had been damaged during construction.
- Glass-fiber reinforced concrete for wall panels was subject to the unanticipated problem of bowing with exposure to sunlight.
- The marble panels used as cladding on the Amoco Building in Chicago had to be replaced with granite because of excessive bowing and degradation of strength from aging.
- The widespread use of timber treated with fire retardant in roofs has required major repairs because of unanticipated fractures after the materials had been in service for many years.
- Stucco applied over insulation on thousands of homes and buildings has had to be removed and replaced because the wood framing underneath has rotted; thousands of other buildings will probably have to be repaired for the same reason.

The defining conditions for a good structure, Hanson said, are adequate strength, acceptable serviceability, and long-term durability. Mechanical response factors, (i.e. load resistance, stability, fatigue resistance, and fracture resistance) must be addressed to ensure structural integrity.

According to Professor Hanson, the mechanisms of deterioration of the primary construction materials (i.e., concrete, steel, masonry, and timber) are quite well known, at least at the level required of an engineer. Concrete materials, as well as masonry materials, may be subject to scaling due to freezing and thawing, chemical attack, alkali-silica reaction, and corrosion of embedded reinforcements. The deterioration of structural steels is mainly due to corrosion, and the deterioration of timber is due mainly to decay. The rate of deterioration (i.e., durability) is greatly affected by environmental factors, as well as the details of construction. However, our understanding of these mechanisms is currently not sufficient to enable us to make quantitative life predictions. Additional research to enhance understanding of the basic mechanisms is critical to improving the durability of materials and structures.

Professor Hanson emphasized however, that reviews of many infrastructure failures have shown that very few occurred because of deterioration, except when the structure or system had an underlying design or construction defect. Some forms of deterioration seem to slow down or even stop after a period of time. Thus, the deterioration of a material or structure does not necessarily affect safety (See, for example, NRC, 1997 and Levy and Salvadori, 1992). Proper maintenance can prolong the life of materials by slowing their rate of deterioration.

Professor Hanson concluded his presentation by stating that, although the development of a concrete that does not shrink or creep or a steel that does not corrode would be of great benefit to the construction industry, the likelihood of such a material being developed is considered to be very small. Of course, advancements have been, and continue to be, made, but accurate tests for assessing the effects of environmental conditions on their lifetimes will require a much better fundamental understanding of the damage process before they can test results could be used for making life predictions. The adoption of these materials will also depend on their economic advantage in a highly competitive market. Thus, Hanson believes that the lifetimes of structures are more likely to be extended by improvements in the quality of construction, than the use of new materials.

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Infrastructure Considerations: Surgical Implant Devices

Jack E. Lemons,
University of Alabama,
and John Anderson,
Case-Western Reserve University

Dr. Lemons began by stating that the quality of life continues to be an important aspect of human welfare, especially as the population ages. Thus, two important issues for surgical implants and reconstructions are longevity and quality of function. The primary issues related to the longevity of implant devices include time of implantation, patient age and level of activity, and systemic health and level of function. Many devices constituted from synthetic materials (biomaterials) can function for decades, affording complete freedom from chronic pain and the continuation of normal activities. Some surgical implant reconstructive systems are known to have shorter lifetimes, however, and, in some situations, successive revisions may have even shorter lifetimes.

Dr. Lemons explained that devices for surgical reconstruction of the musculoskeletal system are subjected to high-magnitude forces (up to seven times body weight) and, because of the dimensions of the anatomical sites, device components can be subjected to mechanical stresses approaching the strength limits of the biomaterials. The biochemical environment is a harsh organic and salt-containing solution (saline), which can cause corrosion and reduce the stability of interfaces for attachments between devices and supporting tissues.

Using joint and tooth-root replacement systems as examples, Lemons and Anderson then reviewed the research, development, and application experience required for the introduction of a new materials design. Both speakers stressed the need for basic research and development, an understanding of the biomechanical and biochemical properties of the biological host, and the types and sources of degradation of biomaterials. They also explained why standardized methodologies would be helpful for monitoring device-related outcomes.

As High Performance Integrated Circuits Enter the National (and International) Infrastructure, How Do We Know They Are Reliable?

Richard Wachnik,
IBM Microelectronics Division

Integrated circuits are critical parts of the data and telecommunications infrastructure. Although a good deal of effort has been expended in trying to understand the detailed phenomena underlying the degradation of integrated circuits, determining their stability or reliability is often largely empirical. This is partly a reflection, Wachnik said, of the pace of change demanded by the economics of the industry. For many products, conservative design practices are used to minimize the risk of being left behind in performance or function. The rapid obsolescence of new products makes many aggressive practices conservative in hindsight. Thus, there is tremendous leverage in building reliability into the process and ground rules, and less in accurately describing degradation phenomena. Wachnik believes that this paradigm will change as integrated circuit technology matures. Barring unforeseen innovations, future competitive performance and density will depend on pushing reliability to its limits and providing product designers with easy access to the tools required to implement the most aggressive possible designs.

Integrated circuit technology can be divided into three subdisciplines: (1) devices; (2) chip-level interconnections; and (3) higher level interconnections and product reliability. The assessment and understanding of the reliability of integrated-circuits draws on many subdisciplines, including physics, chemistry, and materials science.

The most critical degradation mechanisms of silicon devices are hot carriers; dielectric degradation and breakdown; and radiation effects. Dielectric degradation

includes polarization, which affects performance, and leakage, which affects dynamic circuits and potentially affects static circuits. Radiation effects include single-event upsets as well as radiation damage. Assessing the reliability of silicon-based devices depends on knowing the locations of the energy carriers and the kinetics of defect formation by energetic carriers.

Accelerated testing can be done by increasing the applied voltage and internal fields to heat the carrier distributions. Temperature accelerates dielectric breakdown and polarization, and increased radiation flux accelerates radiation effects. The details of operation can then be used to scale the actual stress time for actual products. The understanding of hot-carrier degradation has progressed the most rapidly because of its close relationship with device design and the ease with which degradation kinetics can be examined using electrical characteristics of the device. Advancing the understanding of radiation effects, and especially dielectric breakdown, has lagged behind, partly because of difficulties in studying the mechanisms in detail.

The reliability or stability of the chip-level interconnections, or wires between the transistors, depends on assessing the kinetics of diffusion that are driven by stress gradients or momentum transfer from the carriers in the circuits. Electromigration failure can be accelerated by increasing both temperature and current. The acceleration of stress migration is problematic, however, because the increases in temperature that speed diffusion also tend to reduce the stress, which is the driving force of failure. The reliability of higher level interconnections or packaging is governed by mechanical factors (e.g., fatigue in particular) and electrochemical factors (e.g., moisture entering the circuit or its physical interface). Accelerated fatigue testing is done by increasing the amplitude during thermal cycling. Increasing humidity, temperature, and voltage can accelerate corrosion, as well as mechanical degradation from swelling or crack formation.

Wachnik explained that much of the focus on wiring, or interconnections, has been on describing semi-empirical kinetic models of time to failure. Successful, robust processes degrade gracefully, not catastrophically. Thus, making accurate parametric descriptions of graceful degradation available to product designers will be important in the long term. Wachnik also explained that the role of the dielectric separating the wires becomes critical when new materials are introduced. Although this has not yet become a problem, it is a significant and practical issue in defect-controlled reliability.

According to Wachnik, high-performance first-level and second-level packaging depends on providing high-density area connections between integrated circuits and the substrates and boards to which they are attached. The reliability of the interconnection requires that careful attention be paid to the mechanical properties of the material and solders, as well as their sensitivity to moisture. Because of trade-offs between cost and complexity, a careful evaluation of the role of moisture in the overall reliability of the product should be carefully evaluated.

Wachnik noted that his presentation was focused on concerns about the product wearing out when the lifetime of the product is limited by the material and/or its application. Another critical problem is finding, analyzing, and controlling defects that can cause early failures.

Wachnik concluded his presentation with a reminder that many opportunities remain for improving our understanding of the degradation of integrated circuits and improving predictive capabilities. Some areas related to process integration should be investigated in cooperation with industrial development and fabrication organizations, but some (e.g., physical and chemical investigations of degradation mechanisms) should be pursued by academic and research-oriented organizations.

Durable Glass for Thousands of Years? That Is the Question.

Carol M. Jantzen,
Savannah River Technology Center

Dr. Jantzen began by emphasizing that durable glasses used to stabilize a wide variety of hazardous, mixed (i.e., radioactive and hazardous), and radioactive wastes require modeling and assessments of the long-term stability of glass under a variety of environmental conditions. Because disposal scenarios vary greatly, the effects of kinetic parameters must also be modeled. Because the wastes being stabilized vary greatly, the effect of the composition of the glass on long-term stability must also be modeled. This is especially important for glasses used to stabilize highly radioactive waste. In these cases, the glass must be durable and retain radioactive species for thousands of years until they decay.

The chemical durability of glass is a complex phenomenon that depends on both kinetics (e.g., temperature, length of time the glass contacts a solution, exposed surface area, volume of the solution, and glass surface) and thermodynamics (e.g., glass composition, including the concentration of oxidized and reduced species; and glass homogeneity). Long-term durability modeling is usually based on acceleration of the dissolution process by the acceleration of one or more of the kinetic test protocol parameters. Extreme caution must be used to maintain the dissolution mechanism being modeled, to verify the long-term durability using natural analogs, and to perform service-life tests in actual disposal environments. The mechanisms modeled for glass durability are complex. Dissolution occurs when individual ions diffuse out of, condense in, or precipitate on the leached layer via one of four operative mechanisms: ion exchange; matrix dissolution; accelerated matrix dissolution; or surface layer (possibly of a protective or passivating nature) formation. These mechanisms control the overall durability of glass.

According to Dr. Jantzen, the modeling for the past 70 years of the durability of glass as a simple function of composition has shown that the durability response is nonlinear. Consequently, most durability models are either empirical or kinetic. Early kinetic models treated glass dissolution as a simple diffusion process. More recent models mathematically describe the glass dissolution mechanisms in the form of time-dependent master equations rather than as simple diffusion processes. Although the kinetic models describe the leaching behavior of a given glass, they cannot predict which of a given group of glasses will be most durable or whether a waste glass of composition A will be as durable as a given natural analog of composition B.

Dr. Jantzen concluded her presentation with a discussion of the thermodynamic hydration energy reaction model (THERMO™). Thermodynamic energy additivity was first proposed as a model for understanding the mechanistic relationships between glass structure, composition, and physical properties as early as 1945. Thermodynamic modeling was applied to medieval and Roman window glass in 1977. Modeling of complex waste glasses, initiated in 1982, resulted in the development of an improved model, THERMO™, in 1995.

THERMO™ linearly predicts the durability of glass from its composition by mechanistically modeling both general glass dissolution and accelerated glass dissolution. These mechanisms are modeled as a function of solution pH and weak acid-strong base equilibria. THERMO™ discriminates between the durability response of homogeneous or phase-separated glasses by a compositionally dependent, phase-separation discriminator. The model can predict the durability of glass in environmentally specific (e.g., pH-Eh) environments. Predictions of thermodynamic reaction products derived from THERMO™ can be used as input to computer codes used for reaction-path modeling and long-term durability assessments in a variety of disposal (repository) environments.

Life-Cycle Performance in the Electric Utility Industry

John Stringer,
Electric Power Research Institute

Dr. Stringer began his presentation by stating that the electric power system in the United States is a single, very large, interconnected entity. For the purposes of this presentation, however, he divided the system into three distinguishable components: generation, transmission, and distribution. The failure of a single component in any part of the electric power system, however, can result in serious and expensive consequences, and concerns about potential failures are increasing as the system ages.

Forty percent of U.S. power generating capacity will be more than 30 years old by the year 2000, and many parts will be considerably older. The generation component involves: coal-fired thermal systems, which are responsible for approximately 55 percent of the electricity generated in the United States; natural-gas-fired systems, which include Rankine and Brayton-cycle based systems; oil-fired systems; nuclear-power thermal generators, which currently represent about 20 percent of generating capacity; hydroelectric generators; and a very small percentage of other sources, including biomass-fired systems, wind turbines, and solar photovoltaic systems. The major lifetime issues are related to the significant fraction of thermal generating plants that are more than 25 years old, which was their notional lifetime. Many hydroelectric plants are even older, some having been built before the Hoover Dam, which is more than 60 years old.

Dr. Stringer said the power transmission and distribution components are also old and that the determination of their remaining life is complicated by their inaccessibility. For example, New York City has an extensive underground distribution system, some of which dates to the time of Edison. A significant part of the transmission component was put in place in the 1950s, and a second part was laid in the 1970s as the demand for power grew. Much of the transmission system consists of "cable in pipe." Examinations have shown that the cable itself may have a lifetime of more than 100 years, in the right circumstances, but that the conduit can deteriorate even if the casing (pipe) is unaffected. For example, the major failure that blacked out Auckland, New Zealand, appears to have resulted from a rise in the temperature of the cable, which caused the dielectric to fail; this failure appeared to be the result of a decrease in the thermal conductivity of the surrounding earth (the "root cause") related to weather conditions.

The main technique for avoiding failure is to attempt to determine the remaining lifetime of critical components to guide so-called "run/repair/replace" maintenance strategies. This approach involves (1) identifying the critical failure, or life-limiting, processes; (2) identifying the root causes of these failures; (3) determining whether a damage accumulation process can be identified that would allow a life fraction to be measured; and (4) developing instrumentation and inspection procedures for making predictions. EPRI has been developing models for several key components (e.g., combustion turbine blades, thick-section pressure components in steam systems, and boiler tubes) for a number of years. These are computer-based systems, in some cases resembling expert systems, to assist operators. In addition to deciding on remedial actions, these systems can also advise an operator of the effect on component lifetime of operations outside the nominal range. This approach has been advocated for dealing with infrastructure lifetime issues, Stringer concluded, and opportunities for advancement include the development of smart materials and systems.

TWO FOCUS BRIEFINGS

Two additional invited presentations were given during the course of the workshop. The first focus briefing, by Professor Kenneth Reifsnider of Virginia Polytechnic Institute and State University, was a discussion of life-prediction issues associated with infrastructure applications. The talk was given before the subgroup discussions, which took place on the first afternoon of the workshop. The second briefing, by Dr. Jonathan W. Martin of the National Institute of Standards and Technology, focused on accelerated testing. This talk was given on the second morning of the workshop, prior to the second subgroup deliberations.

Life-Prediction Approaches for Infrastructure Applications

Kenneth Reifsnider,
Virginia Polytechnic Institute and State University

For the purpose of life prediction, Professor Reifsnider described "life" as a function of time, cycles, or history to the "failure" of a "component." Failure was defined as unsuitability of service based on measurements of stiffness, strength, properties, appearance, and other factors. He defined a component as a structure, element, joint, bond, or sub-element. Life prediction for infrastructure is complicated by complex environments, long service lives (often exceeding 100 years), dynamic and stochastic applied conditions of load, strain, temperature, and moisture, and the quasi-brittle, reinforced materials of which infrastructure is constructed.

The basic issues in life prediction are understanding physical degradation processes at the basic or constituent level; modeling physical rate processes and the evolution of material states; establishing independent physical observables that track the processes; modeling the effects of combined processes; and validating models on "real" structures. He then described the four elements of life prediction:

- the need to describe the physical behavior, i.e., damage and failure modes
- modeling the behavior, including discrete events and multiple processes
- identifying measurable independent observables as inputs to the models
- actual life predictions, which are extensions, generalizations, and accelerations of laboratory experience

Professor Reifsnider explained durability and the damage-tolerance approach to life prediction, described relevant environmental factors, and described the specific mechanism of polymer degradation. He then presented data on a number of physical processes affecting service life and showed how these relationships could be incorporated into models of physical processes, and, ultimately, into more complex, predictive models. He described a damage accumulation approach for modeling the combined interactive effects of fatigue, creep, stress rupture, environment, and microdamage. This model has been applied to life prediction of a buried multilayer composite pipe and a highway bridge incorporating composite elements.

He then offered some observations on life prediction of composites. Changes in composite properties may not follow changes in matrix properties; property evolution may be substantial; and mechanical/thermal/chemical coupling may be significant. He noted the need for analysis and experiments on changes in material states; a materials science base for dependence relationships with time, temperature, and environments; and data with which to populate models.

Accelerated-Testing Approaches for Infrastructure Applications

Jonathan W. Martin,
National Institute of Standards and Technology

Dr. Martin described a reliability-based methodology for predicting the service life of infrastructure materials. The current durability methodology has been used in the construction and other industries for at least 80 years to simulate natural outdoor weathering factors in the laboratory. Improving the predictive capabilities of this methodology, however, has proved to be difficult. The problems have generally been ascribed to inadequacies in laboratory-based aging tests, especially the difficulty of isolating the ideal "balance of weathering factors." According to Dr. Martin, however, the failure of the current methodology can be attributed to faulty premises, inadequacies in experimental design, and the difficulty of replicating weather conditions realistically over time.

Dr. Martin then described an alternative reliability-based methodology that has a strong mathematical and scientific basis and a long history of successful applications in the electronics, medical, aeronautical, and nuclear industries. A number of experiments with coatings and other construction materials have already been conducted using this method, and the results indicate that this methodology will be generally applicable to a wide range of infrastructure materials, components, and systems (Martin et al., 1996).

He noted that implementation of a reliability-based methodology will require substantial changes in the current experimental procedures including: (1) the design of improved exposure equipment; (2) the systematic characterization of the initial properties of coating systems; (3) the quantitative characterization of each weathering variable in the in-service environment; (4) the quantification of macroscopic degradation and relating submacroscopic to macroscopic measures of degradation; (5) the use of experimental design techniques in planning and executing short-term, laboratory-based experiments, and (6) the development of computerized techniques for storing, retrieving, and analyzing collected data. Dr. Martin believes that these changes will be justified by greater reliability of the models and the speed of obtaining results.

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Appendixes

A

Workshop Agenda

Workshop to Develop a Research Agenda for Test methods and Models to Simulate Accelerated Aging of Infrastructure Materials
August 24 and 25, 1998
MONDAY, August 24, 1998

8:00 a.m.	Continental Breakfast (in Room GR 130)
(Open Session) 8:30 a.m.	**Welcoming Remarks: Workshop Objectives and Agenda**
	Richard G. Little, Director, Board on Infrastructure and the Constructed Environment
	David L. Morrison, Chair, Committee to Develop a Research Agenda for Test Methods and Models to Simulate Accelerated Aging of Infrastructure Materials
	Ken Chong, National Science Foundation
8:45 a.m.	**Self-introduction of attendees** (who you are, what you do)
9:00 a.m.	**Plenary Address: Issues in Infrastructure Aging and Deterioration**
	John M. Hanson, North Carolina State University
9:45 a.m.	**Break**
10:00 a.m.	**System Durability, Reliability, and Degradation Issues**
	Biomaterials - *Jack Lemons, University of Alabama* *James Anderson, Case Western Reserve University*
	Electronic Devices - *Richard Wachnik, IBM Corporation*
	Nuclear Waste Containment - *Carol Jantzen, Westinghouse Savannah River Corporation*
	Energy - *John Stringer, Electric Power Research Institute*
12:00 noon	**Lunch** (in meeting room)
(Open Session) 1:00 p.m.	**Focus Presentation: Issues in Life Prediction**
	Kenneth Reifsnider, Virginia Polytechnic Institute

1:45 p.m. **Roundtable Discussions**

Define objectives for life prediction in infrastructure systems
Useful methods for infrastructure systems
Limiting areas

3:45 p.m. **Break**

4:00 p.m. **Synthesis of Roundtable Discussions**

What is the state of knowledge?
What needs to be done?

5:00 p.m. **Recess for the Day**

TUESDAY, August 25, 1998
8:00 a.m. Continental Breakfast

(Open Session) 8:30 a.m. **Focus Presentation: Issues in Accelerated Testing**

Jonathan Martin - National Institute of Standards and Technology

9:15 a.m. **Roundtable Discussions**

Define objectives for accelerated testing in infrastructure applications
Useful methods for infrastructure systems
Limiting areas

10:45 p.m. **Break**

11:00 p.m. **Synthesis of Roundtable Discussions**

What is the state of knowledge?
What needs to be done?

12:00 noon **Lunch**

1:00 p.m. **Discussion of Promising Areas**

Setting priorities
Developing the research agenda

4:00 p.m. **Adjourn**

B

Biographical Sketches of Committee Members

DAVID MORRISON (chair) is adjunct professor of nuclear engineering at North Carolina State University and has recently retired as director of the Office of Nuclear Regulatory Research, U.S. Nuclear Regulatory Commission. He was awarded a B.S. from Grove City College and a Ph.D. in chemistry from the Carnegie Institute of Technology. His expertise includes nuclear reactor safety, specifically the life prediction of complex systems. Dr. Morrison was previously a member of the National Materials Advisory Board of the National Research Council (NRC) and has chaired and participated in numerous NRC studies.

CHARLES E. BAKIS is associate professor of engineering science and mechanics at the Pennsylvania State University. He was awarded a B.S. in mechanical engineering from Lehigh University and a Ph.D. in engineering mechanics from Virginia Polytechnic Institute and State University. His research interests include the manufacturing, performance, evaluation, and mechanics of infrastructure materials. His recent research has focused on the structural applications, accelerated-testing methods, and health monitoring of fiber-reinforced polymer reinforcement for concrete.

ALASTAIR N. CORMACK is professor of ceramic engineering in the School of Ceramic Engineering and Sciences at Alfred University. He was awarded a B.A. from the University of Cambridge and a Ph.D. in chemistry from the University of Wales, Aberystwyth. His research interests include: inorganic solid state chemistry, including nonstoichiometry and defect structure; the influence of composition on complex crystal structures and their behavior; computer-based simulation at the atomistic level of complex defect behavior; and mass transport in inorganic solids. Dr. Cormack has participated in several activities for the U.S. Department of Energy related to the properties and performance of glasses and ceramic materials in extreme environments.

THOMAS GATES is a scientist in the Mechanics of Materials Branch at NASA Langley Research Center. He received his M.S. and Ph.D. degrees in aeronautics and astronautics from Purdue University. Dr. Gates' activities at NASA have focused on basic and applied research in the area of constitutive model development for advanced polymer-composite materials. His area of expertise is the formulation of new constitutive relationships and associated testing methods for characterizing the time-, rate-, and temperature-dependent mechanical response of high-strength, high-stiffness polymer matrix composites.

CAROLYN HANSSON is vice president of university research at the University of Waterloo. She received a B.SC. and a Ph.D. in metallurgy from Imperial College, London University. Her research concerns the development and deterioration of concrete-based infrastructure materials. Dr. Hansson was a member of the National Materials Advisory Board and a chair of the NRC Committee on Nonconventional Concrete Technologies for Renewal of the Infrastructure.

DAVID JOHNSON is head of the Metallurgy and Ceramics Research Department of Lucent Technologies. He was awarded a B.S. and a Ph.D. in ceramic science from the Pennsylvania State University. His research interests include the sol-gel processing of glass and ceramics for the fabrication of large pieces of transparent high-silica glass and the life prediction and accelerated aging of fiber-optic materials. He is a member of the National Academy of Engineering.

RICHARD SALZBRENNER is manager of the Materials Performance, Aging, and Reliability Department at Sandia National Laboratories. He was awarded a B.S. from the University of Notre Dame and a Ph.D. in metallurgy and materials science from the University of Denver. Dr. Salzbrenner's areas of research are the effects of materials aging and degradation on system performance and materials-based life prediction of weapon subsystems.

ROBB THOMSON is a senior research scientist at the National Institute of Standards and Technology. He received an M.S. from the University of Chicago and a Ph.D. in physics from Syracuse University. His primary area of research concerns imperfections in solids and their effects on mechanical properties.

ANN CHIDESTER VAN ORDEN was an assistant professor in the Mechanical Engineering Department of Old Dominion University. She was awarded a B.S. from Utah State University and a Ph.D. in engineering materials from the University of Maryland. Her main research interests included the development of failure analysis and life-prediction methodologies for large structures and vessels.

JOHN T. WATSON is acting deputy director of the National Heart, Lung, and Blood Institute for the National Institutes of Health. He was awarded a B.S. from the University of Cincinnati, an M.S. from Southern Methodist University, and a Ph.D. in physiology from the Southwestern Medical School, University of Texas. He is a member of the National Academy of Engineering. Dr. Watson's area of research is the development of life-prediction and accelerated-aging methodologies for biomaterials.

C

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