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# Environmental Cracking—Does It Affect You?

## by Donald O. Sprowls

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### Is Environmental Cracking a Problem?

A highway bridge collapses and many people are killed, drawing attention to the dangerous conditions of all aging structures. A high pressure gas line explodes, killing residents and causing extensive property damage. Cracks appear in main structural parts of first line defense fighter planes. Space shuttle launchings are delayed by the discovery of stress-corrosion cracks in critical components. Nuclear power plants are shut down, with tube failures and other sensitive parts in jeopardy due to environmental attack. This list could be extended easily, to touch the life of nearly every American citizen.[1]

Environmental cracking is a costly form of premature fracture of metal structures touching all corners of life in the United States and other industrially developed nations—and it is *very* costly in terms of public safety and property damage. There is hardly a metal known that does not have alloy systems susceptible to environmental cracking of some sort, and this is the case for certain polymeric materials, as well.

Is environmental cracking a problem? Yes!

### What is Environmental Cracking?

Environmental cracking is a generic term that includes various environmentally assisted cracking phenomena such as stress-corrosion cracking (SCC), corrosion fatigue cracking (CFC), hydrogen stress cracking, sulfide stress cracking, liquid metal embrittlement and other forms of environmentally assisted embrittlement. A distinction among certain of the major causes of premature fracture is shown in Figure 1. This present overview will deal only with SCC and CFC, which are covered by the scope for ASTM Subcommittee G01.06 on Stress-Corrosion Cracking and Corrosion Fatigue, part of Committee G-1 on Corrosion of Metals. For more detailed information, readers are referred to the several references.

### Relationship Between SCC and CFC[2]

SCC is a phenomenon in which time-dependent cracking occurs in a metal product when certain metallurgical, mechanical and environmental conditions exist simultaneously. CFC is a related process but the mechanical driving force is cyclic rather than static, as in SCC. It also differs from SCC by virtue of the universal susceptibility to CFC of pure metals and alloys. When hydrogen is generated as a product of the corrosion reaction causing localized hydrogen embrittlement in some metallic alloys, this embrittlement may interact with the SCC or CFC processes or lead to hydrogen stress cracking (See Figure 1). A common feature of each of these processes is subcritical crack growth, during which cracks grow from existing flaws or initiation sites and increase to a size at which catastrophic fracture occurs. Such fracture occurs when the combination of stress and crack growth increases the stress intensity factor to a value equal to the facture toughness of the material. These phenomena are not mutually exclusive, however, as the processes can have interactions under certain conditions. Failures under all these conditions are regarded are premature fractures because they generally occur at stress levels far below customary design stresses.

### Is ASTM Involved?

ASTM Committee G-1 on Corrosion of Metals was established on January 21, 1964, by action of the ASTM Board of Directors as a means of consolidating similar activities within a number of the ASTM committees. One of the original subcommittees was G01.06. During the ensuing years, members of this subcommittee developed the first SCC testing standards and have conducted symposia documented by eight ASTM Special Technical Publications. ASTM test standards represent a consensus of the best currently available test procedures, supported by experience and adequate data from cooperative testing.

The interest of ASTM in the field of environmental cracking existed long before the creation of Committee G-1, however, as the Society in 1918 held topical discussion on "season" and "corrosion cracking" of brass.[3] Later, in 1945, ASTM published proceedings of a Symposium on Stress-Corrosion Cracking of

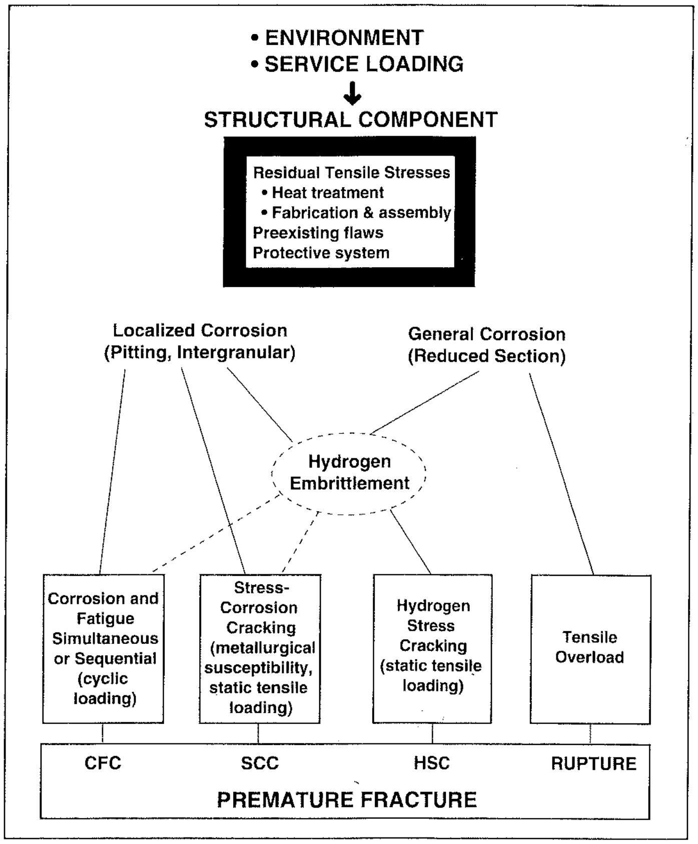


*Figure 1. Causes of premature fracture influenced by corrosion of a structural component. Source: Reference [9].*

Metals jointly with the American Institute of Mining and Metallurgical Engineers.[4]

Is ASTM involved? Again, the answer is yes!

### Stress-Corrosion Cracking

Each of the three conditions for SCC mentioned previously is not only vital for the process, but is also influenced by many complexing variables, as follows:

1.) A metallurgical susceptibility must exist in the metallic alloy, influenced by the chemical composition and metallurgical treatments of the mill product. In general, SCC is most likely with the higher strength alloys and tempers of the metal.

2.) The mechanical condition is a tensile stress/stress intensity in the metal surface—never a compressive stress. The state of stress is a major variable, and the theory of linear elastic fracture mechanics (LEFM) provides a useful method for treating the stress factor in the presence of a crack.

3.) The environmental condition is controlled by chemical and electrochemical variables that are too numerous to mention. Environments associated with SCC of the major high strength structural alloy systems range from natural environments such as sea water, fresh water, marine and industrial atmospheres to complex chemical environments. There are, however, a number of metallic alloys that are susceptible only in the presence of certain chemical species.

The SCC susceptibility of a broad range of alloy systems in various types of environments and industrial applications may be found in three recent publications. [2, 5, 6]

### Testing Techniques

Crucial to any SCC evaluation program is the choice of an appropriate testing technique and the interpretation of the test results.

#### General State of the Art

Although it might seem ideal to use an actual structural component in a simulated service test, this is not practical for most purposes. Rather, it is more expedient to use relatively small precision-made test specimens stressed under controlled conditions.

In the early days of stress-corrosion testing during the 1920s to 1970s, pass/fail tests were made using statically loaded smooth specimen configurations and specific test environments that were primarily industry oriented. During the late 1960s two new accelerated testing techniques based on novel mechanical procedures were introduced.[7, 8] One technique involves statically loaded mechanically precracked test specimens analyzed by using LEFM concepts. The other technique involves application of the load during exposure to the corrodent at a very slow constant strain rate while monitoring both the load and the extension of the specimen until fracture. These newer techniques are more severe than the older techniques and may detect susceptibility to SCC not detected in some materials by the traditional procedures. The older techniques, however, are still advantageous for many purposes.

#### ASTM Standards

The development and use of appropriate standards for SCC testing in both research and characterization of materials for industrial applications is extremely important if continued improvements in the literature database are to be realized. ASTM has been the leader in this endeavor dating back to the early 1970s. Fifteen such standards are published in the current *Annual Book of ASTM Standards* (Vol. 03.02), and three additional ones are in process. Detailed information and general guidance on standard testing techniques are given in References 9, 10, and 11. There presently is no single foolproof testing technique that is free of special limitations on test conditions and free of problems with interpretation of test results.

#### Interpretation of Test Results

Interpretation of test results is the most fallible part of SCC testing and evaluation because it is followed by conclusions and decision-making. The test data provide criteria of SCC susceptibility that are at best imprecise and test dependent; and the limitations of the tests must be understood (Figure 2) to enable proper interpretation of the test results. Although these criteria are not actual properties of the materials in the same sense as mechanical properties, they are nevertheless useful for ranking the expected performance of metals and alloys. Numbers such as thresholds and velocities for SCC, which are eagerly sought by engineers and designers, must be interpreted with caution. [9, 10, 11]

### Stress-Corrosion Cracking: Can We Avoid It?

SCC problems can be avoided by careful attention to the choice of alloys and tempers and especially by the adherence to design and assembly practices that are based on experience and an understanding of SCC factors.

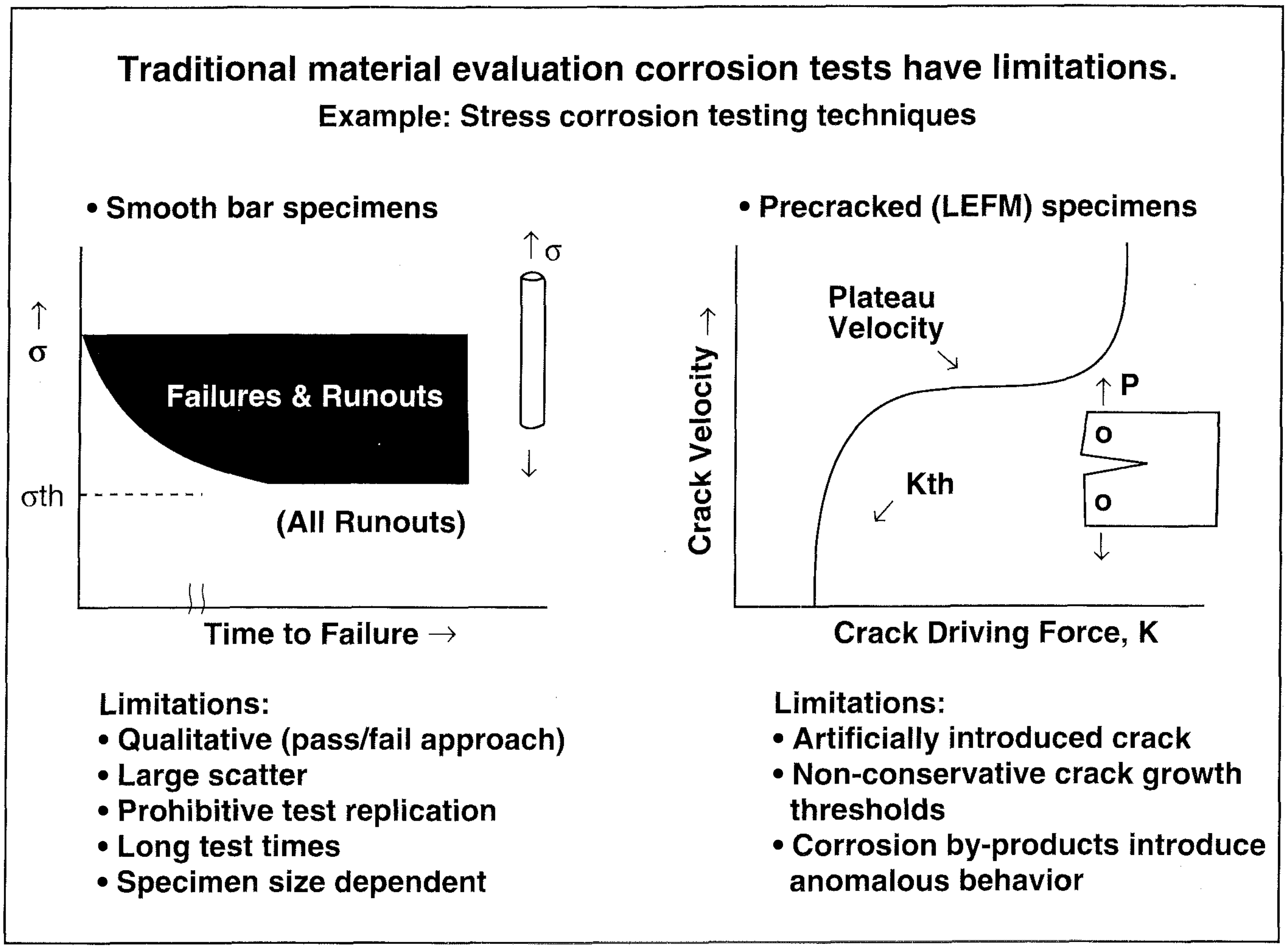
#### Ranking of Alloys

In any design plan for high-performance structures, priority must be given to alloy properties. Ultimately there must be a trade-off among various mechanical properties and characteristics such as strength, fracture toughness, cost, availability, expected service life and maintainability, versus susceptibility to SCC. Various SCC criteria commonly used for ranking the expected performance of materials in service are discussed in Reference 9.

#### Design Philosophies

Two basic design concepts that found original applications as safeguards against metal fatigue also are potentially applicable to SCC failures. The "safe-life" design concept, based on the premise that the total life of a part consists primarily of the initiation of a visible crack, is the one most often considered applicable to the avoidance of SCC problems.

For fracture control in heavy-duty structures, increasing use in being made of the damage-tolerant approach by which design concepts may be qualified as either "slow crack growth" or "fail-safe" structures. The general design strategy is to select materials, configurations and stress levels that provide a slow rate of crack propagation while maintaining high residual strength. The *Damage Tolerant Handbook*, however, presently recommends that the best design policy for handling SCC is to prevent the initiation of cracking rather than controlling its growth as done for fatigue cracking. [12, 13]



**Traditional material evaluation corrosion tests have limitations.**

**Example: Stress corrosion testing techniques**

- **Smooth bar specimens**

**Limitations:**
- **Qualitative (pass/fail approach)**
- **Large scatter**
- **Prohibitive test replication**
- **Long test times**
- **Specimen size dependent**

- **Precracked (LEFM) specimens**

**Limitations:**
- **Artificially introduced crack**
- **Non-conservative crack growth thresholds**
- **Corrosion by-products introduce anomalous behavior**

*Figure 2. Schematic diagrams of traditional plots of SCC test results obtained with smooth bar specimens and precracked (LEFM) specimens with detailed limitations of each type of test. Source: Courtesy of Dr. R. Bucci., member of both ASTM G01.06 and E-8 on Fatigue and Fracture.*

Protective Systems

To avoid SCC in structures built of highly susceptible alloys, precautions must be taken not only with the design and fabrication of components and assembly of the structures, but also with protection of the metal surfaces. One of the most effective preventives is shot peening, which produces a thin layer of metal with residual compressive stress, and a good paint system to protect the shot peened layer from corrosion. It is recognized that, even with the best protective system possible, a corrosion prevention and control program is required in addition to normal maintenance.[14]

### Corrosion Fatigue Cracking

The fatigue strength of a given material generally is degraded in the presence of an aggressive environment (See Figure 3). CFC is not limited to certain metallurgical conditions of the metal or to particular environmental species as are other forms of environmental cracking.

### Testing Techniques

The CFC phenomenon has the possibility of many more variable factors, and the testing techniques are more complex and more numerous than those for SCC testing. It is also more difficult to obtain standard procedures by consensus for CFC than for SCC.

General State of the Art

A common approach to corrosion fatigue is to perform a state-of-the-art fatigue test in the presence of the environment of interest. Committee E-8 on Fatigue and Fracture has developed 10 standards related to fatigue testing that are printed in the current *Annual Book of ASTM Standards* (Vol. 03.01). The only one that deals with corrosion fatigue is E 647, Test Method for Constant-Load-Amplitude Fatigue Crack Growth Rates Above $10^{-8}$ m/Cycle, which contains an appendix specific to CFC growth in marine environments. Procedures for CFC in other environments are not standardized; however, methods have evolved for specific technologies.[16] There is a substantial literature base on CFC including ten Special Technical Publications issued by ASTM. A recent review by R.P. Gangloff,[17] highlighting modern laboratory methods of characterizing the corrosion fatigue behavior of metals in aqueous electrolytes lists 120 references to pertinent literature.

Fatigue Testing Regimes

The basic approaches to CFC tests are analogous to those for SCC tests except for the type of loading (cyclic vs. sustained). Smooth or notched specimens are loaded axially or in bending usually in the elastic stress range in the presence of a corrodent, and the test results are plotted in terms of fatigue strength and fatigue life. Compare those terms in Figure 3 with the σth

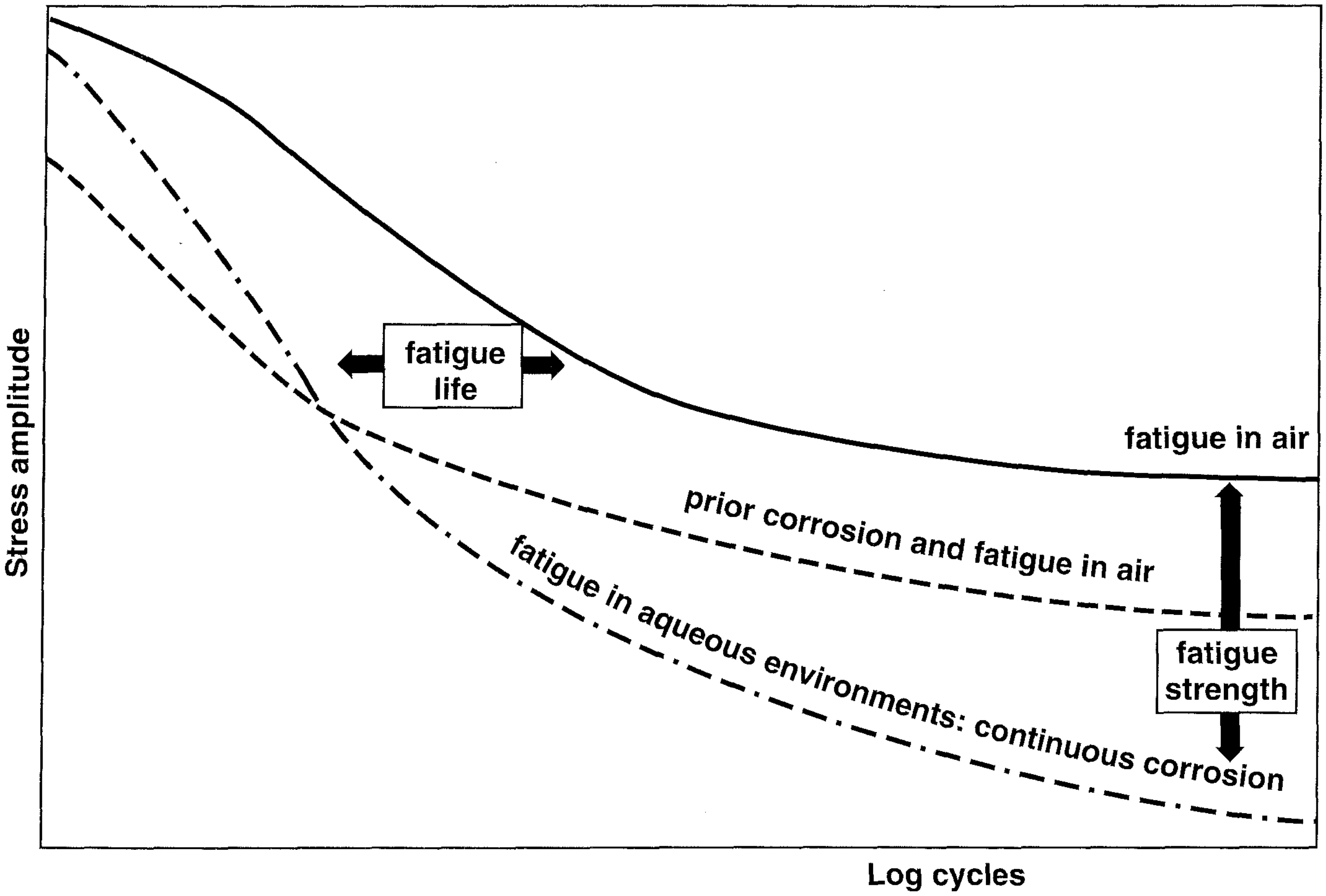


*Figure 3. Schematic of the effects of corrosion on fatigue life and fatigue strength as shown in laboratory tests. Although the traditional definition of corrosion fatigue specifies simultaneous corrosion and repeated cyclic loading (ASTM G15[15]), contemporary investigators often are concerned with corrosion fatigue situations where corrosion has preceded the fatigue in air. Source: Courtesy of R. Wahnhill.*

(threshold stress) and time to failure of the smooth bar specimens in Figure 2. Similarly, with the fracture mechanics approach to CFC, crack propagation rate (velocity) is plotted as a function of the crack driving force, $\Delta K$ (or K) for the precracked (LEFM) specimens in Figure 2. There are various other ways of presenting the test data as illustrated in references 5 and 17.

**Corrosion Fatigue Cracking—Can We Control It?**

While fatigue is inevitable with cyclically loaded high strength metallic structures, and design engineers recommend life expectancies accordingly based on a "fail-safe" design philosophy, some additional things can, and must be done to mitigate corrosion damage leading to premature failures by CFC:

1). Avoid unplanned surface tensile stresses over and above the design stress by selecting stress relieved mill products, and pay close attention to assembly practices to avoid "locked-in" stresses induced during assembly of the components.
2). Use sealants and/or protective coatings in crevices and on other uninspectable surfaces as well as on exterior surfaces.
3). Carry out "corrosion prevention and control programs" involving scheduled inspections to obtain early warnings of fatigue or CFC initiation so that long-term damage tolerance can be maintained. In essence, corrosion must be controlled so that neither excessive material loss (increased applied stress) nor undetected crack initiation will ensue.[14]

**Service Life Prediction—Who Knows "How Long?"**
**Stress-Corrosion Cracking**

Life predictions for susceptible materials are difficult—no, impossible—and should be approached with caution because there are no reliable mathematical models for extrapolating laboratory test results. Lack of reproducibility, range of data scatter, and inability to adequately define/model anticipated service conditions have typically left designers no choice except to choose materials believed to be "immune" to SCC—the "safe-life" concept. Fortunately today, research and development of new alloys and tempers with a focus on improved resistance to SCC has brought many improved materials into the marketplace. But it is still incumbent on the designer to make a proper assessment of the implications of a "degree of susceptibility" in a given application.[9]

**Corrosion Fatigue Cracking**

Early codified design prediction using elastic smooth specimen stress-life (S-N) fatigue data adjusted empirically for time-dependent corrosion effects are being supplemented by LEFM predictions of crack propagation from an inspection-based or estimated initial crack size. Along with this new design philosophy came the "fail-safe" concept, the goal of which was to ensure a redundant load path, so that in the case of a part failure despite detection and maintenance efforts, another component would carry the load to prevent the loss of service-ability.

An accident that raised the whole world's consciousness concerning aging aircraft occurred in 1988 when, during flight near Maui, Hawaii, half of the upper fuselage skin of an Aloha Airlines' 737 tore off.[14] "One of the accident investigation's most important findings was that 'the failure mechanism was the result of multiple-site fatigue cracking of the skin...which negated the "fail-safe" characteristics of the fuselage'...The Federal Aviation Agency (FAA) subsequently issued mandatory "Airworthiness Directives" for all of the commercial transport airplanes to the effect that all corrosion prevention and corrosion control programs (CPCPs) created for each of the aircraft be established on a calendar-time basis, independent of flight cycles or flight hours... Understanding the implication of multiple-site damage (MSD), as it is now called, requires some additional background."[14] While the understanding of failure mechanisms provides significant insights, existing mechanism-based models do not have proven capability for accurately predicting corrosion fatigue behavior beyond the range of laboratory tests.[17]

**About the author:**
Donald O. Sprowls has more than 43 years experience in the field of corrosion testing. He has authored 46 technical articles on topics relating to corrosion and holds a U.S. Patent. Sprowls was awarded the ASTM Sam Tour award in 1974, the ASTM Award of Merit in 1986 and the ASTM Francis L. LaQue Memorial Award in 1993. He became a charter member of Committee G-1 on Corrosion of Metals in 1964 and chairman of Subcommittee G01.06 in 1994. He was made a Fellow of ASTM in 1986. Sprowls retired from Alcoa Research Laboratories in 1983 and now consults on corrosion of aluminum alloys.

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