In My Experience: Observations on the Pace of Technology Advancement in the Remediation Industry

by Craig Divine

Over the nearly three decades of my career, I have observed the introduction and development of numerous new technologies in the remediation industry. Examples include passive diffusion samplers, multilevel sampling (MLS) wells, Bio-Trap® microbial samplers, FLUTe™ borehole liners, En Core® soil samplers, direct-push characterization tools (e.g., hydraulic profiling tool [HPT], laser induced fluorescence [LIF], nuclear magnetic resonance [NMR] logging), compound-specific stable isotope analysis (CSIA), Vertebrae™ well systems, mobile laboratories, field tablets, point velocity probes (PVPs), passive flux meters (PFMs), multiphase extraction (MPE), biosparging, permeable reactive barriers (PRBs), ion exchange (IX) resins, in situ enhanced reductive dechlorination (ERD), in situ chemical oxidation/reduction (ISCO/ISCR), directed groundwater recirculation (DGR), in situ soil stabilization (ISS), in situ thermal treatment and smoldering, extreme soil vapor extraction (xSVE), advanced oxidation processes (AOP), in situ soil stabilization, membrane biofilm reactors (MBfRs), soil washing, foam fractionation, super critical water oxidation (SCWO), electrochemical oxidation, sonolysis, ball milling, and the horizontal reactive treatment well (HRX Well©). These developments have been transformative, greatly advancing our ability (and cost-effectiveness) in characterizing and treating sites, particularly complex sites. The development path of any new technology is complicated and convoluted, and involves risk, iteration, and surprise. However, given the pressing needs and the multi-hundred-billion-dollar size of the remediation industry, I am struck by the relatively slow and uneven pace of development and adoption for many of technologies. Often the time from first the prototype system or pilot test to widespread industry use is a decade or more. In large part, I believe this is a result of the unique structural challenges associated with the inherent stakeholder interests that must be overcome. The key players who affect the timeline for technology development are:

- *Potentially Responsible Parties (PRPs)* hold the liability for contaminated sites. However, site remediation is not their primary business and is not revenue-generating. In most cases, their priorities are risk management, cost avoidance/certainty, and corporate responsibility. Occasionally, they will support development of a new technology if the risk and investment is relatively low and near-term benefits are clear. In some cases, they may be less interested in exclusively funding technology development that might also benefit other PRPs who are competitors in their sector.
- *Consultants* generally provide specialized expertise (usually billed in units of time) to develop the best-fit and most reliable solutions and, as such, they aim to establish long-term trusted advisor relationships with PRPs. Most do not explicitly market or sell products, and typically prioritize technology "agnosticism" to avoid the appearance of a conflict of interest. Larger consulting organizations occasionally support technology and intellectual property (IP) development, but often do so despite (not because of) their primary business model structure. A few, like my employer Arcadis, even have corporately funded formal innovation programs. Technology development benefits the consulting organization primarily by elevating their reputation and brand; in most cases significant revenues are not generated through product sales or royalties.
- *Regulators* are mandated to protect the public and environment and ensure compliance with regulatory standards. While advances in technology will ultimately result in more effective remediation, regulators are not inherently motivated to support new unproven technologies that may increase performance uncertainty and potentially increase a compliance failure risk.
- *Academics* provide key fundamental scientific advances and competently trained practitioners. Generally, available funding is focused on early-stage scientific research and is not targeted toward technology development. Sometimes IP can be developed and licensed to a third parry, but overall, the academy is primarily motivated to develop knowledge. Consequently, successful technology development through to commercialization is rare.

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- *Vendors* directly benefit from sales and licensing of technologies and therefore are motivated to invest in research and development and product development. However, they often impeded by their more limited exposure to the driving needs and challenges. Furthermore, many of these companies are startups or small firms and have limited access to capital, and as a result generally have a narrow focus and on a limited product range.

So, given this landscape, what are the characteristics of a technology that does successfully progress from ideation, to demonstration, to early adoption, and ultimately to widespread commercialization and standard practice? I have observed multiple development paths technologies may follow, and, while all successful technologies must be based on valid science, address a defined market need, and offer a return on investment that supports large scale-up, the process is not prescriptive or formulaic. Nevertheless, it seems to me the technologies that advance the fastest and see the widest acceptance tend to fall into two general categories. Some technologies, like passive sampling (Figure 1, left), are relatively incremental but can rapidly be applied at very large scale, offer little performance risk, and promise predictable cost savings or technical benefits. In this particular case, the Interstate Technology and Regulatory Council (ITRC) accelerated the development and adoption of this technology through technology transfer and the publication of guidance. Also, associated IP protections likely motivated vendors to pursue the market aggressively. Other technologies, like ERD (Figure 1, center and right), are more complex but offer a dramatic step-change in advancement or near-exclusive solution to a high value challenge (e.g., in situ treatment of chlorinated solvents). The successful development and ultimate industry-wide adoption of this technology was supported by direct investment by both PRPs and consultants, and through the development of proprietary reagent products by various vendors. Also, US DoD, through the Strategic Environment Research and Development Program (SERDP) and Environmental Security Technology Certification Program (ESTCP), played an inestimably important role in the development of ERD (and many other technologies) by funding both research in the underlying science and in large scale robust field demonstrations.

Looking to forward challenges, the greatest unmet needs surround per- and polyfluoroalkyl substances (PFAS) and there are distinct features to this market that provide both positive pressure and enhanced risk (i.e., drivers and headwinds) for the commercialization and widespread adoption of new technologies. The scale of the problem is massive, spanning many industries and involving a wide range of waste types and sources, sites are commonly large and often include impacted groundwater, surface water, stormwater, soil, and hardscapes, and there a particularly high awareness and sensitivity by the public to this contaminant class. Consequently, there is a high sense of urgency. However, the science of PFAS is still in early development and regulatory standards and endpoints are evolving. As a result, remediation performance objectives are difficult to define. What can be done to accelerate technology development for PFAS? First, I would recommend increased support of formal collaborations patterned after programs like SERDP/

Figure 1. Left: The author during one of the first deployments of commercially available passive diffusion samplers in 2002. The PRP was interested in changing sampling methods because of the cost savings (~25%) offered by the new technology, and therefore was motivated to develop site-specific comparison data to attain regulator acceptance. Center and Right: Preparing whey-based and corn syrup-based reagent solutions prior to injection for an early implementation of ERD in 2001. At this time little was understood about in situ biogeochemical processes, reagent optimization, injection well system design and hydraulics, and the practical effects of heterogeneity and diffusion into and out of low-permeable geologic materials on injected reagent distribution and remediation system performance. This PRP supported this pilot test work because they had a portfolio of chlorinated solvent sites and recognized the large potential benefit of this nascent (at the time) technology.

ESTCP and the University Consortium (https://theuniversityconsortium.org). These programs are most successful when governed by clearly stated objectives and exhibit the will to terminate research paths that show little promise and abandon technologies that fail thoughtful and well-defined stage gates. Furthermore, these programs should emphasize technology readiness levels (TRLs) 5 to 7 where scientific funding is limited but the commercial sector generally views as too risky for investment and market development. The technology scale-up phase is also a key bottleneck in the remediation industry, especially for capital intensive technologies. Fortunately, I have observed significant new venture capital in the PFAS treatment market, and continued investment will be necessary for rapid commercialization of developing technologies, especially those with higher risk and costs. However, it is important that investors understand viable commercial models and can distinguish between developing technologies that are *exciting* versus those that are *practical*. An increased focus on knowledge transfer is also recommended and should include both traditional channels (e.g., journal articles, conference presentations, webinars) as well as newer channels such as podcasts and social media that are specifically geared toward the early-career practitioners and regulators. Finally, in some cases, PRPs may consider outcome-based or incentivized risk/benefit sharing contract models with their consultants and other performing contractors to alleviate some of the structural barriers and to innovation and even encourage formal co-creation and joint development activity.

Biographical Sketch

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