The Future of Corrosion Control—
Part 1 of 2

Industry experts share their predictions on where the corrosion industry is headed.

Coatings are currently your first and best defense against the costly effects of corrosion.

But what will you need to be doing tomorrow to protect your assets?

Back in 1943, NACE International was established in Houston, Texas by 11 engineers focused on cathodic protection (CP) to address metal pipeline degradation. Now 36,000+ members strong, NACE has evolved into a worldwide organization that is involved in every industry and area of corrosion prevention and control. Throughout 2018, NACE has been celebrating its 75th anniversary, a milestone made possible by the knowledge, expertise, and continued support of its members from around the globe.

Part of honoring NACE’s history, Materials Performance is dedicating coverage to the future of corrosion control as seen by experts in the field. In this article, six panelists share their predictions on where the corrosion industry is going in the next 25 years and beyond. Panelists, while highlighted in the pages that follow, are also profiled at the end of this article.

NICK BIRBILIS
When considering the important future developments in the industry of corrosion control, the prospects are as complex as they are plentiful. Identifying such prospects requires one to zoom out a little from the technological question (i.e., what will the future of corrosion control resemble?), and consider the key factors or indicators that can be rationally identified as significant in influencing the future of corrosion control. Such factors include, but are not limited to the following.

Legislation
Undoubtedly the unpredictability of politics is something we are constantly reminded of. In many cases, the most (financially and socially) significant decisions when it comes to corrosion control are often placed in the hands of lawmakers. Two significant examples include the phasing out and imminent replacement of chromate-containing corrosion preventative compounds,\(^1\) and the long-term disposal plans for nuclear waste. In the case of chromate replacement, some nations and industries are somewhat more advanced than others; however, it is fair to say that no equivalent (and broadly applicable) alternatives have been found to date—such that the corrosion protection regimes we will see for everything from galvanized garden sheds to the next commercial jetliner are yet to be determined (let alone their long-term durability). The issue of nuclear waste storage varies from nation to nation for countries with nuclear power generation; however, the world is watching for a long-term strategy in the United States, which is yet to be determined following the shelving of the Obama-era Yucca Mountain Repository project.

New Alloys/Materials
The development of new materials is now occurring at a pace greater than ever before. In part, computation has allowed materials design to evolve from what was historically plant trials to documented demonstrations of desktop alloy design with industrial utility.\(^2\) Alloy development has come so far since the second world war that a catchphrase of the automotive industry is “nearly all the alloys used in an automobile are different each 10 years”—meaning that materials we seek to protect are also always evolving. In fact, even in what is considered a very conservative industry—the aircraft industry—the change in the dominant structural alloy of commercial aircraft has also seen an active evolution from the aluminium alloys AA7022, to AA7079, to AA7075, to AA7050, to AA7150, to AA2050—all in the past five decades alone. This latter example relating to the evolution of aircraft alloys is an example of changing the alloy used in order to improve durability (i.e., a decision based on corrosion protection, albeit corrosion resistance inherent to the alloy). In such a vein, the design of corrosion-resistant alloys is an area of active research.

A “hot-topic” at the moment is so-called compositionally complex alloys (a subset of which are often termed high-entropy alloys) that have demonstrated exceptional corrosion resistance in aqueous and atmospheric conditions.\(^3\) Such alloys are not yet optimized in terms of a complete property portfolio for engineering applications, but there is no doubt that future corrosion protection will be dealing with (i) new materials that are presently under development, and (ii) materials with inherent corrosion resistance being designed to be more durable—and not necessitating “traditional” corrosion control. I could add many more examples, but we can look no further from the present rapid uptake of additive manufacturing to produce net-shape components, from a range of new (and old) alloys, with disabilities that are only presently under study.

Complex Systems
The great unknown is the evolution of complex systems. If we went back 15 years (or less), most of us were not carrying around a laptop, let alone a smartphone. Yet now, the pervasive nature of new technology sees us all carrying items that are being used in a manner (and environments) for which such materials have not previously...
been used. In other words, as technologies evolve (in general), it’s very likely we will see more drones, more driverless cars, and then a transition to perhaps flying cars…I paint this picture to emphasize that a flying car would obviously need to be light, and have a unique (cost-effective) propulsion system, as we can’t all afford a superalloy gas turbine. As such, we don’t know precisely what we will be dealing with, but one certainty is that there will be many new materials and technology interruptions, and all will have ramifications in terms of corrosion control.

In regards to complex systems, there are numerous ones that are also presenting the extremes of our capabilities in corrosion protection. For example, the sequestration and transportation of supercritical carbon dioxide (CO$_2$) (in the carbon capture and storage cycle) remains a significant challenge in the case of contaminated CO$_2$; whilst the renewable energy sector (which is not only coming but will be dominant in the next 25 years by all projections) presents durability unknowns in everything from solar thermal generation, to proposed grid storage solutions.

Finally, I will also provide one example that combines both issues of legislation and complex systems, highlighting the complexity of future corrosion control. In most nations, the United States being no exception, automotive emission policy (of which the state of California has amongst the world’s strictest targets) means that lightweight material systems are now being integrated into automobiles. A recent study (2018) by Liu and co-workers$^4$ of General Motors reveals the extreme complexity of a contemporary mass-market automotive “body in white” (Figure 1), indicating that the durability of an automobile relies on the durability of a multi-material system—with widely varying material types (and electrochemical personalities!).

In summary, one thing that we should always remember, especially all of us corrosion engineers (a.k.a., “rust busters”) is that engineering materials are all “anthropogenic”—in other words, man-made. As a result, their properties, good or bad, are our doing. Consequently, we have the ability to create materials with durability in mind, and an increasing responsibility to do so on the basis of the planet’s finite resources. In the future, for corrosion control, we need to be smarter! We also need to learn more from the past, and be more proactive in education. One alarming point that was raised from the most recent of the rotating national surveys on the cost of corrosion (the latest being recently published from a meticulous national survey in China,$^5$ is that the percent GDP cost of corrosion is not dropping…this can only mean that society is not learning, or society is willing to make errors in judgment. Assuming it is not the latter, there is an increasing and even more significant role for NACE International in the future of corrosion control.

**RICHARD B. ECKERT**

Microbiologically influenced corrosion (MIC) impacts many different assets and industries, and yet it is a corrosion process that is still not completely understood—despite the current advances being made in the field of genomics. MIC is typically found to be associated with diverse functional types and genera of microorganisms that develop into biofilms, forming syntrophic or complementary metabolic relationships that enhance microbial growth and activity. The spatial and metabolic relationships between the different members of the biofilm community and the electrochemical process of corrosion are still being investigated. Application of molecular microbiological methods (MMM) in the oil and gas industry has led to a greater understanding of the diversity of bacteria and archaea (and fungi) that exist in production and storage wells, piping, process plants, and tanks; however, characterizing a multitude of different microorganisms has not always been helpful to asset operators who simply want to know how to mitigate MIC. Industry wants a straightforward diagnostic test for MIC that provides actionable results. Genomic methods fall into different...
“omics” scientific disciplines, including:

- **Metagenomics**—the study of genetic material (DNA) from entire microbiological communities in a given environment to understand diversity and function
- **Proteomics**—the study of proteins as a measure of gene expression and cellular activities and functions
- **Metabolomics**—the comprehensive study of chemical metabolites produced by microbiological communities to help characterize their activities

Each of these “omics” produces information that needs to be translated and integrated with other information about the chemical environment and physical conditions in which the collective of microorganisms live, to understand who is there and what they are doing, particularly in relation to corrosion. Since to date there has been no singular data element found that is diagnostic for MIC, a successful future test method would likely need to integrate numerous chemical and microbiological factors using a model and some form of machine learning, based on a large and reliable data set. From such a future model and data set, relationships between the microbiology, chemistry, materials science, and physical conditions of a given environment could be determined and the propensity for MIC positively identified.

Probabilistic modeling tools may be one way to start predicting MIC based on the information available today; in the future, these predictions would then be improved upon as machine learning approaches are developed and incorporated into the model. Thus, future technology for MIC diagnosis would have most of the necessary data built into the tool (model) so that the parameters that needed to be obtained through sampling and analysis would be few, and the technology used to perform any analysis would be contained within one device. With accurate and reliable MIC diagnosis, prevention and mitigation measures could be more effectively applied, resulting in improved asset integrity, longevity, and sustainability.

**FRED GOODWIN**

I work with concrete so most of my comments apply to the corrosion of reinforcing steel in concrete. Concrete is claimed to be the second most common man-made material (after potable water), with about 1 cubic yard produced for every person on the planet per year, resulting in more than twice as much concrete being used than the entire quantity of steel, aluminum, glass, plastic, and wood. Much of this concrete is reinforced with steel to improve its tensile properties. Thermodynamically, steel is going to corrode at some point, but the high alkalinity of the concrete embedment passivates the steel from corrosion until either the pH falls below about 9, deleterious ions ingress into concrete (such as chlorides), or the electrical potential of the steel is influenced such as from stray current leakage. Corrosion of reinforcing steel in concrete is considered to be the primary cause of concrete deterioration. Two universal rules of concrete construction are that concrete cracks and steel rusts.

**Increased Use of Monitoring Technology**

As technology improves and infrastructure deteriorates, monitoring of factors related to corrosion will increase. The objective of monitoring should change from monitoring of the initiation time of corrosion or the rate of corrosion propagation to indications of when preventative maintenance should occur. In other words, monitoring will be used to indicate when protective actions should occur for the greatest effect on the life cycle cost of the structure. Monitoring systems will evolve to be durable for the long life of concrete and be wirelessly connected without requiring external power (such as through radio frequency identification [RFID] technology) and to also be less consuming of power as battery technology improves.

**Increased Usage of Robotic Inspection**

Investigation of corrosion is time consuming and often involves difficult location access, which is costly and potentially hazardous. Drones are already in common use for improved visual inspection as they can locate a camera in areas that would otherwise only be accessible with scaffolding or rope work. Experimentation with drones using contact sensors is beginning where the positioning of the drone will allow contact of a probe to the concrete surface such as for crack identification, resistivity testing, or reinforcing steel location (pachometer or ground-penetrating radar). Positioning and control will continue to improve and allow better and longer access, with eventual development of additional monitoring technologies such as open circuit potential, or even linear polarization resistance. Further development of drone technology will allow improved underwater inspection through miniaturization, perhaps small robots that can crawl to provide up-close inspections.
Preventative and Proactive Maintenance

It has been stated that the most successful concrete repair is the one that is never done. Studies of concrete repairs indicate that the durability of the repairs is usually less than the durability of the remaining structure. This is caused by dissimilarities of the repair material to the host concrete (such as restrained shrinkage occurring in the fresh repair material bonded to concrete that has long ago stopped shrinking, resulting in cracking and disbondment), failure to address the repair holistically (repairing only locally visible damage rather than addressing the causes of deterioration in the entire structure), and deferring repairs until corrosion damage becomes visible. When one purchases an automobile, it comes with a manual that includes scheduled maintenance to extend the vehicle service life. If one ignores changing the oil, then in a few years one will replace the engine. On the other hand, if one were to change the oil every 1,000 miles (1,609 km), the service life will be greatly extended but the maintenance cost will also be quite high. For a concrete structure a maintenance plan needs to be developed and implemented to determine the “sweet spot” for concrete maintenance to maximize the service life and minimize the maintenance cost, just like the car service manual does for the vehicle owner. Since each structure is different, the maintenance plan will need to be customized and the inherent value of the plan communicated to the owner.

Service Life Analysis, Life Cycle Costing, and Asset Management

ACI 365.1R describes three types of service life: Technical, Functional, and Economic. Technical service life is the time in service until a defined unacceptable state is reached, such as spalling of concrete, unacceptable safety level, or failure of elements. Examples of the technical end of service life include (a) structural safety is unacceptable due to material degradation or exceeding the design load-carrying capacity, (b) severe material degradation, such as extensive corrosion of steel reinforcement, and (c) excessive deflection under service load due to decreased stiffness.

Functional service life is the time in service until the structure no longer fulfills the functional requirements or becomes obsolete due to change in functional requirements. Examples include (a) the need for increased clearance, higher axle and wheel loads, or road widening, (b) aesthetics become unacceptable—for example, excessive corrosion staining, and (c) functional capacity of the structure is no longer sufficient—for example, a football stadium with insufficient seating capacity.

Economic service life is the time in service until replacement of the structure or part of it is more economical than keeping it in service. Examples include (a) maintenance requirements exceed available resource limits, and (b) replacement to improve economic opportunities—for example, replacing an existing parking garage with a larger one due to increased demand.

If one is considering the service life of a concrete sidewalk, it is replaced when it becomes aesthetically displeasing, uneven, or sufficiently rough to become a tripping hazard. If one is considering the service life of a concrete nuclear reactor containment vessel, the considerations for service life optimization become much more critical. Designing the concrete structures for optimum service life involve many factors such as the concrete quality, the service environment, the attention to detailing, and the protective systems employed. Consideration of the tradeoffs between initial cost, inspection, monitoring, maintenance, downtime, and decommissioning over the service life of the structure is one description of life cycle costing where having a higher initial cost with lower maintenance costs is compared to other alternatives. Asset management is consideration of the life cycle costs of the components of a system such as treatment and distribution of a municipal water system including the intake of raw water, treatment to make it potable, delivery to points of usage, and treatment of the waste water, all of which include many individual components of machinery, pipelines, etc. Service life analysis, life cycle costing, and asset management will continue to expand in complexity and usage to address corrosion-related issues.

Maintenance Incorporated into BIM

Building Information Modeling (BIM) is a process involving the generation and management of digital representations of physical and functional characteristics of construction and is rapidly being accepted as a tool for construction design, scheduling, procurement, and management. In BIM, a three-dimensional model is developed of the structure and construction sequence overlaid to avoid time conflicts (a fourth dimension) and optimize costs (a fifth dimension). BIM also covers spatial relationships, light analysis, geographic information, and the quantities and properties of building components (for example, manufacturers’ details). A logical extension of BIM is to also include the asset management and deconstruction of the structure throughout the building’s service life. Combining all these properties into a model reduction of corrosion issues is a natural consequence, such as through improved detailing, better water management, and service life modeling.
References


MEET THE PANELISTS

Nick Birbilis, FNACE, is the deputy dean, College of Engineering and Computer Science, Australian National University, Acton, ACT, Australia. He specializes in the design and development of corrosion-resistant metals and alloys. A NACE member since 2001, he is a Fellow of NACE and the Electrochemical Society, a member of the CORROSION Editorial Board, and the recipient of the 2012 H.H. Uhlig Award in recognition of outstanding effectiveness in post-secondary corrosion education.

Richard B. Eckert is a senior principal engineer, corrosion management, at DNV GL, Dublin, Ohio, USA, email rick.eckert@dnvgl.com. He has been performing pipeline corrosion/failure investigations and forensic corrosion engineering for over 35 years. An expert on MIC, he is a NACE Internal Corrosion Specialist. He is past chair of the Publications Activities Committee and Education Activities Committee and chair of NACE Task Group 254, “Detection, Testing, and Evaluation of Microbiologically Influenced Corrosion (MIC) on Internal Surfaces of Pipelines.” He received the NACE 2004 Presidential Achievement Award, 2014 NACE Distinguished Service Award, and 2017 AUCSC Colonel George C. Cox Award.

Fred Goodwin is head of BASF Construction Chemicals Global Corrosion Competency Center, Beachwood, Ohio, USA. He is a chemist with more than 30 years of experience in construction chemicals. He is a member of NACE, ICRI, ACI, ASTM, SDC, and SSPC. He is a Fellow of ASTM, ACI, and ICRI; honorary member of ASTM C01 and C09; chair of NACE TG 050, member of the ICRI Technical Activities Committee (TAC), ACI D90 TAC Repair & Rehabilitation Committee, and SSPC 8.3 Commercial Floor Coatings; received the ASTM Award of Merit (2016), the JCPL Editors Award (2006, 2010, and 2012), ACI 2011 Delmar Bloem Distinguished Service Award, Strategic Development Council, and received the 2015 Jean-Claude Roumain Innovation in Concrete Award. He is a NACE certified Corrosion Technologist and was named a Top 25 Innovative Thinker by Technology Publishing (2012).

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