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by Robin Cantor, Ph.D., and Albert W. Bremser, Ph.D., CFA

The Safety of Chemical Products

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by Neil S. Shifrin, Ph.D.

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Berkeley Research Group, LLC
2049 Century Park East, Suite 2525
Los Angeles, CA 90067
510.550.4380
info@brg-expert.com

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BRG REVIEW

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From the Desk of the Editor

Welcome to the fifth issue of the *Berkeley Research Group Review* ("the *Review*"), the official publication of Berkeley Research Group, LLC. BRG was founded in 2010 by a group of distinguished academics and private-sector professionals in the fields of economics, finance, healthcare and data analytics. Today, BRG has over 500 experts and consultants in 26 offices worldwide who apply innovative methodologies and analyses to complex problems in the business and legal arenas.

In this issue of the *Review*, we highlight BRG's Environmental Services practice, wherein our experts and consultants combine backgrounds in economics, environmental science, engineering, and regulation to provide a single integrated source for independent, objective expert testimony in litigation and tailored, valuable insights in consulting assignments. This issue features three papers from two of our leading experts in this field, Robin Cantor, Ph.D., and Neil S. Shifrin, Ph.D.

Our first paper presents a discussion on market share theories of liability and the associated issues that need to be considered. Courts have used these liability theories to apportion damages among multiple defendants when the exact defendant causing the plaintiff's injuries is unknown. For example, assume three competing firms produce an identical lead-based paint. The paint is later found to cause environmental damage, but it is impossible to ascertain which paints were used where. The court may then allocate damages based on the market shares of the three producing firms.

Our second paper focuses on the safety of chemical products and methods of addressing the associated risks. There are at least three ways to address potential health risks from products: 1) remove the toxic compounds; 2) provide information to allow informed buying/use decisions; and 3) create negative incentives, such as by lawsuits, after harm has been caused. The advantages and disadvantages of these methods are discussed.

Our third paper begins by providing an overview of the nature of chemical leaks and spills and then summarizes available information on the impact and extent of occurrences of leaks and spills due to key sources: accidental spills, mechanical equipment failure, corrosion, and geologic conditions and other natural phenomena. The paper concludes with a case study of the problem of leaks and spills in the manufactured gas industry that was active from 1850 to 1950.

As always, we hope to use the *Review* to provide our audience with a "good read" and to improve our connections with clients, recruits, peers, and colleagues. We expect that the *Review* will stimulate discussion and debate around key issues we face today. With this in mind, we welcome comments or feedback our readers may have about the subjects we address in the *Review*.

Kindest regards,

C. Paul Wazzan, Ph.D.
Editor

Robin Cantor
Berkeley Research Group

Robin Cantor, Ph.D., specializes in applied economics, environmental, energy, and health economics, statistics, and risk management. She has a B.S. in mathematics from Indiana University of Pennsylvania with a specialization in statistics, and a Ph.D. in economics from Duke University with a specialization in econometrics.

Dr. Cantor has served on science review and advisory panels for organizations such as the National Academies of Science, National Science Foundation, Johns Hopkins University Graduate Part-Time Program in Environmental Engineering and Science, Carnegie Council on Ethics and International Affairs, National Oceanic and Atmospheric Administration, and National Academy of Public Administration. In 2011, she edited a volume on product liability for ABA Publishers.

Contact information:
Email: rcantor@brg-expert.com
Phone: 202.448.6729

Albert W. Bremser

Albert W. Bremser, Ph.D., CFA, has extensive experience in litigation and specializes in breach of contract and fiduciary duty involving financial analysis and economic damages, energy regulatory and litigation matters involving financial and economic analysis, and securities litigation involving investment portfolios and individual companies.

Dr. Bremser received a Ph.D. in finance from Virginia Tech, an MBA from the University of Pittsburgh, and a B.S. in commerce from the University of Virginia. Dr. Bremser's experience includes financial and economic analysis, financial statement analysis, quantitative analysis, and the use of option pricing techniques. His background includes knowledge of accounting principles, accounting transactions, general statistics, and econometrics. Dr. Bremser has taught Introductory Corporate Finance and Real Estate at Virginia Tech.

Contact Information:
Email: al@bremser.us
Phone: 202.489.4796

Neil Shifrin
Berkeley Research Group

Neil S. Shifrin, Ph.D., consults on a wide range of environmental engineering topics, including water quality, contaminant fate and transport, hazardous waste site cleanups, and environmental response cost liability/allocation. His experience extends back to the nation's first Superfund projects, such as Love Canal, and includes many complex contamination problems, such as PCBs in major receiving waters, dioxins in the Great Lakes, TCE in large aquifers beneath major cities, and CSO pollution of Boston Harbor.

Dr. Shifrin has extensive experience with dense nonaqueous phase liquid (DNAPL), site investigation, remedy concepts, monitoring programs, property redevelopment, historical waste practices, cost allocation, manufactured gas plants, PBT chemicals, solvents, and biological processes.

Contact information:
Email: nshifrin@brg-expert.com
Phone: 781.966.2900

Market Share Liability from an Economics Perspective

Introduction[1]

An important intersection between law and economics occurs in the consideration of industry-wide, collective, or market share theories of liability. These collective theories are used as alternatives to the traditional process where plaintiffs must prove causation to recover damages from defendants.[2] Courts have used these liability theories to apportion damages among multiple defendants when the exact defendant causing the plaintiff's injuries is unknown.

The first case to allow a plaintiff to collect damages based on market share liability without identifying a specific defendant was *Sindell v. Abbott Laboratories*, tried before the California Supreme Court.[3] In *Sindell*, all the named defendants manufactured a drug—diethylstilbestrol (DES)—that used the same formula. It was not possible for either the plaintiff or the defendants to determine who manufactured the DES that caused the harm to the plaintiff. The Court decided that "[e]ach defendant will be held liable for the proportion of the judgment represented by its share of that market

1 The views expressed herein are those of the authors and should not be construed as representing the positions of Berkeley Research Group, LLC or Exponent, Inc., or other experts at these firms. Any errors are our own.

2 See, e.g., Russell J. Jackson, "Products Liability: Market-Share Liability," *The National Law Journal* (July 9, 2007); and George L. Priest, "Market Share Liability in Personal Injury and Public Nuisance Litigation: An Economic Analysis," in Ilya Somin and Todd J. Zywicki (eds.), *Supreme Court Economic Review*, Chicago and London: The University of Chicago Press (2010).

3 Judith Sindell, Plaintiff and Appellant, v. Abbott Laboratories et al., Defendants and Respondents, 26 Cal.3d 588, 607 P.2d 924, 163 Cal. Rptr. 132 (1980); Naomi Sheiner, "DES and a Proposed Theory of Enterprise Liability," *Fordham Law Review* 46(5): 963–1007 (1978); and Denise N. Taylor, "California Expands Tort Liability under the Novel Market Share Theory: *Sindell v. Abbott Laboratories*," *Pepperdine Law Review* 8(4): 1011–1043 (1981).

unless it demonstrates that it could not have made the product which caused plaintiff's injuries."[4] The Court determined that "…each manufacturer's liability would approximate its responsibility for the injuries caused by its own products."[5]

After *Sindell*, other courts have considered market share liability for injuries associated with products as varied as lead paint, blood products, and firearms. In consideration of market share liability, courts have reviewed certain factors that address the particular aspects of the product, its market, and its risks:

> (1) the generic nature of the product; (2) the long latency period of the harm; (3) the inability of plaintiffs to discover which defendant's product caused the plaintiff's harm, even after exhaustive discovery; (4) the clarity of the causal connection between the defective product and the harm suffered by plaintiffs; (5) the absence of other medical or environmental factors that could have caused or materially contributed to the harm; and (6) the availability of sufficient "market share" data to support a reasonable apportionment of liability.[6]

A policy rationale for using market share liability is that it will incentivize manufacturers to produce safe products and provide an incentive for the manufacturers to internalize the costs associated with product risks in the costs of doing business. Similarly, economics considers market share liability in a number of contexts, including liability assignment, liability apportionment, deterrence, and risk sharing. The imposition of market share liability by the courts has implications for the economic incentives to modify commercial behavior, such as minimizing pollution. Theoretical and empirical studies support a liability assignment that can create a "market" for continuing abatement or prevention of pollution. Certain supply-chain

4 *Sindell* (1980), 612.
5 *Sindell* (1980), 612.
6 American Law Institute, "Restatement (Third) of Torts: Product Liability," Section 15 cmt. c (1998).

market conditions favor particular levels of liability assignment to ensure that this "market" operates effectively. The economics literature identifies conditions under which market share liability is likely to achieve welfare-improving outcomes from pollution abatement goals that reduce product risks or increase abatement care.

The Risk-Reduction Incentive Favors an Emphasis on the Pollution Source

The economics literature identifies the primary social-welfare rationale for market share liability to internalize the costs of harm by products when manufacturer identification is impossible.[7] The economics literature considers the question of market share liability for environmental pollution liability and addresses the interaction of economic behavior and liability rules. In general, liability can serve three main goals: compensation, corrective justice, and deterrence. Corrective justice often emphasizes the harm-causing behavior. Deterrence or risk reduction will be better served by a liability rule when the linkages between the risk and the product supplier are discernible. The conditions that best support a risk-reduction objective for the assignment of liability are:

1. The risk is ongoing
2. The magnitude of the risk is primarily influenced by the supplier of the injuring product
3. The magnitude is influenced by the level of care by the supplier
4. The magnitude is influenced by the output level of the supplier

Imposing legal liability for damages resulting from environmental pollution creates a "price" and a "market" for the damaged environmental resource

7 See, e.g., Priest (2010); Kathleen Segerson, *Economics and Liability for Environmental Problems*, Burlington, VT, and Aldershot, UK: Ashgate Publishing Company (2002); and Susan Rose-Ackerman, "Market Share Allocations in Tort Law: Strengths and Weaknesses," *The Journal of Legal Studies* 19(2): 739–746 (1990).

or, in an economic sense, consumed by the commercial activities and their suppliers.[8] The creation of this market gives rise to a related market for pollution abatement (care), since the suppliers can reduce the cost of liability by abating risks. If liability costs can be passed to consumers, then the subsequent price increase to products polluting the environment will encourage consumers to seek less-damaging products.

When multiple polluters exist, the economics literature supports apportioning liability so each polluter internalizes the damage cost. If each unit supplied imposes the same risk on environmental resources, then market share liability will appropriately price the environmental resources to each supplier.

Empirically, economists have found that the behavioral changes induced by liability rules vary over different circumstances, in part because the actual economic conditions and the applicable legal rules are far from the ideal theoretical assumptions. Nonetheless, the environmental economics literature supports using liability rules to assist in creating effective markets and implicit pricing for environmental resources. Because products can involve complex and widely distributed technologies, it is both an economic and a technical question regarding which line of commerce in a complex supply chain could best deliver the desired behavior modifications following a particular liability assignment.

A Complex Supply Chain Affects the Selection of Any Given Level for Market Share Liability

Market shares are measured by referencing a set of suppliers and users and their substitution possibilities. Industries will typically reflect the activities of many product markets in supply chains extending into many geographic

8 See, e.g., Kathleen Segerson, "Liability and Penalty Structures in Policy Design," in Daniel W. Bromley (ed.), *The Handbook of Environmental Economics*, Cambridge, MA: Blackwell Publishers Inc. (1995).

areas. The availability and cost of data about the products or suppliers associated with the alleged harm can influence what, if any, market share measures are used for apportionment.

The economics literature also addresses the role of contractual relationships between different lines of commerce in the supply chain and environmental pollution.[9] If liability is assigned to upstream manufacturers, then they can potentially shift the liability cost to the product price for the downstream polluter. Although the higher cost will generally reduce the output level downstream, it will not necessarily improve the level of care by downstream polluters. The behavior modification will still require contractual conditions that "price" the pollution level by downstream suppliers that impose a risk on the manufacturer rather than on third parties. The more supply layers between the manufacturer and the downstream supplier, the more unlikely that contractual conditions could be executed effectively due to the transactions and monitoring costs.

In addition, significant equity issues might arise from a pure market share approach with complex supply chains. An apportionment based on pure market share liability might be confounded by intermediate suppliers selling to downstream manufacturers. When defendants are not in the same line of commerce, pure market share liability will not apportion damages to the complete set of named defendants. Defendants might also have widely differing circumstances in their ability to pay for the apportioned damages. Profit share liability has been suggested as a solution to the equity issues inherent in a market share allocation.[10] While perhaps an attractive solution to address the imbalance of profits from commercial undertakings, ascertaining the profit data for activities that might have begun decades ago will likely pose a costly informational challenge for the courts.

9 See, e.g., Kathleen Segerson, "Risk and Incentives in the Financing of Hazardous Waste Cleanup," *Journal of Environmental Economics and Management* 16(1): 1–8 (1989).

10 See, e.g., Benjamin Thomas Greer, "Market Share Liability Shouldn't Die: Proposed Application to Agricultural Pesticides and the Need to Refine the Apportionment of Liability," *San Joaquin College of Law* 17(1): 85–108 (2007).

Conclusion

Damage allocation rules that rely on economic data and measures of commercial success are likely to be more complicated and challenging than traditional tort theories to apportion liability and affect commercial behaviors. From an economics perspective, a continuing pollution abatement problem and the distributional complexities that might exist in a particular industry support a liability apportionment that considers the pollution abatement consequences of its assignment at all levels of the supply chain. The complexity of actual markets and industries and/or the availability of complete data to support the use of market share liability remain sources of significant concern regarding not only the reliability of the apportionment measures but also the incentive effects on pollution abatement.

The Safety of Chemical Products[1]

Introduction

Many consumer products contain chemicals that might offer unhealthy exposures. The health risk of such products depends on the actual exposure and how a product is used or misused, in addition to the product's potential for chemical emission. Household cleaners, plastics, flame retardants, pesticides, and personal care products are a few types of products that have the potential for health risks.

There are at least three ways to address potential health risks from products: 1) remove the toxic compounds; 2) provide information to allow informed buying/use decisions; and 3) create negative incentives, such as by lawsuits, after harm has been caused. McDonough and Braungart[2] make a case for removing toxic chemicals from products. Post-sale product liability and defense considerations, as well as a rating system for buying/use decisions, are discussed below.

Product Liability

Over the last several years, product liability and product safety have become high-priority issues for policies and business decisions.[3] The application of damages from product liability can be viewed as either punishment or the provision of incentives for safer products. The tension in business

1 This paper will be included in a forthcoming SpringerBriefs publication, tentatively titled *Environmental Perspectives: A Brief Overview of Selected Topics.*

2 William McDonough and Michael Braungart, *Cradle to Cradle, Remaking the Way We Make Things*, New York: North Point Press (2002).

3 Robin Cantor, "Product Liability," in W.S. Bainbridge (ed.), *Leadership in Science and Technology: A Reference Handbook*, Thousand Oaks, California: Sage Publications Inc.: 281–288 (2012).

communities between demand for increased product safety and decreased liability serve to highlight the complexity of issues that corporate risk managers, policy makers, business advisors, and consumers wrestle with on a daily basis to manage product risks.

Product liability is an important area of the U.S. legal and regulatory systems and is also important in the context of enterprise risk management (ERM). Modern ERM emphasizes a proactive product liability focus in a world with many different types of risks. For that reason, ERM has inexorable links with the incentives and penalties inherent in the legal and regulatory structures under which enterprises operate.

Product liability theories and standards have evolved from a traditional foundation in specific and demonstrated manufacturer causation to more complex theories of market, successor, and other "controller" liabilities. In turn, this has expanded the set of issues surrounding questions such as: *Who absorbs the cost of damages, and over what time period?* In this section, we address the expanding scope of product liability issues in the context of ERM and post-sale liability.

In the United States, incentives to limit or manage product liability are most typically associated with tort litigation. "Product liability" is a general term that applies to several possible causes of a compensable injury, traditionally including negligence, breach of warranty, and fraud. While these causes continue today, contemporary product liability litigation often focuses on causes based on defect considerations, in addition to claims about manufacturer conduct. Importantly, strict liability for known or reasonably known product defects can attach to the manufacturer even if there is no aspect of negligence or improper conduct. Not surprisingly, this legal view is controversial from a law and economics perspective that emphasizes efficiency and maximizing innovation and product development.[4]

4 See, e.g., A. Mitchell Polinsky and Steven Shavell, "The Uneasy Case for Product Liability," *Harvard Law Review* 123(6): 1437–92 (2010).

Modern product liability legal standards distinguish three categories of product defects:

1. Manufacturing defects: when the product departs from its intended design, regardless of the level of care exercised by the manufacturer

2. Design defects: when the reasonably known risks of harm posed by the product could have been reduced or avoided by the adoption of safer commercial technologies or product alternatives

3. Inadequate instructions or warnings defects: when the reasonably known risks of product-related injuries could have been reduced or avoided by reasonable instructions, labels, or warnings[5]

Damages paid to injured parties are essentially the *ex post* imposition of an increase on the cost of production. In the post-sale world of products, however, production might have occurred long ago and possibly involved parties that no longer exist. Even when production is not in the distant past, the (explicit or implicit) economic agreements in the supply chain often do not specify how unanticipated production costs should be allocated among the parties. This is not surprising, given that the mitigation costs of the risks may have been completely unanticipated at the time these contracts and economic relationships were active. Nonetheless, science and technology have facilitated our capabilities to identify and measure exposures to potentially harmful substances in products that enter the stream of commerce. These exposures are sometimes associated with potential injuries, for which it can be difficult or even impossible to identify the parties responsible for the harmful products. Examples of these types of exposures occur with pharmaceutical products, water contamination, air pollution, and product additives widely used in many applications.

Under traditional liability theories, the determination of many aspects of causation is complicated by requirements for evidence, assignment of

5 Restatement (Third) of Torts: Prods. Liab. (1998).

responsible actions by the various parties, the limits of scientific knowledge, and the manifestation of injuries. The legal system sometimes provides an alternative mechanism for compensation for exposure to these risks. Courts have considered alternative, although controversial, theories of product liability that have been and are based on industry data and market participation of the suppliers, rather than on specific proof about the individual conduct of a particular manufacturer.

In addition, product liability is not based solely on defects known at the time of sale, but can also attach to any part in the supply and distribution chain if the product defect reasonably should have been known to the controlling party. Other considerations removed from the specific time of sale might include liability for post-sale failure to warn, and successor liability.

Whether the threat of tort actions provides sufficient private incentive for manufacturers to have effective monitoring, product recall, and risk management strategies in place is an important social issue. For example, rulings in a number of prominent lawsuits relating to off-label usage and promotion of drugs indicate that the onus for proper labeling and disseminating information relating to drug usage and potential harms rests with the manufacturer.[6] In this respect, measures such as supplier verification, approval programs, and informative labeling may facilitate effective reductions in product liability risk faced by manufacturers.

Going forward, science will continue to change the need for ERM to monitor diligently for future consequences and sources of product liability. Genotoxicity is an example of an emerging area in risk monitoring. This area builds on research that suggests that exposure to chemicals during embryonic development can result in DNA changes that might lead to toxic tort allegations. From a manufacturer's perspective, this introduces a new outlook on legacy liabilities that may persist even after the product has been discontinued for generations.

6 Monica M. Welt and Elizabeth L. Anderson, "Changing Perspectives on Chemical Product Risks," *John Liner Review* 23(3): 58–72 (2009).

Given the substantial costs imposed by tort proceedings, parties in market transactions often attempt to limit their liability for injuries by adding either warning labels to products or liability-release provisions to sale, rental, or licensing contracts. Some commentators have noted that when a pre-contractual relationship exists between sellers and consumers, tort damages are a socially inefficient means of internalizing the costs of accidents or injuries.[7] Ultimately, product prices reflect tort damages. According to this view, consumers and society would be better off if buyers and sellers negotiated directly to determine the sharing of risk for defective products based on which party can most effectively bear the risk. This view supports the use of limited product warranties, product labeling, and liability release provisions in contracts or at the point of sale to lower product costs and encourage the use of risky but beneficial products.

Product Safety Rating

A potential enhancement for ERM would be a chemical product rating system. Such a system would provide manufacturers with a rational way to consider their products while providing consumers with pertinent information for buying and use decisions. An effective product rating system would not necessarily eliminate products with lower ratings, because lower-rated products might still have large enough benefits to remain viable. Both risks and benefits are important.

A useful product safety rating system would consolidate elements scattered through various government efforts in existence today, but should be a voluntary system that is simple to understand. The issues involved with product safety can be incredibly complex, but a rating system will only be successful if it is simple. Effectiveness depends on many factors, but two conditions worth considering are ease of use and the ability to complete the user's understanding of the risks. Perhaps it is best to split the rating

7 Paul H. Rubin, *Tort Reform by Contract*, Washington, DC: AEI Press (1993).

system into two parts: a summary rating and easy access to supplemental information. The challenge for development of a rating system will be to capture the important issues while packaging it in an understandable and meaningful way—simplistic elegance, not simplistic ignorance.

Easy access to supplemental information may allow for a simpler summary rating system if it allows users to expand their understanding of the ratings, compare their exposures to that assumed by the rating, and compare across products for purchase and use decisions. Such easy access in today's internet and smart-phone world is practical and provides an interesting Silicon Valley project.

But delivery is only half the challenge; the key to product rating success will be to make the information meaningful. For example, much pertinent information exists, such as in U.S. Environmental Protection Agency (USEPA) pesticide registration material, Materials Safety Data Sheets (MSDS), USEPA's toxicity database (IRIS (Integrated Risk Information System)), or the U.S. Centers for Disease Control and Prevention's Toxicity Profiles—but this information is not meaningful to consumers. It is not reasonable to expect consumers to sift through LD50s (lethal dose 50 percent of the time) in toxicity profiles and create their own method of comparison. It is recognized that meaningful simplification will be challenging because it will involve notions of toxicity, exposure, and risk communication—but it is necessary.

The mere presence of a toxic compound in a product is only part of the story. Consumers must also understand if their use of a product offers higher exposures than what is assumed by the rating system, in case they want to seek a safer-rated product for their higher exposure pattern. Thus, easy access to the assumed exposure for each product rating (e.g., shampoo used once a day in a five-minute shower) would be useful. It may be that consumers wash their hair twice a day, but a safer-rated product does not wash as well, so the benefits of the less-safe product outweigh the risks. In a market economy, consumers should have the right information to make that decision. Importantly, empowering consumers with accessible information has effectively and substantially changed their relationship in other markets, such as healthcare and energy, and it could do the same for consumer products.

It will not be easy to create an effective chemical product rating system and meaningful supplemental information to go with it. However, such a system could satisfy the consumer on many levels, and manufacturers could use the system to develop safer products with marketing advantages.

Product Gestalt

The most important issue for product safety today is to recognize it as a problem. In most cases, people are exposed to more and higher levels of chemicals from the products they use than from hazardous waste Superfund sites. Yet consumers and producers are at a comparable stage to medicine use prior to the U.S. Food and Drug Administration.

While reactive product liability responses have a place after the damage is done, it is also possible to do a better job preventing harm in the first place. Such a proactive stance involves better product design and a simple rating system with straightforward access to additional and pertinent information. Manufacturers certainly want to make products safer, and much progress is being made. Clearly, the products we use have benefits, but consumers need a new lexicon to weigh those benefits against potential risks.

Chemical Leaks and Spills

Introduction

Historical leaks and spills are responsible for a significant portion of today's Superfund cleanups. Since about 1974, the Clean Water Act has required spill prevention and containment, but leaks and spills continue to create pollution issues today. Underground leakage remains difficult to detect, and engineers continue their struggle with leak prevention.

Even a small leak, equivalent to a leaky faucet, can create a liquid chemical pool of about 4,000 gallons in the subsurface if left undetected for 50 years. That is enough to contaminate 100 billion gallons of groundwater if that chemical (e.g., benzene) had a drinking water standard of 5 micrograms per liter (µg/l). Unquestionably, responsible parties at Superfund sites pay dearly for this issue, but it is important to understand how leaks and spills occur in order to help prevent them in the future.

This paper begins by providing an overview of the nature of chemical leaks and spills, as recognized in the engineering literature and by the U.S. Environmental Protection Agency (USEPA). This paper then summarizes available information on the impact and extent of occurrences of leaks and spills due to key sources: accidental spills, mechanical equipment failure, corrosion, and geologic conditions and other natural phenomena. Finally, the paper provides a case study of the problem of leaks and spills in the manufactured gas industry that was active from 1850 to 1950. Many of the references presented are dated, which demonstrates how longstanding the issue has been, and how some of today's conditions at Superfund sites were inadvertent. Modern engineering has considerably improved the means of controlling leaks and spills (e.g., corrosion protection), but leaks and spills still occur and remain significant. Engineering journals continue to advertise improvements and solutions.

Leaks and Spills: Occurrence and Detection

A leak is a release from a storage or conveyance vessel—for example, a drip from a pipe, pump, or tank. A spill is an unintended release, usually during transfer—for example, the drip from a gas station nozzle when we fill our cars, a kicked-over can, or an oil tanker ripped open by running ashore. Leaks and spills occur throughout modern society, at home, in public spaces, and in industry. Although their potential environmental or health effects have not been understood in the past, the element of economic loss has always been a consideration. Industry generally has viewed leaks as a waste of valuable material.[1, 2] Some companies have even had leak-prevention committees,[3] a reflection of how seriously companies addressed leaks.

Industrial facilities are a key source of leaks and spills, because they often have many tanks, pipes, and pumps. Many tanks, pipes, and appurtenances are located underground to conserve manufacturing space and avoid weather or traffic. A leak from such subsurface equipment is much more difficult to detect than one from aboveground equipment.[4, 5, 6] The USEPA's underground

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1 L. Schmidt, C.J. Wilhelm, and O.S. Jones, *Disposal of Petroleum Wastes on Oil-producing Properties, with a Chapter on Soils and Water Resources of Kansas Oil Areas.* R.I. 3394, U.S. Department of the Interior, Bureau of Mines, Report of Investigations No. 3394 (1938). 21 pp.

2 R.F. Weston, "Waste Control at Oil Refineries," *Chem. Eng. Prog.* 48(9): 459–467 (1952).

3 H.E. Morriss, "How Monsanto Controls Air and Water Pollution," *Oil Gas J.* 53(8): 114–116 (1954).

4 R.L. Greene, "Steam Plant Apparatus," in *Proceedings of the American Gas Association Second Annual Convention, November 15–20, 1920, Hotel Pennsylvania, New York, NY: Technical Section:* 224–230 (1920).

5 U.S. Environmental Protection Agency (USEPA), *Underground Motor Fuel Storage Tanks: A National Survey. Volumes I and II.* Prepared for USEPA, Office of Pesticides and Toxic Substances, EPA-560/5-86-013 (1986, May). 577 pp.

6 G.C. Whipple, "The Disposal of the Waste Products of Gas Works," *Eng. Record* 58(16): 434–437 (1908).

storage tank (UST) program emphasizes this point. In the 1980s, USEPA determined that the limit of leakage detection from USTs was about 0.05 gallons per hour, or 1.2 gallons per day.[7] Of the several million USTs in service at the time, USEPA estimated that almost 300,000 were leaking, with about half of the leaks reaching groundwater.[8, 9, 10] Weston (1944) reported that 0.5 to 3.0 percent of crude oil in large refineries "escape[s] to the sewers in the form of free oil from leaks, spills, etc."[11] Lindsey (1975) reported that "[o]ver 13,000 spills representing nearly 20 million gallons (Mgal)" were released in the United States annually.[12]

Inadvertent and undocumented leaks and spills can occur through a number of mechanisms, including accidental spills (e.g., overfilling tanks, drippage during material transfer, overturned or broken tanks as materials are transferred); mechanical equipment failure (e.g., cracked or broken piping, tanks, and pumps; loosened or broken pipe joints); corrosion; and geologic conditions and natural phenomena (e.g., damage from fire, floods, earthquakes, and ground subsidence).[13] USEPA has similarly confirmed these mechanisms during its consideration of UST leakage—corrosion, overfills, installation mistakes, and pipe failure.[14]

The impact of these mechanisms often is more pronounced as equipment

7 USEPA, *Straight Talk on Tanks: Leak Detection Methods For Petroleum Underground Storage Tanks And Piping, EPA EPA-510-B-05-001* (2005, September; revised April 6, 2009).

8 USEPA, *Musts For USTs: A Summary Of Federal Regulations For Underground Storage Tank Systems*. Office of Solid Waste and Emergency Response, EPA 510-K-95-002 (1995, July). 40 pp.

9 National Fire Prevention Association, *Underground Flammable and Combustible Liquid Tanks*, Boston (1964, 1986).

10 USEPA, *Musts for USTs: A Summary of the New Regulations for Underground Storage Tank Systems*, Office of Underground Storage Tanks, EPA-530/UST-88-008 (1990, July). 39 pp.

11 R.F. Weston, "The Waste Disposal and Utilization Problems of the Petroleum Industry," in *Proceedings of the First Industrial Waste Utilization Conference, Purdue University, Lafayette, IN*: 98–125 (1944).

12 A.W. Lindsey, "Ultimate Disposal of Spilled Hazardous Materials," *Chem. Eng*. 23: 107–114 (1975).

13 New York State Department of Environmental Conservation (NYSDEC), *Technical Resource Material: Transport and Storage Vessels* (2006).

14 USEPA (1986).

ages—nearly everything "wears out" at some point. In addition, new equipment often leaks when first put in service and tested, a condition engineers refer to as "shakedown." Thus, leaks may occur during the entire service period of equipment: at first during shakedown, and later due to aging. Writing about oil refineries, Roy F. Weston, an environmental engineer in the 1950s, noted that "[l]eaks and spills are practically unavoidable…"[15] While they may be unavoidable, they are not really predictable. Other general observations about leakage include:

- From interviews, inventory records, and direct measurement of tank tightness, USEPA estimated that 35 percent (189,000) of all underground motor fuel storage tanks leaked at an average rate of 0.32 gallons/hour (7.7 gallons/day; 2,800 gallons/year).[16]
- Tank leakage rates as high as 1 gallon/day were still sometimes undetectable as of 1986.[17]
- Examining records from all 50 states, consulting firm Versar, Inc. (1986) identified 12,444 UST release incidents between 1970 and 1985. Since many releases had not been reported, these incidents represented "only a fraction of the total number of underground storage tank releases."[18]
- In 1977, "pipeline breaks and leaks cause[d] about 500 spills a year, discharging over 1 million gallons of oil."[19]
- Of the oil pipeline leaks documented in 1997, 18 percent were "due to outside force or third-party damage," 16 percent were

15 Weston (1952).
16 USEPA (1986).
17 USEPA (1986).
18 Versar, Inc., *Summary of State Reports on Releases from Underground Storage Tanks*. Report to USEPA, Office of Solid Waste (Washington, DC), EPA-600/M-86-020 (1986, August). 95 pp.
19 USEPA, *Oil Spills, and Spills of Hazardous Substances.* Office of Water Program Operations, Oil and Special Materials Control Division (1977, March). 38 pp.

"due to material construction defect," and 45 percent were due to "operational incidents."[20]

- As late as 1997, USEPA observed that small leaks representing up to 1 percent of flow could "go unnoticed for weeks."[21]
- Despite regulations and operational improvements in the fluid transportation industry, USEPA noted there were still about 20 large oil spills (1,000 barrels or more) and 1,401 hazardous liquid spills on U.S. pipelines between 1988 and 1994, representing 1.2 million barrels of lost product.[22]

Despite how widespread the leaks have been and still remain, there is a long history of literature describing both how engineers believed equipment could be made leak-free and also the required diligence to detect and repair leaks. For example, Meade and Alrich discussed many types of leaks that could occur, while describing how to design/construct equipment to avoid them.[23, 24] Even during that early industrial era, there were many recommendations about how to repair leaks if they occurred.[25, 26] On the other hand, the problem was relentless and has been long recognized as requiring constant diligence to avoid and fix leaks.[27, 28]

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20 USEPA, *EPA Office of Compliance Sector Notebook Project: Profile of the Ground Transportation Industry Trucking, Railroad, and Pipeline*. Office of Enforcement and Compliance Assurance, EPA/310-R-97-002 (1997, September). 134 pp.

21 USEPA (1997).

22 USEPA (1997).

23 A. Meade, "The Storage of Gas," in A. Meade (ed.), *Modern Gasworks Practice (Second Edition)*, London: Benn Brothers, Ltd. (1921).

24 H.W. Alrich, "Gas Tanks Now and Then, *Am. Gas J.* 148: 75–79 (1934).

25 H.A. Allyn, "Gasholder Construction," in *Proceedings of the New England Association of Gas Engineers at the 27th, 28th and 29th Annual Meetings, February 17–18, 1897, February 16–17, 1898, February 17–18, 1899, Boston, MA*, New Bedford, MA: New Bedford Printing Company: 150–172 (1898).

26 P.W. Prutzman, "Sulphur and Oil Gas," in *Proceedings of the Fifteenth and Sixteenth Annual Meetings of the Pacific Coast Gas Association, September 17–19, 1907; September 15–17, 1908, Santa Cruz, California* (1907).

27 Whipple (1908).

28 J.R. Wohrley, "Tar Extractors," in *Proceedings of the American Gas Association Second Annual Convention, November 15–20, 1920, Hotel Pennsylvania, New York, NY: Technical Section* (1920). 480 pp.

Leaks and Spills: Key Sources

This section provides examples of the impacts from leaks and spills that result from accidental spills, mechanical equipment failure, corrosion, and geologic conditions or other natural phenomena.

Accidental Spills

According to Versar, Inc. (1986), accidental spills accounted for approximately 15 percent of all reported releases. Examples and statistics regarding accidental spills include the following:

- Unloading oil from the bottom of a tank car results in the loss of "a gallon or two every time a car is unloaded."[29]
- Rail tanks used for transporting fluids occasionally developed leaks, causing "alarming accidents."[30]
- "Over 13,000 spills representing nearly 20 Mgal of potentially damaging and dangerous materials occur yearly in the US."[31] Of the 20 million gallons of materials released annually circa 1975, 5 percent resulted from accidental spills.
- "Overfilling of underground tanks and product transfer spills occur in commercial and industrial settings… Frequently, a tank may become so full that there is no room to drain the

29 F.H. Shelton, "The Nuisance Question in Gas Works," in *Proceedings of the New England Association of Gas Engineers, 27th, 28th, and 29th Annual Meetings, February 17–18, 1897, February 16–17, 1898, February 17–18, 1899*, New Bedford, MA: New Bedford Printing Co.: 314–323 (1899).
30 N. Calvert, "Manufacture of Concentrated Gas Liquor," *Gas Journal* (1953, December 23): 791–796.
31 Lindsey (1975).

delivery hose prior to disconnection, leading to a product spill of up to 25 gallons."[32]

- "The documented quantity released from overfills is less than 100 gallons in most cases."[33]
- Lancy noted that the "second most severe pollution hazard… [was] accidental discharges… [and] nearly every process solution… is prone to be discharged through an accident… while not common… to spring a leak of such magnitude… a slow leak [of] 1 to 2 inches/day could go undetected for months…"[34]

Mechanical Equipment Failure

While accidental spills contribute to product losses, large product leaks are primarily due to mechanical equipment failure.[35] Equipment failures that may result in loss of product include catastrophic failures (e.g., explosions), equipment flaws, or improper equipment installation that cannot be tested until actual startup (engineers call this period "shakedown"); and mechanical wear, which occurs as equipment is used over time. For example, gas works tanks installed in the early twentieth century often leaked as they were first filled.[36, 37] Poorer, older construction techniques or materials often caused

32 D.S. Etkin, "Analysis of Oil Spill Trends in the United States and Worldwide," in *International Oil Spill Conference*: 1291–1300 (2001). Accessed at: http://www.environmental-research.com/publications/pdf/spill_statistics/paper4.pdf
33 Versar, Inc. (1986).
34 L.E. Lancy, "Pollution Control in Plating Operations," in H.F. Lund (ed.), *Industrial Pollution Control Handbook*, New York: McGraw-Hill Book Co. (1971).
35 Versar, Inc. (1986).
36 Howard, "What is the Best Method of Stopping Leaks in a Brick Tank?" in *Proceedings of the Western Gas Association, 24th Annual Meeting*: 306 (1904).
37 W. Wallace, "Reminiscences of the Gas Business," in *Proceedings of the Fourth Annual Meeting of the Indiana Gas Association, January 17–18, 1912, Indianapolis, IN* (1912). 98 pp.

tank and pipe leaks.[38, 39] Examples of mechanical wear include pump bearing/ seal wear, loose fittings, worn gaskets, worn joints, cracks or ruptures, vibration or other friction disturbances, and damage from external sources (e.g., collision with outside equipment).[40] Statistics regarding mechanical equipment failure include the following:

- Of the approximately 20 million gallons spilled annually circa 1975, approximately 13.8 million gallons (69 percent) were released due to equipment failure.[41]

- Besselievre, a well-known wastewater engineer, noted, "Regardless of good housekeeping and maintenance, pumps will occasionally leak at the glands… No matter how good the housekeeping may be in an industrial plant, leakage will occur."[42]

- When considering control technologies for pumps, flanges, and valves in the coke industry, USEPA noted the experts who questioned whether these technologies would enable facilities with equipment leaks to achieve compliance with proposed regulations.[43]

- As of 2001, "[s]tructural failures are the most common cause of US pipeline spills, representing 40% of spills. Seventy-five

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38 J.H. Braine, "Repairs of Leaks in Sectional Gas Holders: Detailed explanation of the method of procedure to be used in repairing various kinds of leaks" (excerpt), *Am. Gas Assoc. Mon.* (1927, February): 71–72.
39 W. Mooney, *The American Gas Engineer and Superintendents' Handbook*, New York: Mooney (1888).
40 Versar, Inc. (1986).
41 Lindsey (1975).
42 E.B. Besselievre, *The Treatment of Industrial Wastes*. New York: McGraw-Hill Book Co. (1969).
43 USEPA, *Benzene emissions from coke by-product recovery plants, benzene storage vessels, equipment leaks, and ethylbenzene/styrene process vents: Background information and responses to technical comments for 1989 final decisions* (1989).

percent of structural failure is attributed to corrosion, 15% to defective pipes, and 10% were attributed to defective welds."[44]

Corrosion

Corrosion also plays a prominent role in product releases to the environment.[45] "Corrosion results when bare metal [e.g., steel or iron used in tank and pipe construction] and soil and moisture conditions combine to produce an underground electric current that destroys the hard metal. Over time, corrosion creates holes and leaks develop."[46] This natural, electrochemical deterioration of metal manifests as rusting, pitting, cracking, and blistering. In 1986, 25 years after fiberglass tanks came into industrial use, Versar, Inc. estimated that 89 percent of tanks subject to UST regulation were constructed of steel.[47] Small losses due to corrosion are problematic to detect and prevent, especially for underground equipment, and can accumulate to a large volume of lost material.[48] Little was known for many years about how to manage corrosion,[49] but today there are textbooks on the subject and cathodic protection is the norm. Statistics regarding corrosion of tanks and pipelines include:

- Versar, Inc. (1986) found that "[c]orrosion is the dominant cause of failure for tank systems [USTs] more than 10 years old. For example, 71% of the failures of tank systems between 11 and 20 years old, and 60% of those more than 20 years old, were caused by corrosion."

- Regarding unprotected steel USTs, Meehan stated, "Under average conditions, tank perforation and leakage develop in

44 Etkin (2001).
45 Versar, Inc. (1986).
46 USEPA (1995).
47 Versar, Inc. (1986).
48 Etkin (2001).
49 D. Finley, "Corrosion of Underground Pipe," in *Proceedings of the Thirty-third Annual Convention of the Pacific Coast Gas Association, August 23–27, Pasadena, California*: 241 (1926).

fifteen to twenty years. Corrosion-induced failures should generally be suspected for bare steel tankage with otherwise unexplained leakage beginning ten to thirty years after tank installation."[50]

- Twenty percent of oil pipeline leaks documented in 1997 were due to corrosion.[51]
- As of 2001, "[s]tructural failures are the most common cause of U.S. pipeline spills, representing 40% of spills. Seventy-five percent of structural failure is attributed to corrosion…"[52]
- Gorman noted how engineers "in all sectors of the petroleum industry" in the 1920s and 1930s fought a never-ending battle against corrosion, and hence against leaks.[53]
- Jackson noted the problem that leakage was often not detected because tank corrosion was often underground.[54]
- Hendrickson noted leakage problems from pipe corrosion.[55]
- Bigness noted that corrosion has been a problem since the Iron Age: "when water put in its appearance the steel equipment

50 R.C. Meehan, "A Natural History of Underground Fuel Tank Leakage," *Environmental Claims Journal* 5(3): 339–348 (1993).
51 USEPA (1997).
52 Etkin (2001).
53 H.S. Gorman, "Eliminating Corrosion and Monitoring Flows," in H.S. Gorman (ed.), *Redefining Efficiency: Pollution Concerns, Regulatory Mechanisms, and Technological Change in the U.S. Petroleum Industry*, Akron, OH: The University of Akron Press: 195–214 (2001).
54 W.C. Jackson, "Distribution Costs as Affected by a Combined 'Dri-gas' and Naphthalene Washer," *Gas Journal* (1930, May 28): 512–515.
55 A.V. Hendrickson, "Abstracts of Papers Relating to Gas Manufacture," in *Institution of Gas Engineers: Transactions, 1929–30*: 782–827 (1930).

began to suffer… tanks have been known to be corroded to failure in less than six months…"[56]

Geologic Conditions and Other Natural Phenomena

Frost heaves, sinkholes, other subsidence events, and even tree roots cause many pipes and tanks to rupture. Infiltration/inflow studies for sewer systems in hundreds of towns across the United States confirm this, and government agencies have programs to study and prevent these occurrences. One recent sewerage study found 13 percent of 60,000 feet of pipe examined to be leaking, primarily at "gusher" or "runner" amounts.[57] Older tanks were often built with masonry placed into the ground for support, but the ground could shift and cause cracks in the masonry.[58, 59] Temperature variations also have long been known to cause ruptures and other types of leakage.[60] Comprehensive statistics regarding releases related to natural phenomena include the following: of the 20 million gallons of materials released annually circa 1975, 8 percent resulted from natural phenomena such as floods or earthquakes;[61] and Versar, Inc. reported that approximately 7 percent of UST releases in its study were caused by natural phenomena.[62]

56 L.G. Bigness, "Corrosion has been a problem since the iron age and research has done little to combat it when hydrogen sulphide is the activating agent; control of moisture tends to minimize attack," *Oil Weekly* (1929, January 25): 27–35.
57 J. Rinner and S. Pryputniewicz, "To Zoom or not to Zoom," *Civil Eng. Pract.* 23(2): 33–40 (2008).
58 H.W. Alrich, "Brick, Concrete and Steel Holder Tanks," in *Proceedings of the American Gas Institute, 5th Annual Meeting, held October 19–21, 1910, in New York, NY:* 567–607 (1910).
59 L.J. Willien, "Disposal of Gas Plant Wastes," *Gas Age* 349(4) (1920).
60 J.S. McIlhenny, "Removal of the Last Traces of Oil and Tar from Water of Condensation," in *Proceedings of the Ohio Gas Light Association Twenty-first Annual Meeting held at Hotel Schenley, Pittsburgh, PA, March 15–17, 1905* (1905).
61 Lindsey (1975).
62 Versar, Inc. (1986).

The Case of the Manufactured Gas Industry

The manufactured gas industry, which operated from about 1850 to 1950—through the pinnacle of the Industrial Revolution—was ahead of its time for wastewater and byproduct engineering. It provides a good example of a leak/spill legacy, as its 3,000 mostly urban sites receive state Superfund cleanups today. A review of about 200 contemporaneous papers from that industry reveals the following common occurrences of historical leaks and spills, remedies, and improvements attempted (italicized text indicates direct quotes or paraphrasing).

- A Practical Treatise on the Manufacture and Distribution of Coal Gas, 1877—provides numerous examples of leaks and how to prevent them, with a good example of shakedown issues: *On filling the tank, about three months after its completion, unexpectedly, it lost considerably during the first few days.*[63]
- Boston Gas photo, 1886—*Subsurface major leak in gasholder at startup* (so severe it was noticed, and the holder was excavated/repaired).[64]
- The Manufacture of Illuminating Gas, 1887—discusses gas leaks from steel pipes: … *notwithstanding the utmost care [of sealing the joints] there is considerable leakage…*[65]
- The American Gas Engineer and Superintendents' Handbook, 1888—[gas]*holders can leak... poor pipe casting can cause ruptures.*[66]
- Gasholder Construction, New England Association of Gas Engineers, 1898—*perfectly tight tanks have been the exception rather than the rule... may sooner or later develop leaks which*

63 W. Richards, *A Practical Treatise on the Manufacture and Distribution of Coal Gas*, London: E. & F.N. Spon (1877).
64 Boston Gas Archive of Boston College Burns Library, Boston Gas Photo (c. 1886).
65 J.D. Weeks, "The Manufacture of Illuminating Gas," *Chantaguan* 8: 164–166 (1887).
66 Mooney (1988).

may be difficult to remedy... there is no doubt in my mind that many steel bottoms will become leaky in the future.[67]

- Repairing Holder Tanks, 1891—*Tight gasholders are the exception, leaky ones the rule; at least this has been my experience…*[68]

- Self-Instruction for Students in Gas Manufacture, circa 1900—*tightness of the tank depends, to a great extent, upon the material of which the earth backing is formed and the care…*[69]

- What is the Best Method of Stopping Leaks in a Brick Tank? 1904—*After the tank was finished and filled with water, it cracked….*[70]

- Removal of the Last Traces of Oil and Tar from Water of Condensation, 1905 (Ohio Gas Light Association)—*sudden changes in temperature [addressed so as to]... not produce leakage.*[71]

- Repairing the Cup of a Two-Lift 500,000 Cubic Foot Gas Holder, 1907—*The leaks had from time to time been patched with soft patches, using an iron clamp with red lead putty…*[72]

- Report of the New Jersey Sewerage Commission, 1908—*Sources of Liquid Wastes... Leaks, or drips from tar tanks, scrubbers and condensers, receiving tanks, purifiers, relief*

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67 Allyn (1898).

68 F.C. Sherman, "Repairing holder tanks," *Am. Gas Light J.* (1891, March 9): 331–333.

69 Mentor, *Self-Instruction for Students in Gas Manufacture, being answers to questions based on the honors grade syllabus in gas manufacture of the city and guilds of London Institute,* Second Edition, London: The Gas World Offices (c. 1900).

70 Howard (1904).

71 McIlhenny (1905).

72 G.S. Colquhoun, "Repairing the Cup of a Two-Lift 500,000 Cu. Ft Gas Holder," in *Proceedings of the Fifteenth and Sixteenth Annual Meetings of the Pacific Coast Gas Association, 1907 and 1908, Santa Cruz, CA*, Pacific Coast Gas Association: 47 (1907).

holders, oil barrels, oil tanks, pipes, etc., which may seep into the ground... Often... important leaks occur in tanks sunk in the ground [and are not discovered].[73]

- The Disposal of the Waste Products of Gas Works, 1908—*The various leaks... are partly avoidable but some cannot be easily done away with. If the leaks occur... above ground... they can be done away with. Often... below ground. In former days it was a common custom to put all these tar tanks, settling tanks, etc., in the ground and build them of wood. In time... leaky…*[74]

- Catechism of Central Station Gas Engineering in the United States, 1909—*almost impossible to build a brick [holder] wall that will be water tight of itself [but it is possible with proper technique].*[75]

- AGA Proceedings, Brick, Concrete and Steel Holder Tanks, 1910—*The brick tank seems to be regarded as the criterion of prudence and conservatism* [but not well founded—goes on to discuss conditions when brick tanks can crack (e.g., nearby pilings or poor mudding) and offers 40 pages of design instruction].[76]

- Reminiscences of the Gas Business, 1912—*When the holder was filled a great many leaks were found.* [i.e., shakedown].[77]

- Ballantine v. Public Service (New Jersey) suit, 1914—*Expert witness in the trial noted it is "perfectly well known that concrete may have lots of regular network with cracks in it not*

73 G.W. Fuller, *Report of the New Jersey Sewerage Commission*, Somerville, NJ; The Unionist-Gazette Association, State Printers (1908).
74 Whipple (1908).
75 Trustees Gas Educational Fund, *Catechism of Central Station Gas Engineering in the United States*, Second Edition (1909).
76 Alrich (1910).
77 Wallace (1912).

yet visible to the eye," and that "if such were the case it would leak water and tar."[78]

- Gas Light Journal, 1914—*question of storing tar in a masonry holder should be carefully studied, for tar may be lost by leakage…*[79]

- Operation of Gas Works, 1917—*Experience has shown that a masonry tank will allow very little coal tar to seep through it but water-gas tar frequently escapes* [and recommends steel tanks for CWG tar].[80]

- The Disposal of Wastewater from Water Gas Plants on Streams adjacent to Parks, 1919—*In the early days... tar waste from the works had leaked through broken pipe lines and from the wooden separator box…*[81]

- Steam Plant Apparatus, 1920—*we are all prone to overlook leaks that are out of sight and the average gas man has trouble enough without looking for more.*[82]

- Producer Division, Committee Report, 1920—*piping developed leaks due to change in chemistry from change in feedstock.*[83]

- The Demand Limiting Meter and Engineering Problem involved in the Application of the Three-Part Rate as a Basis

78 Court of Errors and Appeals of New Jersey, P. Ballantine & Sons v. Public Service Corporation of New Jersey (No. 76), in *The Atlantic Reporter* 91, Permanent Edition: 97 (1914, June 16).

79 A. Hansen, "Tar," *Am. Gas Light J.* 23: 362–366 (1914).

80 W.M. Russell, *Operation of Gas Works,* First Edition, New York: McGraw-Hill Book Company (1917).

81 L.R. Dutton, "The Disposal of Wastewater from Water Gas Plants on Streams adjacent to Parks," *Am. Gas Assoc. Monthly* 1(4): 191–193 (1919).

82 Greene (1920).

83 R.F. Bacon and W.A. Hamor, Producer Division, Committee Report, in *Proceedings of the American Gas Association Second Annual Convention, November 15–20, 1920, Hotel Pennsylvania, New York, NY: Technical section* (1920). 480 pp.

of Selling Gas Service, 1920—*In general, the leakage rate will vary in direct proportion to the rate of gas deman*d.[84]

- Tar Extractors, 1920—*large amount of leakage [if tar extractors are not built properly].*[85]

- Disposal of Gas Plant Wastes, 1920—*Brick holder pits sometimes develop cracks from settling. Leaks often occur in gas, tar and oil lines which cause considerable damage before they are discovered.*[86]

- The Storage of Gas, 1921—discusses the many types of leaks and how to design/construct to avoid them.[87]

- Disposal of Wastes from Gas Plants, 1921—*water overflows the top of the tank and scatters all the water and tar around the adjacent yard space* [accident—letting the bell rise too high].[88]

- Wrinkle No. 8 to Stop Leaks in Pump Pits, 1922—*seepage through the walls of a concrete pump pit* [and how to fix it, example of how many types of equipment leaked].[89]

- Gas Engineers' Compendium: A Collection of Statistics, Formulae, Rules and Data for the Everyday Use of Gasworks Officials and Students, 1924—*shows conclusively that, when properly made, they are quite tight* [benefits of reinforced

84 H.D. Hancock, "The Demand Limiting Meter and Engineering Problems Involved in the Application of the Three Part Rate as a Basis of Selling Gas Service," in *Proceedings of the American Gas Association Second Annual Convention, November 15–20, 1920, Hotel Pennsylvania, New York, NY: Technical section* (1920). 480 pp.
85 Wohrley (1920).
86 Willien (1920).
87 Meade (1921).
88 F.W. Sperr, "Disposal of Wastes from Gas Plants," *Gas-Age Record* (1921): 566–571.
89 J.E. Kelley, "Wrinkle No. 8 to Stop Leaks in Pump Pits," in *Proceedings of the Twenty-ninth Annual Convention of the Pacific Coast Gas Association, September 19–21, 1922, Santa Barbara, California*: 451 (1922).

concrete, which was viewed as a solution to a pervasive problem of leaking holders].[90]

- Corrosion of Underground Pipe, 1926—*is a subject on which there is a considerable lack of information.*[91]

- Repairs of Leaks in Sectional Gas Holders, 1927—*A great many small leaks will be found to occur on seams and rivets which can be repaired...*[92]

- Corrosion Has Been a Problem Since the Iron Age, 1929—*when water put in its appearance the steel equipment began to suffer and in some parts of that field tanks have been known to be corroded to failure in less than six months…*[93]

- The Manufacture, Distribution and Utilization of Gas, 1930—[Gas] *Oil tanks ... surrounded by earth dikes... should a serious leak result…*[94]

- Gas Holder Inspection Service, circa 1930—*hidden corrosion [causes leaks], inspection services.*[95]

- Distribution Costs as Affected by a Combined "Dri-Gas" and Naphthalene Washer, 1930—*corrosion out of sight [holder leaks/damage].*[96]

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90 Ernest Benn Limited, *Gas Engineers' Compendium: A collection of statistics, formulae, rules and data for the everyday use of gasworks officials and students* (excerpt), New York: D. Van Nostrand Co. (1924).
91 Finley (1926).
92 Braine (1927).
93 Bigness (1929).
94 C.E. Reinicker, *The Manufacture, Distribution and Utilization of Gas*, Ann Arbor, Michigan: Edwards Brothers, Inc. (1930).
95 Stacey Bros. Gas Construction Co., Gas Holder Inspection Service, *Bulletin No. 1-44* (c. 1930).
96 Jackson (1930).

- Abstracts of Papers Relating to Gas Manufacture, 1930—regarding pipe corrosion.[97]

- Removal of Sulfur by Oxide and Liquid Purification, 1931—*purifiers have also been made with brick or concrete bottoms and sides but they cannot be relied upon for tightness.*[98]

- Gas Tanks Now and Then, 1934—*When these same [masonry] designs ...the results were frequently very unsatisfactory and the leakage so great that it was necessary to reconstruct the tanks. [new design (steel tanks) are better]*[99]

- The New Modern Gas Works Practice, 1934—*need to prevent holder corrosion.*[100]

- Works and Distribution Inspection Report, 1934 (Concord, New Hampshire, inspection)—*water is seeping through a long horizontal crack in the concrete retaining wall around this holder tank...*[101]

- Industrial Wastes from the Equipment Manufacturers' Viewpoint, 1939—*increase... yields... by plugging leaks…*[102]

97 Hendrickson (1930).

98 J.J. Morgan, "Removal of Sulfur by Oxide and Liquid Purification," in J.J. Morgan (ed.), *A Textbook of American Gas Practice: Volume I: Production of Manufactured Gas,* Maplewood, NJ: Jerome J. Morgan: 804–855 (1931).

99 Alrich (1934).

100 A. Meade, *The New Modern Gasworks Practice,* Third Edition, Entirely Rewritten and Greatly Enlarged, of "Modern Gasworks Practice," Volume 1, Eyre & Spottiswoode: London (1934).

101 United Gas Improvement Company (UGI). Works and Distribution Inspection Report, Concord Gas Company, Concord, NH. (1934, November 14).

102 C.L. Knowles, "Industrial Wastes from the Equipment Manufacturers' Viewpoint," *Ind. Eng. Chem*. 31(11): 1338–1345 (1939).

- Manufacture of Concentrated Gas Liquor, 1953—*rail tanks used for transporting the concentrated liquor occasionally developed leaks… alarming accident-tank was overflowing…*[103]

Several observations can be made from this long—albeit abbreviated—list. First, leaks were common but never intentional. Second, many factors caused leaks and spills. Third, when maintenance was possible, leaks were fixed. Finally, tank technology improvements reduced, but did not eliminate, leaks.

Conclusion

Leaks and spills represent a significant source of subsurface contamination. Their historical causes were numerous but inadvertent—for every report of a leak or its cause, there would appear to be a corresponding report of how to fix or avoid it. Nevertheless, their occurrence was endemic despite engineering improvement and left a legacy of significant modern-day environmental response. Some causes have been fixed with today's engineering knowledge of corrosion and materials/construction, and regulations attempt to manage the impacts of leaks and spills. Despite today's improvements, however, the problem will likely continue for as long as fluids need engineered storage and transport.

103 Calvert (1953).

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