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Cleanup and Complexity: Nuclear and Industrial Contamination at The Santa Susana Field Laboratory, California

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Abstract

Environmental contamination, a legacy of industrial activity borne by numerous sites around the world, poses health risks for surrounding communities and presents serious cleanup challenges. One such site, the Santa Susana Field Laboratory (SSFL), served as an aerospace and nuclear energy research facility for over 50 years, during which time radioactive and other hazardous materials were unintentionally and intentionally released into the surrounding environment. These releases, including the partial meltdown of a sodium reactor, were hidden from the public for three decades. The site is now located in suburban Los Angeles, with 730,000 people living within a 10-mile radius. This paper evaluates the technical and social challenges underlying site cleanup at SSFL, including a complex geological setting, uncertain contaminant information, and a convoluted, evolving regulatory framework. These challenges, paired with historical secrecy on the part of responsible organizations and unclear layers of responsibility, have led to uncertainty and distrust within the surrounding community. Lessons learned from other remediated sites are assessed and recommendations for the SSFL cleanup are provided.

Graphical Abstract

Keywords Nuclear contamination · Industrial contamination · Remediation · Environmental regulation

Introduction

Numerous sites around the world face the challenge of cleaning up historical industrial and nuclear contamination, so as to undo environmental degradation and mitigate threats to human health. Among these is the Santa Susana Field Laboratory (SSFL). Located just outside Los Angeles, California, SSFL was the site of extensive aerospace and nuclear research from 1948 to 2006. Throughout its history, recurrent radiation releases and poor disposal practices for rocket fuel and other hazardous substances led to extensive contamination in the area by radionuclides and other chemicals. The most famous

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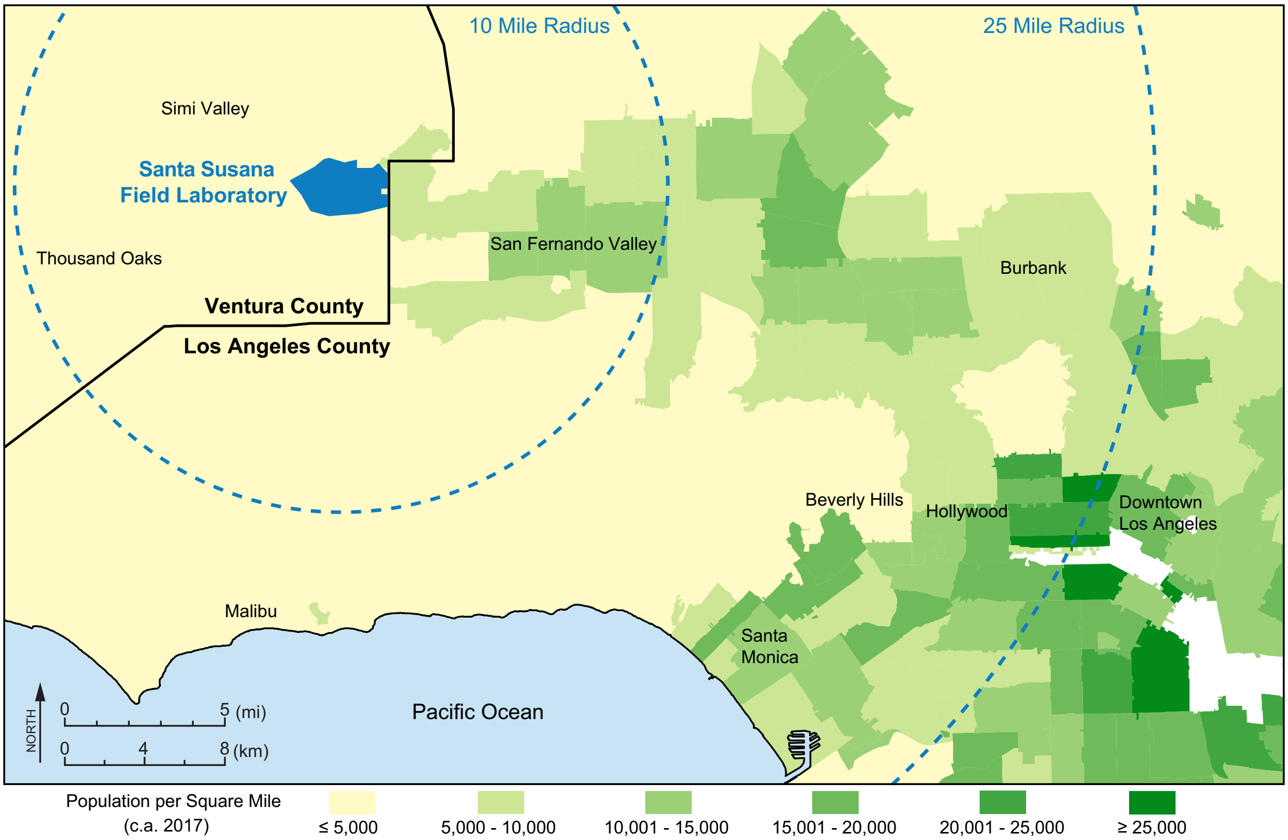

Fig. 1 The SSFL (in blue) is located in Ventura County, California. The property borders Los Angeles County in the Santa Susana Mountains, a hilly region between Los Angeles suburbs in the San Fernando Valley and Simi Valley

contamination event occurred when the Sodium Reactor Experiment, the United States' first commercial nuclear power plant, suffered a partial meltdown in July 1959 (Ashley et al. 1961). Now, 60 years later, over 730,000 people live within 10 miles of the site (Fig. 1). Regulatory agencies have known about its contamination since 1989. Recently, the November 2018 Woolsey Fire, which started on the SSFL property, and assertions of unusual cancer related deaths have reignited community concerns about the spread and effects of this contamination. However, SSFL is still not cleaned up.

One of the primary obstacles to remediation of the SSFL site is the complex character of its contamination and setting. In the remediation literature, *complexity* generally focuses on technical challenges: heterogeneous types of contamination, a variety of transport pathways, complex geology, and long timescales (National Research Council et al. 2013; Price et al. 2017). However, many contamination problems are also social problems (Cappuyns 2016). Not only do they affect people's health and wellbeing, they are characterized by competing value systems and diverse sets of stakeholders; decisions about cleanup thus pose ethical—not just technical—questions.

This research aims to expand the definition of complexity in site remediation and cleanup beyond purely technical considerations. We investigate the scientific, social, and regulatory challenges underlying the SSFL cleanup. It is a quintessential wicked problem (Rittel and Webber 1973; Balint et al. 2012), characterized by uncertain science and competing social values. We describe the complexity of SSFL, including a unique and hard-to-characterize geological setting, a mixture of radioactive and conventional contaminants, and a social setting with diverse social values, competing perceptions of risk, and unclear responsibility, then evaluate how these complexities have served as barriers to effective[1] cleanup. We then draw on lessons learned at other locations to identify possible approaches to hasten cleanup and address community unrest. There are numerous sites like SSFL around the world, with historical contamination at various stages of cleanup; by assessing the full range of barriers and opportunities to cleanup at SSFL,

[1] Effectiveness can be defined numerous ways, e.g., cleanup to relevant regulatory standards, cleanup to a level satisfactory to activist groups, or cleanup that minimized community discomfort. We do not prioritize a single definition, but arguable the SSFL case has not met any of these.

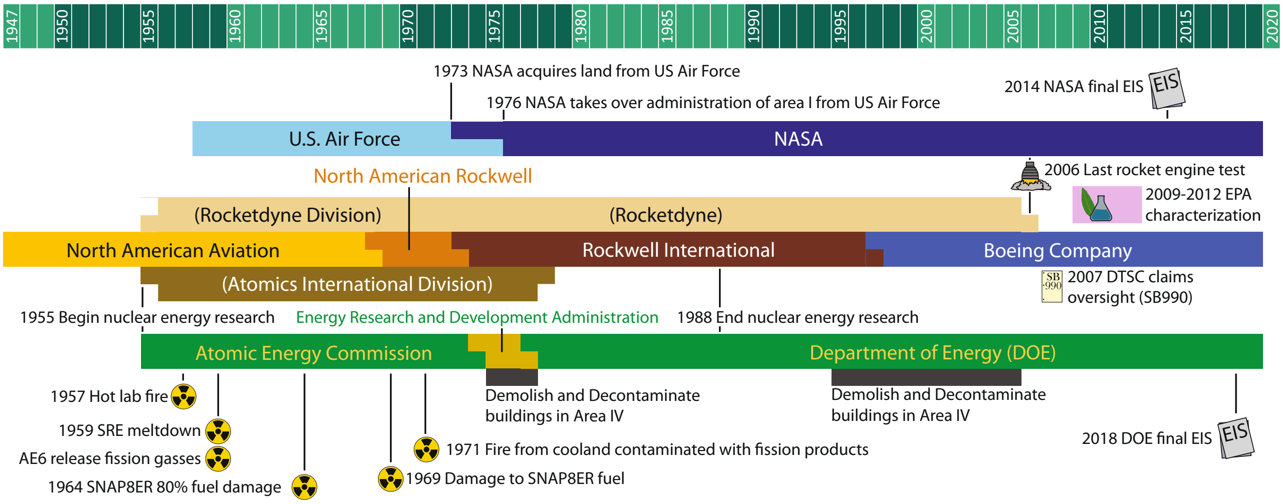

Fig. 2 A timeline of SSFL. Named colored blocks show site ownership lineages; text indicates important events

we hope to contribute to a broader strategy for addressing global nuclear and industrial contamination.

Background

SSFL is located on a rocky hilltop along the Ventura County-Los Angeles County boundary in the Santa Susana Mountains. North American Aviation (NAA) first used the site in the late 1940s for rocket engine technology contract work with the U.S. Army and U.S. Air Force. During the 1950s, NAA restructuring created two divisions: Rocketdyne, which continued rocketry research, and Atomics International, which began nuclear technology work at SSFL on behalf of the Atomic Energy Commission (AEC) (U.S. Department of Energy Office of Environmental Management 2017). NAA eventually leased property to the AEC, which established the Energy Technology Engineering Center (ETEC) in the early 1960s (U.S. Department of Energy Office of Environmental Management 2017). Likewise, a portion of the site was transferred to the Air Force in 1968. In 1967, NAA merged with Rockwell Corporation to form North American Rockwell, later rebranded as Rockwell International. In 1974, following extensive public criticism of AEC, Congress replaced the AEC with the Energy Research and Development Administration, which overtook AEC's activities at SSFL until 1977, when the Department of Energy (DOE) was created to consolidate all government nuclear research activities. In 1988, nuclear testing was discontinued at the site. In 1996, the Boeing Company purchased the aerospace and defense divisions of Rockwell International, including its SSFL laboratories. Research activities at the site concluded by 2006 (MWH 2007; Hennigan 2012).

Given the historical involvement of NAA, the Air Force, and AEC, today Boeing, the National Aeronautical and Space Administration (NASA), and DOE are responsible for cleanup. The tortuous history of SSFL's management is summarized in Fig. 2.

The laboratory is divided into four "areas" (I through IV) that focused on either A) rocket development for weapons and space exploration or B) nuclear energy. Part of Area I is owned and operated by Boeing; historic uses included rocket engine test areas, an advanced propulsion test facility, burn pits, a thermal treatment facility, laboratory facilities, and administration buildings. The rest of Area I, owned by NASA and operated by Boeing, contained a liquid oxygen plant. Area II, owned by NASA and operated by Boeing, was the primary site of rocket engine testing. Area III, owned and operated by Boeing, was used for component and system testing. Area IV is operated by Boeing, with ownership shared between Boeing and DOE. Uses included energy technology research at ETEC, nuclear reactors, facilities for removing cladding from nuclear fuel rods, and research facilities for liquid metals, heat transfer, coal gasification and liquidation, and lasers. Two buffer zones are owned by Boeing, and were not used for industrial activities (MWH 2007).

Known Contaminants and Their Sources

The nuclear activities performed at SSFL were diverse, including ten small reactors and seven facilities housing significant quantities of nuclear material (Oldenkamp and Mills 1990). During the AEC era, fission products from the reactors were repeatedly vented to the environment, as in the 1959 sodium reactor experiment in which partial melting of fuel elements occurred (Hart 1962). The fabrication and disassembly of nuclear fuel components, composed primarily of uranium and plutonium but also incorporating many lighter fission product radionuclides, were conducted on-site (Sapere Consulting, Inc, The Boeing Company 2005). The diversity of activity, conducted over several decades, gives rise to corresponding diversity in the type and chemistry of the site's radioactive contaminants.

In 2009, the US Environmental Protection Agency (EPA) initiated a study of radioactive soil contamination at Area IV, revealing higher than expected levels of several radionuclides, including cesium-137, strontium-90, and plutonium-239 (Sapere Consulting, Inc, The Boeing Company 2005; HydroGeoLogic, Inc. 2012; US Department of Energy Office of Environmental Management 2018). Cesium-137 and strontium-90 are produced when a uranium nucleus fissions, while plutonium-239 is produced when uranium absorbs a stray neutron produced by earlier fission processes. This contamination can be attributed primarily to the uranium-fueled nuclear reactors operated on-site. Despite EPA's comprehensive characterization, uncertainty remains regarding the precise nature and extent of contamination. For example, EPA "suggested additional evaluation," as it was unable to determine whether the detected presence of contaminants like uranium resulted from site activities or from background contributions (US Department of Energy Office of Environmental Management 2018).

A variety of nonradioactive, hazardous chemical compounds were also used in research and testing. These compounds and their by-products have been identified in soil and groundwater or are predicted to constitute a portion of contamination due to their use. Examples include petroleum products (diesel fuel, hydrazine fuels, kerosene-based fuels, hydraulic oils) (Center for Environmental Risk Reduction 2006; US Department of Energy Office of Environmental Management 2018), chlorinated compounds (trichloroethene, 1,1,1-trichloroethane, and polychlorinated biphenyls) (Center for Environmental Risk Reduction 2006), other organic solvents, volatile organic compounds, semi-volatile organic compounds, oxidizers, asbestos, 1,4-dioxane, mercury, and heavy metals (MWH 2007; National Aeronautics and Space Administration 2010a). Hazardous chemicals were used in a variety of settings, including outside (e.g., during a rocket engine test or in leaded exterior paint), and in laboratories or workshops with varied waste containment systems. Liquid chemical compounds were stored in above- and below-ground drums and tanks; powdered compounds were stored in jars, drums, and other containers (MWH 2007).

These chemicals were disposed of by a variety of legal, legal at the time, and illegal methods, as was common practice at the time. Three on-site landfills were created for nonhazardous construction debris. Ponds were used as repositories for liquid wastes, such as in Area I where unwanted fuel was poured and then burned (CH2MHill 2008). Ponds were also used to dispose of solid wastes that would react with water. For instance, drums of sodium were rolled into ponds, then shot with a firearm so they would explode (Senate Bill 990 2007). From 1958 to 1971, lined and unlined "burn pits" were used to dispose of hazardous materials deemed too dangerous to transport on public highways[2], a practice eventually halted due to air pollution concerns (SSFL Analytical Chemistry Unit 1981). However, chemicals continued to be disposed by pouring them into containers and then burning them, which came to public eye after a 1994 explosion killed two employees and injured others (Reed 1996; Guccione 2002). It was common practice to refrain from taking notes or records during illegal waste disposal; the total amount and types of contaminants disposed of on-site is unknown (Guccione 2002).

Scientific/Technical Challenges

Challenges of addressing contamination

Cleanup protocols for industrial contamination, as outlined by EPA, are meant to "minimize or eliminate potential threats to human health and the environment and the need for future corrective action at the site" (Environmental Protection Agency 2009). Industrial waste can cause cancer, damage organs, and contribute to heavy metal poisoning. These compounds may exist in mobile forms that migrate quickly or immobile forms that stay bound in place. Some products may degrade over time, while others are stable at ambient conditions.

Radioactive contamination is distinguished by the inclusion of radionuclides: unstable atoms that emit ionizing radiation as they decay to different chemical elements. Exposure to radiation can pose poses a serious threat to human health as it can deleteriously alter the behavior of cells, inducing afflictions such as cancer (United Nations Scientific Committee on the Effects of Atomic Radiation 2000). The particular health effects induced by radiation exposure depend on both the total radiation dose to which one is subjected and the rate at which that dose accumulates (Shore 2014). Risks from legacy environmental contamination, like that at SSFL, are generally associated with chronic exposure to relatively low dose rates. In these cases, radiation exposure arises from proximity to contamination in one's daily living environment and the uptake of radionuclides into the human body (Smith et al. 2000; Hinton et al. 2007; Tamponnet et al. 2008).

The health effects of the corresponding low dose/low dose rate exposures are uncertain (Prasad et al. 2004; Mullenders

[2] Burn pit disposal may also have been motivated by frustrations with acquiring permits and the costs of dumping materials in the ocean (Miller 1958).

et al. 2009; Dauer et al. 2010; Shore 2014; Shore et al. 2018, 2019). Much of the relevant scientific data comes from populations subjected to distinct exposure conditions, such as those resulting from nuclear bombings (Diaz-Maurin 2018). Recent epidemiological studies of populations exposed to low dose/low dose rate radiation have helped to address this shortcoming, but further research is needed (Shore et al. 2018, 2019). This scientific uncertainty makes it challenging to address any risk to the public that might arise from such contamination, and to communicate that risk to the affected public.

In addition to health effects, the duration of radioactive contamination is an important dimension in both remediation and public attitudes towards such efforts. While radioactive contaminants will decay over time, many relevant radionuclides decay over long timescales. For example, two of the significant radioactive contaminants produced by SSFL, cesium-137 and strontium-90, decay with half-lives of 30 and 28 years, respectively. This means, for example, that after 28 years half of the atoms in a given quantity of strontium-90 will have decayed to nonradioactive zirconium, while the rest remain radioactive. Contamination with these radionuclides may therefore pose an intergenerational problem. Plutonium-239 decays with a half-life of 24,100 years, far longer than any human society has persisted. Thus, contamination with this isotope might be considered functionally permanent.

Natural transport of material from the site

Movement of both radioactive contaminants and hazardous wastes are governed by the site's geological setting. SSFL is located in the transverse mountain range, primarily upon Chatsworth formation bedrock, sedimentary layers of sandy and loamy turbidites that are broken with faults and fractures (Verhoff and Spaulding 2011; Cilona et al. 2016). Chaparral shrublands, known for their flammability, cover the majority of the soil. Soils are well-draining and loose, consisting of weathered fragments of bedrock and organic material. SSFL's topographic, climatic, and geological setting create an erosional environment where materials from the laboratory site are moved and removed by streams, groundwater, wind, animals, people, and gravity. Materials migrate off-site primarily by water-driven sediment transport.[3] In the region, most sediment movement happens during relatively rare extreme rainfall events (Warrick and Milliman 2003) and can be strongly influenced by other factors, such as earthquakes or wildfire (Warrick et al. 2015). Sediment movement is thus variable, with difficult-to-estimate potential extremes.

The bedrock is highly (40%) exposed at the surface (HydroGeoLogic, Inc. 2012) and is relatively porous, making it permeable to groundwater. The bedrock dips north, encouraging groundwater flow in that direction, but the extensive faulting and fractures can alter the rate and direction of flow. The topography results in seeps and springs that return groundwater to the surface, with 154 springs identified on-site (Department of Toxic Substances Control and Los Angeles Regional Water Quality Control Board 2014). The geologic complexity at SSFL makes accurately modeling groundwater flows an extreme and time consuming challenge relative to most hydrologic systems, resulting in particularly high uncertainty.

Groundwater monitoring is complicated by SSFL's complex geology, but a network of 450 wells and piezometers has led the CA Department of Toxic Substances Control (DTSC) to state that no groundwater contaminant pathways lead to off-site seeps (Department of Toxic Substances Control and Los Angeles Regional Water Quality Control Board 2014). Some on-site seeps are discharging volatile organic compounds, which are periodically collected using pumps or vacuum trucks (Department of Toxic Substances Control and Los Angeles Regional Water Quality Control Board 2014). Studies of groundwater wells outside SSFL boundaries have not identified radionuclides originating from the site (Department of Toxic Substances Control and Los Angeles Regional Water Quality Control Board 2014). Long term plans involve continued monitoring of off-site wells and seeps, and a statement that "actions" will be taken if contaminants originating from SSFL are detected (Department of Toxic Substances Control and Los Angeles Regional Water Quality Control Board 2014).

A surface water drainage divide splits SSFL, with a total of 19 surface water outfalls exiting the site (Department of Toxic Substances Control and Los Angeles Regional Water Quality Control Board 2014). Northern outfalls drain into the Calleguas Creek basin in Ventura County, and southern and eastern outfalls drain into the Los Angeles River basin. These outfalls only flow during and immediately following rainfall events. Along some of the outfalls, extensive concrete stormwater catchments have been implemented to improve outfall water quality (Department of Toxic Substances Control and Los Angeles Regional Water Quality Control Board 2014). Current monitoring efforts have noted exceedances of allowed contaminants, such as excess lead, 2,3,7,8-Tetrachlorodibenzo-*p*-dioxin, water acidity, and bacteria in some of the outfalls during a 2014 storm (Department of Toxic Substances Control and Los Angeles Regional Water Quality Control Board 2014).

[3] Human activities, such as cleanup efforts relocating dump trucks full of contaminated sediment, could easily exceed geologic sediment movement, but are highly dependent on short term changes in policy or management decisions.

Historically, contaminants presenting the most immediate environmental concern, such as fuel vapor and gas phase radionuclides, were released by air, and have likely long since left SSFL's premises, but materials currently on-site may still migrate off-site via wind. During periods of intense winds known as Santa Ana Winds, soils and sediment may become airborne. Returning exposed soils to a vegetated state or treating exposures can reduce dust (US Department of Energy Office of Environmental Management 2018).

Predicting the environmental mobility of radionuclides is particularly challenging. The three radionuclides that compose the bulk of SSFL's contamination are known to exhibit mobility in the environment, and their transport can be further enhanced in surface and groundwater by colloid mechanisms (Chen et al. 2005; Novikov et al. 2006; Rod et al. 2010; Maher et al. 2013; Batuk et al. 2015). The particular characteristics of the radionuclide-bearing particles, determined in large part by their origins, further influence transport. For example, plutonium released in a fire differs physically and chemically from plutonium leaked from a storage tank; particles from these two sources would therefore behave differently in the environment even if they were compositionally identical (Batuk et al. 2015). SSFL's long operational history and myriad release pathways make it difficult to constrain the precise origin (and thus to predict the future transport) of any particular radioactive contaminant.

Options for cleanup

Despite these challenges, SSFL has cleanup options. Facing the uncertain and effectively permanent nature of radioactive contamination, remediation requires the extraction or isolation of radionuclides from the environment (Hamby 1996; Abbotts 2011). Efforts typically target contaminated facilities or structures, soils, and water. First, characterization of the contamination is performed via the collection of samples and analysis of the radionuclides present. This reveals the type and spatial distribution of contamination. Next, structures are demolished, soils excavated, and water filtered or chemically treated to separate radionuclides. In some cases facilities and equipment might be scrubbed or coated so as to remove or seal in contamination prior to disposition (Abbotts 2011). Finally, because radionuclides cannot be destroyed barring infeasibly costly nuclear methods, the collected materials must be disposed of elsewhere. The ultimate fate of this material depends on its waste classification, a product of the type, extent, and origin of its radionuclide contamination (Lowenthal 1998).

Nonradioactive industrial contaminants present additional cleanup options. Cleanup progresses by understanding the materials present and carrying out risk assessments, building local partnerships, controlling for further emissions or contaminant movement, and eventually reaching a state of closure at which the site will not need further attention (Environmental Protection Agency 2009). The cleanup may involve a variety of options which either collect and remove materials, prevent materials from moving, or use chemical or physical processes to break down the hazardous materials into less hazardous forms.

Environmental cleanup became a focus of laboratory activities in the 1990s, building on somewhat routine decommissioning and demolition activities in the mid 1970s and ongoing since the 1980s (US Department of Energy n.d.; US Department of Energy n.d.; National Aeronautics and Space Administration 2014; US Department of Energy Office of Environmental Management 2018). Some radiologically contaminated soils have been removed, in one case down to vacuumed bedrock that was then capped with clay to minimize further movement of contaminants in the bedrock (US Department of Energy n.d.; California Department of Toxic Substances Control 2010). Industrial contamination efforts include ongoing collection of debris, removal or biotreatment of some contaminated soils, and removal of some contaminated water (California Department of Toxic Substances Control 2010; Department of Toxic Substances Control and Los Angeles Regional Water Quality Control Board 2014). Environmental Impact Statements by DOE and NASA suggest the planned application of many of the previously mentioned techniques to achieve decontamination (National Aeronautics and Space Administration 2014; US Department of Energy Office of Environmental Management 2018); an EIS has not been prepared for Boeing-controlled areas.

Governance and Societal Challenges

Decontamination offers a means of undoing the environmental degradation at SSFL and ameliorating risks to human health. Yet beyond this technology, cleanup is a sociopolitical process that involves balancing environmental, financial, legal, and ethical issues (Light and Higgs 1996). Central to this social dimension is determination of who must carry out cleanup and what cleanup is meant to accomplish. Clearly, the responsible party must restore the site's environment. However, this involves compromise, as complete reversion to the site's former state is impossible (Katz 1992) and cleanup itself can have deleterious effects —excavation and water treatment degrade wildlife habitat and liberate otherwise immobile contaminants (Whicker et al. 2004). Being unable to fully negate the harm done, the responsible party might be obligated to provide restitution or to demonstrate reform to reduce the likelihood of further malfeasance (Basl 2010). At SSFL, the rules and regulations regarding who is responsible for cleanup and how much cleanup is “enough” add additional layers of complexity, and the implementation of these rules has bred ongoing distrust among the community.

Regulatory Setting

Regulations dictate who is responsible for cleanup and what they are required to do. A common tenet of hazardous waste cleanup is the *polluter pays* principle, that the individual or entity that releases contamination into the environment should bear the costs of its effects and cleanup (Larson 2005). Polluter pays is often invoked for ongoing pollution, justifying collection of permit fees or taxes from polluting industries that can be used to reverse harm done. For retrospective pollution like that at SSFL, the mechanisms for making polluters pay are less clear. In these cases, many countries use lawsuits to “restor[e] injured parties to their original condition” (Latham et al. 2011, p. 746).

The process for hazardous material cleanup in the US is formalized in the Resource Conservation and Recovery Act of 1976 (RCRA) and the Comprehensive Environmental Response, Compensation, and Liability Act of 1980 (CERCLA or “Superfund”). RCRA dictates how hazardous waste can be transported and disposed of. CERCLA sets standards for how much cleanup is necessary and who is responsible, and authorizes EPA as the primary agency overseeing cleanup. Under CERCLA, EPA defines who the responsible party is for a given waste site; usually the current owner of the site is responsible for cleanup and payment. However, at SSFL, there are three “owners” — Boeing, NASA, and DOE—and much of the site’s contamination was inherited from a complex web of previous operators (see Fig. 1).

To further complicate matters, SSFL is not regulated directly under CERCLA. In 2007, the California legislature passed Senate Bill 990, which mandated that SSFL be regulated under California’s Health and Safety Code (a higher standard than CERCLA requirements) and authorized California’s DTSC to be the lead oversight agency for cleanup, rather than EPA. SB 990 also prevents SSFL’s owners from selling or leasing the land until DTSC deems remediation complete. In 2009, the director of the California EPA “rejected an offer to list Santa Susana as a federal Superfund cleanup site because the federal standards did not meet the state's requirements” (Hiltzik 2014), opting to leave oversight with the state. While a 2014 court case deemed SB 990 to be unconstitutional, DTSC remains the lead agency overseeing SSFL’s decontamination. Lastly, under the Atomic Energy Act of 1954, DOE is responsible for decommissioning and demolishing buildings where nuclear activities took place.

Thus, SSFL has three owners (two public and one private) and three primarily responsible oversight agencies (DTSC, DOE, and EPA). This means that no single organization can be held fully liable for cleanup activities or lack thereof.

What needs to be cleaned up and how is also a moving target. This is partly due to the evolving decisions about responsibility: CERCLA’s cleanup requirements differ from those of SB 990. In 1995, DOE and EPA entered a joint agreement that all DOE sites (including SSFL) would be cleaned up to CERCLA’s standards, which mandate that water sources meet maximum contaminant levels under the Safe Drinking Water Act (SDWA) as well as water quality criteria set by the Clean Water Act (Bearden 2012, p. 11). Generally, requirements for drinking water are more stringent than for other uses. However, as SSFL is no longer directly regulated under CERCLA, it is unclear whether the SDWA requirements still apply, or whether cleanup is instead subject to requirements set by California’s Health and Safety Code (HSC § 25356.1.5).

Cleanup standards are further influenced by recent shifts in formal cultural and historical designations of SSFL property. Burro Flats Painted Cave, located in Area I and II, contains painted and etched symbols predating European settlement (California State Parks 2019). The cave is located in a transition zone between historic settlement areas of Chumash, Tongva, and Tataviam (Fernandeño) peoples (National Aeronautics and Space Administration 2010b); members of the modern Fernandeño and Chumash tribes played key roles in the cave being registered as a National Historic Site. In April 2008, NASA completed an additional archeological survey of Areas I and II, prompting the expansion of Burro Flats Painted Cave’s boundaries to include newly identified features (National Aeronautics and Space Administration 2010b).

SSFL’s role in space exploration was recently documented by NASA and the National Park Service (NPS). Six rocket test stands, which NASA believes are eligible for nomination to the National Register of Historic Places given their role in space exploration and the Cold War, were documented using 360-view photography, 3D modeling, animations, and drawings which can be viewed in an interactive NPS website (National Aeronautics and Space Administration (n.d.)).

While recognizing the cultural and historical significance of SSFL is important, some parties are concerned that it has the potential to weaken the regulatory standards for cleanup. While CERCLA still dictates the primary standard (assuming SSFL is regulated under CERCLA) (Schatzman 1992), Boeing has argued that it will remediate the site to levels adequate for recreational use, not residential use, concerning local stakeholders (Abram 2017). Even absent the lessening of standards, cultural designation complicates site restoration as, under the National Historic Preservation Act, decisions about cleanup must now be made in consultation with the California State Historic Preservation Officer.

Interactions with the Affected Community and Other Stakeholders

Those carrying out decontamination must work with a vast array of stakeholders: federal and state regulatory agencies, local governments, public interest groups, and residents of nearby communities. Each of these groups has their own interests in the cleanup, requiring value judgments about tradeoffs between these interests. SSFL's list of interested stakeholders is long. Besides the three oversight agencies, numerous regulatory agencies dictate particular activities on the site, such as water and sediment discharges (e.g., Los Angeles Regional Water Quality Control Board, US Army Corps of Engineers), disturbances to habitats and protected species (e.g., California Department of Fish & Wildlife), and impacts on air quality (e.g., Ventura County Air Pollution District). A variety of community groups have been vocal advocates for cleanup, and nearby residents are directly affected by cleanup decisions. The SSFL property is immediately adjacent to 48 parcels, and 730,000 people live within 10 miles of the site.

There are distinct challenges to working with community groups around contaminated sites. First, the public's concerns tend to be removed from technical minutiae of radionuclide transport or dose effects. Even data pertaining to more comprehensible issues, like cancer risks, provide little clear guidance to the public. For example, epidemiological studies on whether or not former SSFL workers suffer from elevated cancer rates due to occupational exposure have yielded conflicting conclusions (Ritz et al. 1998, 2000; Boice et al. 2011). Likewise, assurances that contamination poses little immediate health risk will not mollify activists concerned about the intergenerational inequity inherent in plutonium contamination that remains for tens of thousands of years (Ahearne 2000).

This incommensurability between the social and technical dimensions of remediation is compounded by the effects of uncertainty and incomprehensibility on public perceptions of nuclear risk. Sociologists have described public responses in terms of terror, dread, and a "sense of ever-present peril" (Erikson 1991). Surveys of public attitudes towards radioactive contamination are dominated by imagery of danger, sickness, and death (Slovic et al. 1991), and individuals living near contaminated sites can even develop post-traumatic stress disorder and other forms of psychological distress (Bromet et al. 2011). This anxiety is so intense that nuclear risks commonly dominate public discourse regarding contaminated sites, even in cases where nonradioactive chemical contaminants present greater threats to public health (Till et al. 2002).

Nuclear dread can prove a hindrance to public buy-in, support, and cooperation. Because the public often perceives radioactive contamination as a product of technological hubris and malfeasance on the part of government or corporate authorities (associated with controversial technological activities like nuclear reactor operation or weapons production), affected communities are often skeptical of environmental remediation technologies (Flynn et al. 1998). This technological stigma tarnishes trust even at the individual level, as the scientists, policymakers, and other authorities charged with causing contamination are rarely distinguished from their counterparts handling cleanup. Combined with authorities unwilling to engage with a fearful public, this stigma can establish a narrative of antagonism that precludes cooperation (Erikson 1990; Diaz-Maurin 2018). That this problem of trust can harm public policy outcomes is illustrated by the public response to government recommendations in the wake of the 1979 nuclear accident at Three Mile Island. The governor of Pennsylvania advised that ~3500 people (children and pregnant women) temporarily relocate, prompting ~200,000 people to flee an average of 100 miles (Erikson 1991).

At SSFL, the lead agencies and responsible parties have not been particularly effective in their interactions with the public. Atomics international hid contamination for decades (a common trend at contaminated sites), setting expectations among the public that the organizations in charge would be secretive and deceptive. Since then, Boeing and the regulatory agencies have certainly been more forthcoming, for instance creating websites to share documents publicly. However, several factors continue to erode trust. For instance, Boeing and DTSC's websites have a number of missing or broken links concerning SSFL which, viewed by a skeptical public, suggest that information used to exist but has been suppressed (intentionally or accidentally). The day after the Woolsey Fire started on SSFL property, DTSC posted a press release that "DTSC is actively monitoring the fire… Our scientists and toxicologists have reviewed information about the fire's location and do not believe the fire has caused any releases of hazardous materials that would pose a risk to people exposed to the smoke" (Department of Toxic Substances Control 2018a). This brief statement, with no actual scientific information—only an appeal to expertize—was not enough to assuage public fears; multiple blog and newspapers postings highlighted worries that the fire would spread contamination (Physicians for Social Responsibility 2018; Hirsch 2019). One blog wrote:

> "instead of leveling with the public about the seriousness of this massive toxic release, DTSC claims—without disclosing any measurements or methods—that what's left behind doesn't test toxic.

> If past experience is any indicator, the agency will eventually release some of that data for the public to examine, and there will be all manner of problems with it." (Collins 2018)

highlighting an instinctive mistrust of DTSC's statement (DTSC did publish an interim report on the effects of the Woolsey Fire a month later (Department of Toxic Substances Control 2018b)).

Community Responses to Secrecy, Complexity, and Uncertainty

When news about contamination at SSFL was first made public in 1989, a number of community groups formed in response. Several were officially sponsored. First, at the request of a local congressman, EPA created the SSFL Interagency Workgroup in 1989 (Santa Susana Field Laboratory Work Group 2019). DTSC discontinued facilitation of the group in 2012, but it is now funded by the Community Improvement Fund and coordinated by Physicians for Social Responsibility-Los Angeles. While membership has varied, the SSFL Workgroup has included representatives of multiple regulatory agencies, several local NGOs, and local homeowners. The Workgroup's primary goal is to "keep the community informed about the contamination at SSFL and assure its thorough cleanup" (Santa Susana Field Laboratory Work Group 2019). Second, the SSFL Community Advisory Group, which oversees cleanup decisions, was created by CalEPA in 2012 (SSFL CAG). Members include local residents, former Atomics International workers, and tribal representatives. Finally, the SSFL Advisory Panel was a group of scientists convened by local legislators to conduct independent studies on SSFL; they have not been active since 2007. While these groups were initially sponsored by regulatory agencies, they lack any authority to mandate particular cleanup activities.

Several other organizations are purely resident-driven. The Rocketdyne Cleanup Coalition (Rocketdyne Cleanup Coalition 2019) (founded 1989) was started by a group of concerned residents. More recently, the mother of a Simi Valley child with cancer started Parents Against the Santa Susana Field Laboratory (Parents Against the Santa Susana Field Laboratory (n.d.)). Both groups aim to share information and hold decision-makers accountable for site cleanup. Lastly, two prominent stakeholder groups, Physicians for Social Responsibility-Los Angeles and the Committee to Bridge the Gap, were founded in other locations prior to 1989 but have actively advocated for SSFL cleanup.

A general theme of distrust of governmental and commercial organizations is prevalent among these community groups. There are regular complaints that Boeing, DOE, and DTSC are trying to weasel their way out of cleanup. Some community members feel that the SSFL Community Advisory Group is a front group created by DTSC so they don't have to clean up (Collins 2016). The December 2018 Environmental Impact Statement (EIS) for DOE's remediation plan (US Department of Energy Office of Environmental Management 2018) was criticized for not selecting a sufficiently stringent cleanup alternative. In a letter to DOE, Physicians for Social Responsibility wrote that the EIS "breaks DOE's promises to the community that it would repair the longstanding environmental damage and risk to public health that it created by decades of grossly negligent operations" (cited in Grigoryants 2019). DTSC was similarly concerned that the EIS violated a 2010 agreement between DOE and DTSC. Other critics blame "Trump's Department of Energy," claiming that it the EIS represents a "plan to kill SSFL cleanup" (Collins 2019). While it is impossible to say whether these claims are true and the DOE is attempting to remediate to a less-than-satisfactory standard, this episode demonstrates the level of distrust among stakeholders.

As is expected in the cleanup of most contaminated sites, there have also been a number of lawsuits between the active parties. For instance, in 2013, Physicians for Social Responsibility and several other nonprofits sued DTSC and Boeing, claiming that they violated the California Environmental Quality Act by not undertaking an environmental assessment for demolition activities on the site. Boeing sued DTSC (Boeing Co. v. Movassaghi), alleging that the decision for California to supercede CERCLA was unconstitutional.

Discussion

Lessons Learned from Other Decontamination Activities

SSFL has a number of complex features that, in combination, serve as barriers to effective cleanup. The natural setting is exceptionally complex, with erosion-prone geology and sporadic rainfall, and the site has numerous types of contamination. Regulatory implementation has been repeatedly delayed by changes in authority, creating opportunities for lawsuits and a lack of clearly defined responsibility. In particular, California's decision to supercede CERCLA—thinking DTSC could manage the cleanup more efficiently—has slowed the process and sidelined an agency (EPA) with extensive expertise. Historical secrecy and continued delay makes the public distrustful of the responsible parties' dedication to cleanup.

In determining the best course of action for addressing contamination at SSFL, it is instructive to consider prior instances of hazardous and radioactive material cleanup. By

2020, the DOE Office of Legacy Management expects to maintain 126 sites at which some degree to environmental decontamination has been undertaken (Carter and Miller 2013). Yet few are comparable with SSFL in terms of its mixed, partly transuranic radionuclide contamination, its proximity to a population center, and the complex web of federal, state, and community organizations involved. Sites of reactor accidents (e.g., Chernobyl or Fukushima Daiichi) and nuclear weapon production (e.g., the Russian Mayak complex or the American Rocky Flats site) have been extensively researched, and might therefore serve as valuable sources of insight for application to SSFL. Among these, Rocky Flats is unique in that cleanup has been completed. Making it even more of an outlier, decontamination was accomplished ahead of schedule, under budget, and with broad stakeholder support, such that the effort has been touted as a model for cleanup elsewhere (Cameron and Lavine 2006). At the same time, the "success" of this effort has proved contentious among the local populace. Although it is but one among the many remediation efforts undertaken to date, Rocky Flats and the extensive literature surrounding it offer valuable and relevant lessons in cleanup strategies and pitfalls.

History

The Rocky Flats Plant was established by the AEC in 1951 to produce plutonium components for nuclear weapons. Despite its distinct mission, the site mimicked SSFL in many ways (Abbotts 2011). It was operated on behalf of the DOE by a succession of contractors, including Dow Chemical Company and Rockwell International. It was located 15 miles from Denver, a major urban area. Most importantly, its operational history was littered with accidents and releases of radioactive contamination.

Recurrent releases, such as from leaky drums of radioactive waste stored in open fields, were regularly withheld from the public (Ciarlo 2009; Abbotts 2011). Eventually, a 1969 fire brought public scrutiny to the site, after which high levels of plutonium were measured in the surrounding soil. Public opposition mounted and, following a 1989 FBI raid, Rockwell International pled guilty to criminal violations and ceased plant operation (Kaiser-Hill, LLC 2006). Like SSFL, major contaminants left behind included a mixture of radionuclides (mainly uranium, plutonium, and americium) and conventional hazardous materials (e.g., beryllium) (Till et al. 2002; Abbotts 2011).

Only months after the federal raid, the EPA placed Rocky Flats on its Superfund National Priorities List, starting what was described by Senator Allard of Colorado as "the best example of a cleanup success story ever" (The Associated Press 2005). In 1995 the DOE predicted that cleanup would take 65 years and cost $37 billion (US Department of Energy 2018). Yet Kaiser-Hill, the contractor, finished decontamination in 2005 at a cost of $7 billion (Clark et al. 2007). In 2018, portions of the site reopened to the public as the Rocky Flats National Wildlife Refuge, finishing what has since been touted as a model for quick, cost-effective remediation (Cameron and Lavine 2006).

Successes

Why was cleanup so successful? While myriad factors distinguished the Rocky Flats effort from those at comparable sites, its outcome is broadly attributed to two factors: innovative management practices and reliance on a strong technical basis for remediation. On the management side, DOE faced a strong incentive to revamp its decontamination approach. DOE's Environmental Management program came under fire in the mid-1990s for chronic delays and budget escalation, with several members of Congress calling for its elimination (Abbotts 2011). In response, DOE adopted new management practices at Rocky Flats, including more precise definition of goals, a financial incentive structure that awarded contractors when milestones were met early, and close cooperation with state government (Cameron and Lavine 2006; Clark et al. 2007; Abbotts 2011). Working groups representing a broad range of local stakeholders were solicited for input on everything from decontamination thresholds to the manner in which land should be used after remediation (Abelson 2006; Abbotts 2011).

This novel managerial approach was coupled with a willingness to adapt remediation strategies as new technical information became available. State-of-the-art measurement and simulation of radionuclide transport in the environment yielded models that guided the design of cleanup and dialog with stakeholders (Clark et al. 2007; Batuk et al. 2015). This collaborative modeling approach helped the contractor in "understanding stakeholder views" and ultimately "using the information assembled from them to drive innovation" (Clark et al. 2007; Ulibarri 2018). For example, the public voiced concerns that rainy spring conditions might mobilize soil-bound plutonium disturbed by cleanup activities. This prediction ran counter to those of existing models, but rather than dismissing these concerns, DOE and Kaiser-Hill revisited their simulations. They identified a previously overlooked colloidal erosion and sediment transport process that significantly enhanced radionuclide mobility, prompting revision of the site remediation plan (Clark et al. 2007).

Failures

However, the Rocky Flats approach was far from a panacea. Echoing SSFL, the purported responsiveness of DOE and its contractor to public input has been characterized as a façade, with some arguing that the remediation process was mostly planned even before site characterization was completed (Moore 2005). One activist said he "thought we were being invited to help design the house of the cleanup, but really what we were being invited to do is to rearrange the furniture a bit" (Ciarlo 2009).

Locals' criticism primarily centered on changes to the precise end-state towards which decontamination proceeded. Some initially envisioned residential or commercial use (Abbotts 2011), but a government coalition later decided on a wildlife preserve (Abelson 2006; Coates 2014). This shift to an undeveloped, protected area is common to other DOE cleanup efforts, such as that at the former Fernald uranium processing facility (Powell et al. 2006, 2009). It serves to reduce the necessary level of decontamination (much as historical and cultural designations may do at SSFL), and shift discourse from imagery of environmental degradation to that of preservation and habitat stewardship (Krupar 2011). Many activists viewed this as a disingenuous ploy to reduce costs (Moore 2005; Coates 2014) or, recalling the role of technological stigma in public perceptions of nuclear contamination, "a calculated attempt to erase awareness of past misdeeds" (Coates 2014).

Distrust was further magnified by the secrecy inherent to Rocky Flats' former weapons production mission. During operation, knowledge of plant activities was intentionally compartmentalized to bolster information security (Ciarlo 2009). Information on accidents was suppressed, breeding an adversarial relationship with the local community that hindered subsequent cleanup (Moore 2005).

Lessons Learned

Given their broad similarities, many of the lessons learned during the Rocky Flats cleanup are applicable to SSFL. Innovative management practices can be implemented at SSFL if a single organization is willing to provide dedicated, centralized leadership. The detrimental effects of public distrust can be mitigated if collaboration with stakeholders and the establishment of a clear technical basis for remediation are prioritized.

On the other hand, pitfalls encountered in the Rocky Flats case reveal what should be avoided at SSFL. Currently, the secrecy and uncertainty associated with Rocky Flats is mirrored at SSFL due to operators' reticence to engage transparently with the public and the difficulty of disentangling the site's complex, poorly documented web of activities, operators, and stakeholders. Ambiguity regarding postremediation site use and access, a factor at both Rocky Flats and SSFL, adds to this uncertainty. Finally, as at Rocky Flats, the information provided to locals near SSFL is frequently incomplete or even contradictory. For example, the public has recently heard from DTSC of delays in cleanup, but with no further explanation (Harris 2018); it has been told that fires will not spread radioactive materials, while hearing the opposite from activist groups (Barboza 2018). Concerted efforts to replace uncertainty and secrecy with transparency are necessary if the public is to be brought onboard as a collaborator.

Conclusion and Recommendations

This paper has explored the challenges underlying the cleanup of hazardous and radioactive contamination at the Santa Susana Field Laboratory, a site that represents many of the same challenges faced by other historically contaminated locations around the world. While cleanup at SSFL has been hindered by a complicated geological setting, numerous types of contamination, a complex and evolving regulatory landscape, and extensive distrust by members of the stakeholder community, there are opportunities for the responsible parties at SSFL and other contaminated sites to move forward more effectively.

First, effective remediation requires detailed knowledge of the precise nature of the contamination and its transport in the environment, both of which are lacking as SSFL. Dedicated site characterization is necessary to design an effective cleanup strategy and to provide comprehensive information to concerned stakeholders.

However, effective remediation is not just a technical problem (Gilmore 2001). To achieve buy-in and cooperation from the public, the responsible parties should solicit, engage with, and—to the extent possible—accept their input. As demonstrated by the Rocky Flats case and research on related environmental challenges, collaborative approaches generally yield more durable solutions than less interactive approaches (Ulibarri 2015, 2018). DTSC writes that they "encourage public participation and comments and are always searching for ways to collaborate on our efforts" (California Department of Toxic Substances Control 2019), but our review suggests minimal engagement with feedback they receive.

To work toward collaboration, a broadly acceptable end-state should be identified in dialogue with the community. A concrete, shared vision of the precise goal of remediation is necessary to avoid public perceptions of duplicity or malfeasance when technical obstacles inevitably arise. As cleanup progresses, the active provision of clear information regarding site contamination, legal obligations, and the technical basis for remediation can help counter the vast uncertainties currently associated with SSFL. To ensure legibility, information should be easily accessible; e.g., all documents could be associated with a summary page with common-language bullet points relating to the scientific findings. Further, opportunities for regular interaction, including public meetings and periodically issued summary documents, can provide opportunities for public learning and input.

Finally, a lesson from SSFL to other sites is their extensive documentation of cultural and historical artefacts. By digitizing the location and architecture of buildings and instruments at SSFL, the owners have ensured that information about the history of nuclear power and aerospace is available to the public should it be desired.

The goal is legitimate institutional reform, demonstrating that misdeeds of the past will not be repeated. Public buy-in rests on the belief that current authorities take the contamination problem more seriously than did previous. Demonstrating respect for public concerns by incorporating participation into the remediation endeavor can counterbalance the detrimental effects of the public's aversion to cooperation (Light and Higgs 1996).

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Compliance with ethical standards

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