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Radiological risk assessment of the Hunters Point Naval Shipyard (HPNS)

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ABSTRACT

Hunters Point Naval Shipyard in San Francisco, California was deemed a Superfund site by the USEPA in 1989 due to chemical and radiological contamination resulting from U.S. Navy operations from 1939 to 1974. During characterization and remediation efforts, over 50,000 radiological soil samples and 19,000 air samples were collected. This risk assessment, conducted in accordance with federal guidelines, represents the first comprehensive evaluation of past, present, and future health risks associated with radionuclides present at the site. The assessment indicated that before site remediation, most radionuclide soil concentrations were at or near local background concentrations. Had such low remedial goals not been established, significant remediation of surface soils would not have been necessary to protect human health. The pre-remediation lifetime incremental cancer morbidity risks for on-site workers and theoretical on-site residents due to radionuclide contamination were found to be 1.3×10^{-6} and 3.2×10^{-6}, respectively. The post-remediation risks to future on-site residents were found to be 6.3×10^{-8} (without durable cover) and 3.7×10^{-8} (with durable cover), while post-remediation risks to on-site workers were found to be 2.6×10^{-8} (without durable cover) and 1.6×10^{-8} (with durable cover). Risk estimates for all scenarios were found to be significantly below the acceptable risk of 3×10^{-4} approved by regulatory agencies. Upwind and downwind air samples collected during remediation indicate that remediation activities never posed a measurable risk to off-site residents. This risk assessment emphasizes the importance of establishing clear and scientifically rigorous soil remedial goals at sites as well as understanding local radionuclide background concentrations.

Abbreviations: AEC: Atomic Energy Commission; BIER: Biological Effects of Ionizing Radiation; BNL: Brookhaven National Laboratory; BRAC: Base Realignment and Closure; HPNS: Hunters Point Naval Shipyard; CCSF: City and County of San Francisco; CDPH: California Department of Public Health; CERCLA: Comprehensive Environmental Response, Compensation, and Liability Act; CRUP: Covenants to Restrict Use of Property; CSM: Conceptual Site Model; DAC: Derived Air Concentration; DoD: Department of Defense; DOE: Department of Energy; FUD: Formerly Used Defense; GBACR: Greater Bay Area Cancer Registry; G-RAM: General Radioactive Material; HRA: Historical Radiological Assessment; IC: Institutional Control; ICRP: International Council on Radiation Protection; IR: Installation Restoration; LNT: Linear No-Threshold; MARSSIM: Multi-Agency Radiation Survey and Site Investigation Manual; NAS: National Academy of Science; NORM: Naturally Occurring Radioactive Material; NPL: National Priorities List; NRC: Nuclear Regulatory Commission; NRDL: Naval Radiological Defense Laboratory; RACR: Remedial Action Completion Report; RBA: Reference Background Area; RI/FS: Remedial Investigation/Feasibility Study; ROC: Radionuclide of Concern; SCRS: Surface Contamination Radiation Survey; SFDPH: San Francisco Department of Public Health; TCRA: Time Critical Removal Action; TtEC: Tetra Tech EC; TtEMI: Tetra Tech EM Inc.; UCL: Upper Confidence Limit; USEPA: United States Environmental Protection Agency; USN: United States Navy; UTL: Upper Tolerance Limit.

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Introduction

Hunters Point Naval Shipyard (HPNS) is located in San Francisco, California (Figure 1) and was designated a Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) Superfund site by the United States Environmental Protection Agency (USEPA) in 1989, due to contamination caused by the United States Navy's (USNs) operations of the shipyard from 1939 to 1974. From a radiological perspective, the possibility for widespread contamination of site surface soils was generally quite low compared to what was found at the three major sites that were a part of the Manhattan Project in World Word II developing the first atomic or nuclear bombs. Those three sites were top-secret and code-named Site X at Hanford, WA where Pu-239 was produced, Site X at Oak Ridge, TN where U-235 was produced, and Site Y at Los Alamos, NM where the bombs were designed and fabricated. These and other sites will be discussed in greater detail later in the manuscript.

Site characterization began in 1984, with remediation beginning in the early 1990s. HPNS was added to the United States Department of Defense's (DoD) Base Realignment and Closure (BRAC) list in 1991. The BRAC program coordinates the closure and repurposing of military installations for productive use, such as housing and/or recreation (U.S. Department of Defense [USDOD] 1990). Consistent with the objectives of BRAC, the property and facilities of HPNS were to be transferred to the City and County of San Francisco (CCSF) once remediation was complete. From 1992 to the present, substantial radiological remediation has been conducted at HPNS, with up to $1 billion spent since the 1990s (Roberts 2018). The Navy continues to lease buildings to nonresidential tenants, who currently use the facilities for a range of artistic, industrial, and commercial enterprises (Innovex-Engineering/ Remediation Resources Group Joint Venture 2019).

Figure 1. Map of San Francisco with the Bayview Hunters Point Community outlined in white. It is noteworthy that the area outlined includes the HPNS site and surrounding community.

Many localized assessments at HPNS were conducted during the remediation process, but they focused only on a comparison of individual soil samples to remedial goals rather than an assessment of the risks posed by the entire site. These assessments identified significant variability in the background concentration of naturally occurring radioactive material (NORM), which is not uncommon. This variability can make establishing and meeting remedial goals a challenge because the goal may be lower than the local background concentration of NORM in soil (Brown 2021).

More than 50,000 radiological soil samples and 19,000 air samples were collected during characterization and remediation of the HPNS site between 1992 and 2017. Despite these extensive characterization and remediation efforts, no site-wide analysis of all the data has been conducted in accordance with traditional risk assessment approaches to characterize the radiological hazards posed by the site. This assessment evaluated the soil and air samples that were collected before, during, and after remediation at HPNS. It focuses only on the radiological aspects of remediation. Chemical contamination of soil was not addressed in this risk assessment because it is being addressed separately through the CERCLA program. This risk assessment should provide an

avenue to understanding the health risks associated with plausible human exposure(s) to radionuclides both on- and off-site.

The USEPA defines risk as "the chance of harmful effects to human health or ecological systems resulting from an environmental stressor" and notes that risk assessment is used to "characterize the nature and magnitude of risks to human health for various populations" (U.S. Environmental Protection Agency [USEPA] 2022). Risk assessment is the determination of qualitative or quantitative value of risk related to a recognized hazard (Laszcz-Davis et al. 2011). It should be noted that this risk assessment is focused on the human health impacts of the site – an ecological analysis was not performed. Risk assessments are used by regulators, for example, to decide what actions are necessary for a hazard to reach acceptable levels for consumers, workers, and citizens.

This risk assessment followed the framework for risk assessments established by the National Academy of Science (NAS) and the USEPA, which requires that hazard identification, exposure assessment, dose-response assessment, and risk characterization be conducted (NAS 1983; United States Environmental Protection Agency [USEPA] 1989). The goal of hazard identification is to determine the capacity of a

contaminant for causing an adverse effect by reviewing the relevant evidence. Exposure assessment is the process of "measuring or estimating the intensity, frequency, and duration of human or animal exposure to an agent currently present in the environment" (NAS 1983; Paustenbach 2002). The goal of dose-response assessment is to "quantitatively describe the relationship between the extent of exposure (the dose) and the likelihood of adverse health effects (responses)" (Lewandowski and Norman 2015). Finally, risk characterization integrates the results from the dose-response assessment and exposure assessment to estimate the risk of a particular contaminant to various receptors on- or off-site.

Since an important part of the dose-response assessment for carcinogens involves low-dose modeling, this topic deserves some discussion. At the time the soil cleanup levels were set for this site, the objective was to have a risk no greater than 3×10^{-4} above background. This target risk was calculated by the USEPA using the linearized multistage model, also known as the linear no-threshold or LNT approach (USEPA 2014). Thus, it is important to understand the characteristics of the LNT so that the degree of conservatism in the cleanup levels can be better understood.

The LNT model is built upon five guiding scientific principles and assumptions: (1) one or two changes in cells can transform and lead to cancer, (2) there is no population-based threshold due to heterogeneity, (3) a transformed cell is irreversibility propagated, (4) if the mode of action (MOA) involves mutation, no threshold is assumed; if no MOA is identified and cancer occurs, mutation is assumed, and (5) a single or few molecules can cause mutation. While these assumptions might have been viable when they were first proposed in 1928, most of them are not currently thought to be valid based on today's expanded scientific knowledge, as these assumptions do not account for all the compensatory mechanisms to cellular damage within humans (Costantini and Borremans 2019; Golden et al. 2019; Tharmalingam et al. 2019; Paustenbach et al. 2021).

A traditional risk assessment approach was adopted to estimate cancer risks for various populations potentially exposed, both on- and off-site, to eight radionuclides of concern (ROCs) (americium-241 [Am-241], cobalt-60 [Co-60], cesium-137 [Cs-137], plutonium-239 [Pu-239], radium-226 [Ra-226], strontium-90 (Sr-90), thorium-232 [Th-232], and uranium-235 [U-235]) that were potentially present at the site due to site-related operations. These eight radionuclides were selected for this risk assessment based on the Navy's 2006 Action Memo, recent Navy work plans (USN 2006, 2018), and professional judgment.

This work should provide a template to assist parties who are responsible for similar remedial efforts to perform their work more economically, while achieving the same objectives for protecting human health and earning the support of the community and other stakeholders. It emphasizes the importance of informing remedial goals with appropriate background soil concentrations and employing rigorous analytical methods when assessing possible radionuclide contamination of soil and air.

Background of the Hunters Point Naval Shipyard site

HPNS covers 934 acres, with approximately 491 acres on land, and the remainder in the tidal zone of the San Francisco Bay (USN 2004). An image of the site is shown in Figure 2. HPNS was operated as a commercial dry dock facility from approximately 1867 to 1939. The U.S. Navy acquired the shipyard *via* a series of purchases and condemnations beginning in approximately 1939. In 1941, they began developing it for various naval shipyard activities.

After World War II, HPNS was used for a variety of purposes, including ship restoration and decontamination of ships involved in nuclear weapons testing in the Pacific Ocean (Figures 3 and 4) (USN 2004). These ships were sandblasted while they were berthed at HPNS to remove radioactive material (Figure 4). Numerous procedures were implemented to ensure that sand and dust were controlled (USN 2004). The sand and debris were routinely collected, drummed, and deposited at least 10 miles offshore into the Pacific Ocean (USN 2004). After each ship was decontaminated, Navy personnel vigorously washed down drydock floors and performed a radiological survey of the drydock (USN 1946, 2004).

HPNS housed the Naval Radiological Defense Laboratory (NRDL) from 1946 to 1969 (Figure 5) (USN 2004). Throughout the 1950s, the NRDL was an important research facility in the United States for the study of nuclear safety (USN 2004). The NRDL also conducted research on the biological effects of exposure to radiation, decontamination technologies, radiation protection measures, nuclear warfare defensive measures, fire protection, and radiation instrument calibration (USN 2004).

It was reported that small amounts of low-level radioactive liquids were authorized for release *via* storm drain and sewer systems on the site; however, the majority of the radioactive liquid waste produced by the NRDL was disposed of at an off-site licensed disposal facility (USN 2004). Animals that were irradiated on the site were considered radioactive waste and were drummed and buried at sea or taken to licensed off-site disposal facilities (contrary to broadly held assumptions, no radioactive materials were put into the incinerator, including test animals) (USN 2004).

The Navy discontinued active shipyard operations at HPNS in 1974. Between 1976 and 1986, various portions of HPNS were leased to private tenants and Navy-related entities, the largest being Triple A Machine Shop, Inc. (USN 2004). Triple A was responsible for maintaining the equipment used on the site. The Navy resumed control of HPNS in 1987 and permanently terminated shipyard operations on 29 December 1989 (USN 2004).

After HPNS was designated a Superfund site, it was divided into various parcels and smaller Navy Installation Restoration (IR) sites. The parcels which comprise most of the original on-land portion of the site are A (consisting of A-1 and A-2), B (including the IR-07/18 sites), C, D-1, D-2, E (including the IR-02 site), E-2, G, UC1, UC2, and UC3. Parcel F represents the portion of HPNS which is below the tidal zone in the San Francisco Bay (Figure 6).

Parcel A was transferred to the City of San Francisco in 2004 after the Navy and USEPA determined that concentrations of radionuclides in those soils did not pose a risk to human

Figure 2. Photo of Hunters Point Naval Shipyard (HPNS), circa 1946 (Unknown 1946).

health or the environment (Innovex-Engineering/Remediation Resources Group Joint Venture 2019). Independent radiological monitoring of dust, groundwater, ground surfaces, and fence lines showed no exceedances of health-standards, and the only radiological materials that were identified and removed from Parcel A were sandblast grit and firebricks (USEPA 2017). The majority of Parcel A was historically used for residences and administrative offices, so the fact that it had little to no contamination was not surprising (USEPA 2017).

In 2002, USEPA conducted a radiological scanner van survey of Parcel A and navigable roads on other parts of the Shipyard. All of the anomalies detected during the scan were attributable to natural occurring sources at levels consistent with what would normally be found in the environment. Radiological surveys conducted by the California Department of Public Health (CDPH) in 2019 in Parcels A-1 and A-2 concluded that there were no radiological hazards (CDPH 2019b, 2019c). A soil testing update of Block 56 within Parcel A released July 11, 2022, reported results from numerous soil borings at various depths up to 7.5 ft. The radiological testing results indicated no radiological contamination and no unacceptable risk to construction

workers, future residents, or the public (Office of Community Investment and Infrastructure [OCII] 2022).

For the remainder of the base at HPNS, the Navy collected soil samples and quantified the risk to human health to determine the acceptability of the concentrations of radionuclides in soil. Using the USEPA guidance, soil samples tested were required to meet their remedial goals for each ROC, and each of the 1309 survey units were required to have an aggregate risk below 3×10^{-4}. The approach used for deeming a series of soil samples acceptable in this risk assessment was slightly different. Specifically, a sophisticated statistical approach was used to calculate the 95th upper confidence limit (UCL) concentration for radionuclides in the soil, and the background concentration for each ROC was subtracted prior to the calculation of risk. This approach was more precise than that of the Navy due to the high number of samples that were below the limit of detection. It is noteworthy that the Navy was not permitted to account for background for any of the ROCs except for Ra-226; all other ROCs were effectively assigned a background soil concentration of zero by the Navy.

Figure 3. Ship restoration activities at HPNS (Unknown 1956).

A number of soil investigations have been conducted at HPNS to delineate the extent of radiological contamination. Characterization studies at HPNS identified and designated 1,309 survey units with potential radiological contamination, based on the Navy's "Historical Radiological Assessment" (HRA) (USN 2004). Portions of parcels which were not believed to be contaminated on the basis of their historic use were not surveyed. Survey unit types included existing and former building sites, ship berths, piers, Installation Restoration (IR) sites, trenches excavated for storm drain/sanitary sewer pipe removal, and radiological screening yards.

Between 1992 and 2003, a series of investigations were conducted by the Navy on soil and in buildings within HPNS. The Navy's HRA, published in 2004, sought to identify the specific locations and the extent to which radionuclides were used at HPNS (USN 2004). From 2005 to 2007, three time-critical removal actions (TCRAs) were conducted. These remediations focused on the removal of chemical and radiological contamination and included radiological soil sampling at the bottom and sidewalls of excavations. A timeline for the main CERCLA radiological activities at HPNS is presented in Figure 7. A base-wide TCRA was conducted between 2006 and 2017, part of which included extensive soil sampling.

In 2012, the Navy raised questions about the integrity of certain soil sampling data collected to characterize post-remediation ROC concentrations. An investigation by the site contractor, in consultation with the Navy, concluded that the likely cause of the limited anomalous soil sample results was that certain site workers had collected soil samples from locations other than those identified on chain of custody records (Tetra Tech EC Inc 2014). Between 2012 and 2016, soil samples from 22 survey units (approximately 480 samples in total) were rejected and replaced by newly acquired sample results. The Navy accepted the contractors' corrective actions

Figure 4. Sandblasting of Naval vessel at HPNS to remove radionuclide contamination (circa 1947) (Art House SF 2019).

and submitted their report to regulatory oversight agencies in 2014 (Tetra Tech EC Inc 2014). To evaluate the possible impact of soil switching, a sensitivity analysis was conducted, and the results are presented in this risk assessment.

Since the 1930s, the soils at HPNS have been a heterogeneous mixture of native soils derived from Franciscan Complex bedrock, material quarried from nearby hillsides, sediments dredged from the San Francisco Bay, and fill from various off-site sources that were used to expand the footprint of the original site, mostly into the San Francisco Bay (USN 2020c). These different soils had a range of concentrations of NORM and other ubiquitous background radioactivity unrelated to historical operations at HPNS which have been distributed and mixed by construction and remediation activities (USN 2020b). The majority of the site is comprised of filled land, rather than natural soil (Figure 8). Appendix 1 contains additional details regarding remedial activities performed at the site.

Groundwater flow at HPNS is generally toward the San Francisco Bay, with recharge occurring from precipitation and tidal flow. Groundwater at HPNS is not suitable for human consumption due to salinity (USN 2004).

The land surrounding HPNS is a mixture of residential, commercial, industrial, and recreational properties. The community of Bayview–Hunters Point is directly adjacent to the western and northwestern boundaries of the site and has a population of approximately 36,000 people. Parcel A has been redeveloped into multi-family apartments and condominiums.

HPNS vs. other radioactively contaminated superfund sites

The use of radionuclides at HPNS was very different compared to other well-known sites deemed to be "Radioactively Contaminated."

As noted, the Hanford site north of Richland, in eastern Washington would ultimately have a nuclear reactor to produce Pu-239 by neutron irradiation of uranium fuel and extensive facilities to separate the Pu-239 from the spent uranium fuel and fission products. It provided the Pu-239 used in the first atomic bomb tested on 16 July 1945 at the Trinity Site in New Mexico and the bomb dropped on Nagasaki, Japan on 9 August 1945. The Oak Ridge site, located in Tennessee, would develop and apply a gaseous diffusion process to produce bomb grade U-235. That product would be used in the atomic bomb dropped on 6 August 1945 on Hiroshima, Japan. The design and fabrication of the weapons were carried out at Los Alamos, New Mexico.

Soon after World War II came to an end, war facilities to fabricate the Pu-239 and U-235 components of nuclear weapons

Figure 5. US Naval Radiological Defense Laboratory building at HPNS (Unknown 1955).

were developed at Rocky Flats, Colorado. Traditional production reactors were built at Hanford bringing the total at that site to eight in 1955. These were all shut down by 1971. A ninth nuclear reactor designed to both produce Pu-239 and electricity was constructed in 1964 and was shut down in 1987.

Research operations at the University of Chicago that were a key part of the Manhattan Project were shifted to a site in the Argonne Forest west of Chicago at Lamont, Illinois and became the Argonne-East Facility. It would soon create a satellite facility, Argonne-West near Idaho Falls, Idaho. The Argonne operations focused on the design and testing of nuclear reactors. Several dozen of these experimental reactors were designed, constructed, and used for short periods of time.

As the Cold War unfolded, facilities were constructed at Savannah River, Georgia to produce Pu-239 and Tritium to fuel fission and fusion nuclear weapons. This included five reactors that were built beginning in 1952 and operated until 1988. To further enhance the U.S. nuclear weapons design capabilities a laboratory was developed in 1952 at Livermore, California.

During the last decade and after the closing of the Rocky Flats facility the Los Alamos facility has reestablished its capabilities for fabricating Pu-239 "pits" for use in refurbished nuclear weapons. Preparations are being made to enhance that capability with construction of new facilities. In addition, consideration has been given to constructing similar fabrication facilities at the Savannah River Site.

Unlike the previously described sites which were/are involved in the design and development of nuclear weapons or reactors, radioactive materials were not produced nor were nuclear reactors operated at HPNS. Instead, it was primarily home to building, maintenance, and repair operations for U.S. naval ships. HPNS also housed the NRDL from its establishment in 1946 until 1969. The NRDL's research at the site dealt exclusively with existing radioactive material, and no reactors were ever operated at HPNS (United States Nuclear Regulatory Commission [USNRC] 2021b).

HPNS vs. other radionuclide exposures

Superfund sites are not the only known sources of public exposure to radionuclides that can offer context to the potential exposures posed by HPNS – the use of nuclear weapons and other releases of radioactive material are also

Figure 6. Map of HPNS by parcel/site. A depiction of current parcels and Installation Restoration (IR) sites at HPNS. Parcel A, including A-1 and A-2, was transferred to the city of San Francisco in 2004 for residential development. Parcel F represents the underwater portion of the site.

Figure 7. A timeline of the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) activities associated with radiological soil remediation at HPNS from 1989 to 2017.

well-documented as having led to contamination of soils, albeit much more severe. The detonations of atomic bombs in Hiroshima and Nagasaki constitute one of the most relevant and well-studied instances of radiation exposure. A series of 14 studies, the most recent of which was published in 2012, assessed the mortality experience of more than 86,000 people exposed to ionizing radiation as a result of these detonations. These studies found no excess deaths in subjects with measured colon doses of less than 500 mrem. A total of 624 subjects were found to have colon doses of more than 200,000 mrem and in this group, 70 excess deaths (56% of observed deaths) due to cancer as well as 36 excess deaths due to noncancer diseases were observed. As reviewed by McClellan (2020) with intermediate doses of

Figure 8. This figure shows the amount of native soil compared to filled land at HPNS. This illustrates why soils at HPNS are highly variable with respect to the concentration of naturally occurring radioactive material (NORM) and other background radioactivity (e.g. global fallout from atmospheric nuclear weapons testing). Note that the dotted line shows the original shoreline as it was in 1935.

Table 1. Half-life and predominant types of radiation emitted for the eight ROCs at HPNS.

Radionuclide	Half-life[†]	Type of radiation emitted[*,†]
Americium (Am-241)	432.2 years	Alpha, beta, and gamma
Cobalt (Co-60)	5.27 years	Beta and gamma
Cesium (Cs-137)	30.1 years	Beta and gamma
Plutonium (Pu-239)	24,110 years	Alpha, beta, and gamma
Radium (Ra-226)	1599 years	Alpha, beta, and gamma
Strontium (Sr-90)	28.8 years	Beta
Thorium (Th-232)	1.4×10^{10} years	Alpha, beta, and gamma
Uranium (U-235)	7.04×10^{8} years	Alpha, beta, and gamma

[*]Radiation emitted includes that associated with decay products of the parent radionuclide as applicable.
[†]Johnson et al. 2012; ICRP (2008).

500–5000 mrem, between 1 and 25% of observed deaths were attributable to radiation exposure. It is noteworthy that at the remedial goals for HPNS, incremental exposure to radionuclides would be approximately 12 mrem/year (mrem/y), far below any level of exposure observed following atomic bomb detonations, and far below exposure levels associated with any increased cancer risks.

Radionuclides of concern (ROCs) at HPNS

The ROCs for this risk assessment were identified by the Navy as having been historically used at HPNS and/or were the focus of recent retesting in Parcel G (USN 2018). Table 1 lists each of the eight ROCs, as well as their half-lives and their predominant type(s) of radiation emitted. The Navy, in agreement with regulatory agencies, stated that any radionuclide that would have decayed through ten half-lives since its time of use at the site was no longer considered a radionuclide of concern.

The USN identified 11 ROCs that were the focus of the base-wide TCRA which was conducted from 2006 to 2017 (USN 2006). Eight of these 11 ROCs are included in this risk assessment. Three of the 11 ROCs (tritium, europium-152 [Eu-152], and europium-154 [Eu-154]) were excluded from this risk assessment for the following reasons. Tritium was identified as an ROC at only nine out of the 1309 soil survey units during base-wide radiological surveys and was only detected four times above background with a maximum measured concentration of 0.25 pCi/g. This is approximately 10% of tritium's remedial goal (2.28 pCi/g) at HPNS. Additionally, Eu-152 and Eu-154 were only classified as ROCs in a single soil survey unit in Parcel G (USN 2006). Neither of these two radionuclides were included as ROCs in the Navy Parcel G retesting work plan (USN 2018). For these reasons, Eu-152 and Eu-154 were also excluded from this assessment.

The HPNS remedial goals (Table 2) were established so that the cumulative incremental cancer risk due to soil would be at or below the acceptable risk criteria of 3×10^{-4}, even if all eight ROCs were present in all soil at or close to their respective remedial goals (Tetra Tech EC Inc 2006). Few, if any, soils contained all eight of the ROCs.

It is noteworthy that one of the main objectives of the base-wide TCRA was the removal of approximately 25 miles of storm drain and sewer piping because of concerns that they were a potential source of contaminant release to the

Table 2. Current remedial goals at HPNS for the eight ROCs (Tetra Tech EC Inc 2006).

Radionuclide	HPNS remedial goal (pCi/g*)
Americium (Am-241)	1.36
Cobalt (Co-60)	0.0361
Cesium (Cs-137)	0.141
Plutonium (Pu-239)	2.59
Radium (Ra-226)	1 pCi/g above background
Strontium (Sr-90)	0.331
Thorium (Th-232)	1.69
Uranium (U-235)	0.195

*To convert to SI units (Bq/kg) multiply pCi/g by 37.

environment. Soil displaced during these activities was tested for contamination and was disposed of off-site when remedial goals were exceeded.

A small number of point sources from operations at HPNS were believed to have led to low-level releases of radionuclides to the environment. The principal mechanisms of release were believed to be spills and leaks to surface and subsurface soil; direct discharge to sewers and storm drains; and discharge *via* soils in landfills or other areas of the site (USN 2004, 2018). The Navy identified drydocks, former NRDL building sites, select outdoor areas, ship berths, and septic, sanitary, and storm drain systems as potentially impacted by low levels of radionuclides (USN 2004). Potential diffuse aerial releases of radionuclides that may have been associated with site remediation activities (e.g. soil excavation) appear to have been quite limited. The resulting airborne concentrations were below occupational exposure limits and airborne effluent concentration limits promulgated by state and federal regulatory agencies. This is not unexpected since dust control measures (e.g. water spray applications and tarps) were used by remediation contractors to minimize fugitive dust issues and to prevent airborne releases.

Methodology

This risk assessment is structured according to the framework established by the USEPA and the NAS, with steps including hazard identification, exposure assessment, dose-response assessment, and risk characterization (NAS 1983). Data collection and analysis approaches are described in detail below.

HPNS soil data

A radiological soil sample database was developed using data from the Navy's soil sampling database as well as from site characterization and remediation documents from HPNS dating from 1992 to 2017. When sample depth was specified, only surface soil samples (0–12 inches below ground surface) were included in this dataset because this is the relevant depth for the vast majority of exposures. Any sample in which a depth was not specified was also included, such that included samples may have been collected at depths greater than 0–12 inches. Samples with unspecified surface depths were primarily collected from trenches, which were excavated to depths of up to 5–20 ft. Site-related contamination in trenches, where present, would have been at or near the

bottoms of the trenches where the sewer pipes and drainpipes were located. Thus, it is conservative (i.e. errs on the side of overpredicting exposure) to include soil samples from trenches that were greater than 12 inches below ground, because this results in an over-estimate of the possible risk to human health (since humans would have virtually no exposure to those soils).

Sediment data were not considered for Parcel F, which is currently undergoing characterization and/or remediation and is often underwater due to tidal influence, nor for the landfills in Parcels E and E-2, as there was (and is) minimal opportunity for human exposure to these surface soils due to fencing and access restrictions. Additionally, radiological data from on-site buildings were not considered, as access to these areas was restricted and on-site tenants would not have been permitted to enter potentially impacted buildings (Innovex-Engineering/Remediation Resources Group Joint Venture 2019).

Historically, an on-site laboratory was used at HPNS to conduct the initial analyses of soil samples. This laboratory used a screening-type analytical method for Ra-226 which yielded results that were biased high (USN 2018). Because of this artificial bias, preference was given to results from an off-site laboratory that used a more definitive analytical method for quantifying Ra-226, when such results were available; however, if on-site laboratory results were the only data available for a soil sample, they were used for this analysis. For soil samples with multiple results from either laboratory, the mean concentration was used in subsequent calculations.

When strontium was analyzed in soil samples, initial analyses were conducted for total strontium activity, with additional analysis for Sr-90 conducted only if total strontium exceeded the Sr-90 remedial goal. Because many total strontium results were lower than the Sr-90 remedial goal, numerous samples were never analyzed for Sr-90 content. These total strontium results were used in this risk assessment as if they represented Sr-90, which resulted in overestimates of actual Sr-90 concentrations.

For soil samples where the ROC result was reported as less than the minimum detectable activity or detection limit (i.e. non-detects), the result was set equal to the detection limit. If multiple non-detect results were available for a single sample, the average of the detection limits for the ROC was used in the soil database. If a detected result and a non-detect result were available for an ROC in a single sample, the detected result and the detection limit were averaged. This approach served to estimate cancer risks that were biased high in order to not underestimate the incremental cancer risks.

After a quality control assessment was conducted on the database, the data were subdivided into pre- and post-remediation sets for the identified 1309 survey units in the parcels/sites at HPNS. Soil samples included in the pre-remediation datasets represent conditions that existed at HPNS prior to the start of radiological remedial actions in the 1990s. These soil data include results from initial systematic sampling of each survey unit and other initial samples collected to assess radionuclides in soil. The pre-remediation dataset also includes all soil samples in

which one or more ROCs exceeded the applicable remedial goals, even where these exceedances are known to have occurred below the surficial 0–12 inch soil layer. Soil samples in the post-remediation dataset represent current site conditions.

Within each parcel/site, the 95% UCL of the mean/median soil concentration was calculated for each ROC (the mean was estimated when there were eight or more detections of an ROC in a dataset, and the median was estimated when there were fewer than eight detections for an ROC). The net UCL concentration was calculated by subtracting the background concentration for each ROC from the total UCL concentration for that ROC.

Upper tolerance limits (UTLs) were also calculated for each ROC in the pre-remediation soil dataset at each parcel/site. Unlike UCLs, which are applicable to the mean or median concentration, the UTLs characterize the statistical upper-bound on individual sample concentrations. The UTL is the same as a confidence limit (CL) on an upper percentile of the distribution – for this analysis, the UTL was defined as the upper 95th CL for the 95th percentile of the concentration distribution. As such, the UTL will always be equal to or larger than the UCL and have a greater chance of exceeding the regulatory standard. The use of the UTL in risk calculations is more stringent because it requires that 95% of all individual measurements be less than the regulatory standard, whereas use of the UCL only requires that the mean be less than the regulatory standard.

These UTLs were used to conservatively evaluate the potential impact of compromised soil samples on the post-remediation risk. It is unlikely that compromised samples were systematically substituted, so this approach characterized the worst-case scenario of the largely random effects of their substitution by applying the UTL to every soil sample in each parcel. Note that previously rejected soil samples were excluded from this risk assessment. Rejected soil samples consisted of those not likely to be representative of the respective survey units (Tetra Tech EC Inc 2014). Details of the UCL and UTL calculations are discussed in Appendix 2.

To accommodate non-detects in our statistical computation of the UCLs and UTLs, the Kaplan–Meier estimator was used for radionuclides with detection frequencies of 50% or greater that fit a normal, lognormal, or gamma distribution; otherwise, nonparametric methods were applied. The nonparametric methods used the measured concentration or

detection limit in their computation. This is more conservative (i.e. more likely to overpredict the actual risk) than using the detection limit divided by a constant, because it will result in larger UCLs and UTLs which will have a greater chance of exceeding a regulatory standard.

The incremental cancer risk due to the presence of each ROC was calculated based on the net UCL for that ROC. The risk value for each of the eight ROCs was then added to calculate the total incremental cancer risk for the contaminated portions of each of the 10 parcels/sites. The equation, a summation over the parcels, is shown below:

$$\text{Total Incremental Cancer Risk} =$$

$$\sum \text{Parcel Cancer Risk} * \text{Contaminated Portion of Parcel}$$

where the parcel cancer risk was calculated in RESRAD-ONSITE using the net UCL for each ROC, and the contaminated portion of the parcel is defined as the ratio of the total area of radiological surveys in a parcel to the total parcel area.

Use of the UCL, rather than the average value, is not standard practice for estimating risk. This approach was used to ensure that the true incremental cancer risk would not be underestimated. Parcel/site risks were then weighted to account for the proportion of contaminated land (by surface area) within the parcel/site by calculating the ratio of the contaminated area ("survey area") of the parcel/site to the total parcel/site area. The risk for the entire remediated site was then estimated by adding the weighted risks across all parcels/sites.

Based on soil samples collected in 2019 from off-site reference background area (RBA) at San Bruno Mountain State and County Park (CH2M Hill Inc 2020), the UCL of the mean/median background concentration of each ROC was also calculated. Details of the UCL calculations are discussed in Appendix 2. The USEPA has indicated that soil samples collected from this off-site RBA should be used to determine background concentrations for HPNS. The background UCL values used in this risk assessment for each ROC are presented in Table 3 along with the HPNS remedial goals. The use of the UCL of the mean/median is different from the statistical approach used by the Navy for the purpose of determining a background value for comparison to HPNS remedial goals.

For this purpose, the Navy chose to use the maximum detected result or the maximum detection limit for each ROC for soils at the off-site RBA as its estimate of background concentrations. This was based on USEPA's request to use

Table 3. Background soil concentrations compared to HPNS remedial goals.

Radionuclide of concern (ROC)	Soil background UCL of the mean/median (pCi/g)[*,†]	Current HPNS remedial goal (pCi/g)[†]
Am-241	0.183	1.36
Co-60	0.045	0.0361
Cs-137	0.095	0.141
Pu-239	0.288	2.59
Ra-226	0.652	1.0 + Background
Sr-90	0.145	0.331
Th-232	0.802	1.69
U-235	0.068	0.195

[*]Background concentrations based on 95% UCLs of the mean for surficial soil samples taken from the off-site reference background areas (RBAs).
[†]To convert to SI units (Bq/kg) multiply pCi/g by 37.

the off-site RBA as the primary background, meaning that the maximum ROC concentrations at the off-site RBA were attributed to naturally occurring radiation or the effects of radioactive fallout from non-HPNS sources.

HPNS air data

During remediation activities at HPNS from 2005 to 2014, approximately 19,000 samples of airborne particulates were collected *via* high-volume air samplers and were subsequently analyzed for gross alpha and gross beta activity.

An air sample database was built that included information on the date and location of each sample, type of sample (e.g. grab, downwind, upwind, and continuous), the start and stop time of sample collection, the time and date the sample was analyzed, as well as sample volume. Any air samples that were below the limit of detection were replaced with the relevant limit of detection. It is recognized that this approach is highly conservative (i.e. likely to overestimate true risk) and acknowledged that better methods have been developed over the years; for example, Miller et al. have illustrated some of the benefits of using Bayesian techniques with exact Poisson likelihood functions for analyzing radioactivity count data that avoid the biasing caused by assuming that all counts were positive (Miller et al. 2002). However, for the purpose of this risk assessment, conservative estimates were presented to emphasize that any actual risks presented by the site are much less than target risk levels.

Approximately, 4500 pairs of upwind and downwind samples were identified, which were defined as data collected on the same date upwind and downwind of a given on-site location. For the upwind:downwind pairs, Wilcoxon matched-pairs signed-rank testing was used to determine whether gross alpha and gross beta downwind concentrations were statistically different from upwind concentrations. Such a comparison allowed for the assessment of the effectiveness of dust control measures used during remediation and evaluation of the loss of potentially contaminated dust, if any, from the site.

Air samples collected at HPNS were often counted within a short period of time after filter collection to determine the level of gross alpha and gross beta present on the filter. The average holding period between when samples were collected and when they were analyzed was 20.5 h. This short turnaround time was acceptable for radiation protection purposes to demonstrate compliance with 10 CFR 20's derived air concentration (DAC) limits and to ensure a safe working environment based upon results of historical air monitoring data. But, as a result of the short turnaround, a large fraction of the measured alpha and beta activities were associated with the presence of unsupported, short-lived decay products of namely radon-222 and radon-220. The term "unsupported" in this context means the parent radionuclides of radon-222 (radon) and radon-220 (thoron) were not collected on particulate air filters since they are inert gases. Because the parent radionuclides were not present on the sample filters, there was no additional ingrowth of activity of short-lived

decay products (e.g. Pb-214) which quickly decrease in activity due to short radioactive half-lives on the order of seconds to hours. The presence of these radon and thoron decay products therefore led to an overestimate of the concentrations of long-lived gross alpha and gross beta activities.

A second database was created for the measured wind speed and direction collected at a weather station near the HPNS site during remediation activities conducted at the site between 2005 and 2012. Further analysis of the wind data was conducted with Python version 3.10.0 (Wilmington, DE, USA).

Dose and cancer risk calculations for ROCs in soil

The RESidual RADioactivity (RESRAD) family of computer-based dose models has been accepted by state and federal regulatory agencies and by the Navy for conducting radiological risk assessments (Argonne National Laboratory 2016; USN 2020b). The RESRAD-ONSITE for Windows® version 7.2 (July 2016) model uses standard or user-defined exposure factors to calculate dose and provides different options for cancer slope factors to calculate estimated incremental lifetime cancer risks for local populations (Argonne National Laboratory 2016; U.S. Department of Defense [USDOD, USDOE, USEPA, NRC] 2000). The software uses inputs of soil ROC concentration (i.e. the exposure point concentration) and accounts for the fate and transport of radionuclides (e.g. radioactive decay).

The cancer slope factors for morbidity selected in the dose model for this risk assessment are those of the DC_PAK version 3.02 (Oak Ridge, TN, USA) software data package in RESRAD-ONSITE (International Commission on Radiological Protection [ICRP] 2008). The slope factors in DC_PAK 3.02 are adopted from the USEPA's Federal Guidance Report No. 13 and the model uses updated nuclear decay and ingrowth data from ICRP Publication 107 and external dose rate coefficients for surficial soils from the USEPA's Federal Guidance Report No. 12 (Eckerman and Ryman 1993; Eckerman et al. 1999; ICRP 2008). To account for cancer risk contributions from short-lived progenies, the slope factors of short-lived progenies were added to that of the parent nuclide. The RESRAD-ONSITE model characterized the cancer risk by calculating the amounts of external exposure and intake and applying the slope factors corresponding to the applicable ROC. It was assumed that the decay products were in secular equilibrium with their parent radionuclide at the point of exposure.

Upper bound exposure parameter values were assigned for areal extent of soil contamination based on the size of each parcel remediated. The depth of the contamination zone was set at 0–2 m bgs. The upper bound of both the area and depth of assumed on-site contamination were used in the RESRAD-ONSITE model so that actual concentrations of radionuclides in soil were not underestimated.

RESRAD-ONSITE determines the external exposure and intakes and then calculates the time-integrated risk of each ROC by considering both the decay of the parent radionuclide and ingrowth of radioactive progeny. Ingestion, inhalation, and external exposure cancer slope factors (risk coefficients for total cancer morbidity) for radionuclides (Table 4) are combined with time-integrated external exposure and intake

estimates to calculate the estimated incremental lifetime cancer risks at HPNS by parcel/site and overall.

The RESRAD-ONSITE model and cancer morbidity slope factors (Table 4) were used to derive estimates of pre- and post-remediation incremental cancer risks for exposure to net concentrations of the ROCs in soil. The exposure parameters used in this analysis are summarized in Table 5. UCL concentrations for pre-and post-remediation data sets were input into the model to calculate soil-related dose and incremental cancer risk associated with the presence of each ROC within each parcel.

Sensitivity analysis to account for potentially compromised soil data

Because approximately 480 soil samples were inappropriately substituted by staff during remediation activities, a conservative sensitivity analysis was used to evaluate whether additional potentially unidentified soil sample substitutions could have impacted the quality of the characterization of the soil and the predicted incremental cancer risks at HPNS. For this sensitivity analysis, the calculated UTLs for the radionuclides in soil were substituted in RESRAD-ONSITE model for all the post-remediation soil samples in all parcels/sites to calculate new incremental cancer risks. The incremental cancer risk values based on the UTLs were then compared to assess whether the soil sample substitution could have a material impact on the risk results (i.e. conclusions about the magnitude of risk).

Table 4. External, ingestion, and inhalation morbidity slope factors for radionuclides of concern at HPNS used in RESRAD-ONSITE calculations.

	Morbidity Slope Factors* (1/y per pCi/g)		
Radionuclide	External	Ingestion	Inhalation
Am-241	2.8×10^{-8}	1.3×10^{-10}	3.8×10^{-8}
Cs-137	2.5×10^{-6}	3.7×10^{-11}	1.1×10^{-10}
Co-60	1.2×10^{-5}	2.3×10^{-11}	1.0×10^{-10}
Pu-239	2.1×10^{-10}	1.7×10^{-10}	5.6×10^{-8}
Ra-226	8.4×10^{-6}	5.2×10^{-10}	2.8×10^{-8}
Sr-90	2.0×10^{-8}	9.5×10^{-11}	4.3×10^{-10}
Th-232	7.3×10^{-6}	4.3×10^{-10}	1.4×10^{-7}
U-235	5.8×10^{-7}	9.8×10^{-11}	2.5×10^{-8}

*Slope factors used in RESRAD-ONSITE are adopted from the USEPA's Federal Guidance Report 13 and included in DC_PAK 3.02 which was selected in the model for the risk calculations. DC_PAK 3.02 includes updated nuclear decay and ingrowth data adopted from ICRP Publication 107 (ICRP 2008).

Table 5. Input parameter values used for RESRAD-ONSITE model.

Parameter	Human Receptor		Notes
Site receptor	On-site resident	On-site Worker/ nonresident Tenant	Applied to resident adult and adult nonresident occupant
Exposure duration (y)	30	30	Actual exposure duration for nonresidents expected to be less
Fraction of time spent indoors	0.5	0.25	RESRAD default is 8760 h/year (i.e. 365 d/y). Resident spends 75% of their time onsite with 50% of that time spent indoors. The nonresident occupant spends 2750 h/y onsite with 82% of that time spent indoors.
Fraction of time spent outdoors	0.25	0.06	Resident spends 75% of their time onsite with 25% of that time spent outdoors. The nonresident occupant or site worker spends 2750 h/y onsite with 18% of that time spent outdoors.
External Gamma Shielding Factor (GSF)	0.7	0.7	Same value used for resident and nonresident occupant
Inhalation rate (m³/year)	8400	20,000	8400 m³/y recommended by ICRP 1975. 20 000 m³/y accepted by USEPA and Navy for prior Parcel B risk screening for construction/industrial worker although average inhalation rate for other nonresidential site occupants are expected to be lower. Note: Inhalation pathway not a significant contributor to risk for either on-site receptor.
Mass loading for Inhalation (g/m³)	0.0001	0.001	Assigned values for all parcels ensures site-wide inhalation risks are not underestimated and do not reflect the added protection at Parcels B, C, D-1, G, UC-1, UC-2, and UC-3 which currently have durable covers post remediation. The default mass loading is a conservative estimate that takes into account short periods of high mass loading and sustained periods of normal activity on a typical farm (Healy and Rodger 1979; Anspaugh et al. 1974).
Soil ingestion rate (g/year)	36.5	36.5	36.5 recommended by USEPA 1997. Actual ingestion rates for nonresidents/ on-site worker are expected to be less than the value shown due to a lower outdoor occupancy fraction and less total time spent onsite as compared to an onsite resident. Increasing the soil ingestion rate to a highly unlikely maximum (120 g/y) for an on-site worker does not increase their risk significantly since external gamma exposures contribute over 95% of radiation doses.
Plant, meat, milk, aquatic, and drinking water ingestion	N/A	N/A	Incomplete pathways – not used with institutional controls in place
Dose/risk factors (morbidity)	DCFPAK 3.2/ ICRP 107	DCFPAK 3.2/ ICRP 107	DCFs and risk coefficients are adopted from Federal Guidance Reports 12 and 13 and include the most current nuclear decay and ingrowth data in ICRP Publication 107 (ICRP 2008).
Cover density (g/cm³)	2.24	2.24	Weighted density value based on site-specific cover combination of gravel base and asphalt surface.
Cover thickness	10 inches	10 inches	Durable cover thickness adjusted to be approximately equivalent to the 10″ base + asphalt cover and used for all parcels except for D-2 and E which do not currently have durable covers. Cover for IR-07/18 (former disposal area) was assigned a 2-foot soil cover.

These parameters were used to calculate doses and incremental cancer risks due to ROCs for both on-site residents and on-site workers/nonresident tenants at HPNS.

Hazard identification

The USEPA classifies all radionuclides as "Carcinogenic to Humans" based on epidemiologic evidence that links exposure to ionizing radiation at sufficient doses to the development of various cancers (USEPA 2015). The occurrence of cancer is related to a variety of factors, including high doses of ionizing radiation, genetics, smoking, alcohol consumption, obesity, low physical activity, low fruit and vegetable consumption, air pollution, and injections from illicit drug use (Kasper et al. 2014). Understanding the occurrence of cancer is difficult, especially in the presence of modifying factors, such as an individual's lifestyle and their genetics. Compounding the problem is that radiogenic cancers (i.e. those caused by radiation) are indistinguishable from non-radiogenic cancers (i.e. those caused by other sources) (National Research Council [NRC] 2006).

Any genuine incremental cancer risk associated with exposure to radionuclides depends on the magnitude of exposure above background. It is important to acknowledge the presence of background radioactivity because all soils throughout the world have measurable concentrations of radionuclides (USNRC 2017). This has historically been acknowledged at sites undergoing CERCLA remediation (USEPA 2002). For example, the USEPA's 2002 report "Role of Background in the CERCLA Cleanup Program" states that,

> Where background concentrations are high relative to the concentrations of released hazardous substances, pollutants, and contaminants, a comparison of site and background concentrations may help risk managers make decisions concerning appropriate remedial actions. The contribution of background concentrations to risks associated with CERCLA releases may be important for refining specific cleanup levels for COCs [contaminants of concern] that warrant remedial action. Generally, under CERCLA, cleanup levels are not set at concentrations below natural background levels. Similarly, for anthropogenic contaminant concentrations, the CERCLA program normally does not set cleanup levels below anthropogenic background concentrations (U.S. Environmental Protection Agency (USEPA) 1996, 1997b, 2000). The reasons for this approach include cost-effectiveness, technical practicability, and the potential for recontamination of remediated areas by surrounding areas with elevated background concentrations (USEPA 2002).

The average person in the United States is exposed to approximately 620 mrem/y of radiation from a variety of environmental, medical, and industrial sources (USNRC 2017). The distribution of these average doses is presented in Figure 9. The major contributing sources are radon and thoron (background) (37%), computed tomography (medical) (24%), and nuclear medicine (medical) (12%).

The annual amount of radiation exposure for a person living in the United States is primarily dependent on geographical location, though a number of studies conducted throughout the world did not find evidence of higher disease rates in geographic areas with higher background levels of radiation exposure (Wang et al. 1990; Lu-xin and Jian-zhi 1994; Richardson et al. 1995; Nair et al. 1999).

Other contributions to radiation exposure are minimal in comparison to these sources. For example, consumer products contribute approximately 2% of average annual exposures whereas industrial sources contribute less than 0.1% (ICRP 2008). Figure 10 depicts annual natural radiation doses at seven different locations within the United States as well as the national average. To put the results of this risk assessment into context, background radiation exposures to an average person living in the U.S. need to be understood and reflected upon so that members of the community are fully informed regarding the incremental cancer risk posed by HPNS before, during, and after remediation.

Radionuclides of concern (ROCs) at HPNS

Brief discussions of the eight ROCs identified at HPNS and the health hazard(s) they pose are presented here.

Radium-226

Ra-226 has a radioactive half-life of 1600 years and is formed when naturally occurring uranium (U-238) undergoes radioactive decay (i.e. radioactive transformation). Ra-226 transitions by alpha decay to form radon-222. Ra-226 decay products (Rn-222, Pb-214, and Bi-214) emit alpha, beta, and gamma radiation in various combinations depending upon which decay product is being evaluated. Ra-226 and its decay products can pose both an external and internal radiological hazard and are responsible for a major fraction of natural radiation dose received by humans. It is naturally present at various concentrations in soils and water in the United States and throughout the world (ICRP 2008; Johnson et al. 2012). Devices that contained Ra-226 (i.e. ship deck markers), the presence of Ra-226 containing radioluminescent paint, and Ra-226 waste storage at HPNS were the primary reasons for its identification as an ROC at the site (USN 2004).

Cesium-137

Cs-137 has a radioactive half-life of 30 years and is a byproduct of nuclear fission. Cs-137 was released to the atmosphere from nuclear weapons testing conducted by the United States, United Kingdom, China, France, and the former USSR from 1946 to 1980 and from nuclear reactor accidents, such as those that occurred at the Chernobyl and Fukushima-Daiichi plants (Eisenbud and Gesell 1997; Balonov 2007; Marianno et al. 2018). As a result of these releases, measurable quantities of Cs-137 can be found in the environment (including soils) and in human tissues. Beta decay of Cs-137 produces a metastable excited state of barium (Ba-137m) with a radioactive half-life of 2.55 min. The decay of Ba-137m to the stable isotope of Ba-137 emits a high-energy gamma ray. Cs-137 is primarily an external radiation hazard although it can pose an internal radiation hazard if ingested or inhaled (ICRP 2008; Johnson et al. 2012). The potential for Cs-137 to be present on ships returning from nuclear weapons tests in the Pacific and Cs-137 use in calibrating radiation detection equipment were the primary reasons Cs-137 was identified as an ROC (USN 2004).

Strontium-90

Sr-90 has a radioactive half-life of 28.79 years and is produced as a fission byproduct of uranium and plutonium. Large amounts of radioactive Sr-90 were produced,

Figure 9. Percent breakdown for various sources of radiation that make up the annual background dose of approximately 620 mrem (6.2 mSv) for an average person living in the United States (Adopted from National Council on Radiation Protection Report No. 160, 2009).

Figure 10. Annual natural radiation dose in various locations in the United States. The majority of the variation is due to geographical location (Mauro and Briggs 2005; National Council on Radiation Protection 2009).

dispersed, and deposited throughout the earth during atmospheric nuclear weapons tests. The hazard from exposure to Sr-90 is due mainly to decay of its Y-90 decay product (half-life of 64 h) which emits an energetic beta particle. The energetic beta particle can pose an internal risk if ingested or inhaled or an external radiation hazard. It is present in most soils in the United States at various concentrations (ICRP 2008; Johnson et al. 2012). The potential for Sr-90 to be present on ships returning from nuclear weapons tests in the Pacific, its potential use in radioluminescent devices, and the presence of Sr-90 contamination at on-site

laboratories were primary reasons it was identified as an ROC at HPNS (USN 2004).

Plutonium-239

Pu-239 has a radioactive half-life of 24,110 years and is produced when uranium absorbs a neutron. Small amounts of plutonium occur naturally, but large quantities have been produced in nuclear reactions or released from atmospheric nuclear weapons tests. Pu-239 transitions by alpha decay. Its decay products emit alpha, beta, and gamma radiation

depending upon which radionuclide is being evaluated and can pose both an internal and external radiation hazard. Pu-239 is present in most soils in the United States at various concentrations (ICRP 2008; Johnson et al. 2012). The potential for Pu-239 to be present on ships returning from nuclear weapons tests in the Pacific and Pu-239 use in calibrating radiation detection equipment were primary reasons it was identified as an ROC at HPNS (USN 2004).

Cobalt-60

Co-60 has a radioactive half-life of 5.27 years and transitions by beta decay, emitting both beta and gamma radiation. Co-60 is produced when neutrons interact with materials in reactors (i.e. steel that contains stable Co-59). The transition or decay of Co-60 forms non-radioactive, stable nickel. Co-60 is primarily an external radiation hazard but can also be an internal health hazard if ingested or inhaled. It is present in some soils in the United States at various concentrations (ICRP 2008; Johnson et al. 2012). The use of Co-60 in calibrating radiation detection equipment, irradiation facilities, and in gamma radiography at on-site laboratories were the primary reasons it was identified as an ROC at HPNS (USN 2004).

Americium-241

Am-241 has a radioactive half-life of 432.2 years and is produced in nuclear reactors when uranium-238 absorbs a neutron to produce U-239 which undergoes transition by beta decay to Np-239 which then transitions by beta decay to Pu-239. Pu-239 then absorbs two neutrons to produce Pu-241 which then transitions *via* beta decay to produce Am-241. Am-241 is also produced during detonation of nuclear weapons. Am-241 transitions by alpha decay. Its decay products emit alpha, beta, and gamma radiation depending upon which decay product is being evaluated. Am-241 can be an external and internal radiation hazard. It is present in some soils in the United States at various concentrations (ICRP 2008; Johnson et al. 2012). The use of Am-241 in commodity items, such as smoke detectors was one of the primary reasons it was identified as an ROC at HPNS (USN 2004).

Thorium-232

Th-232 has a radioactive half-life of 1.4×10^{10} years and can be found at low levels in soil, rocks, water, plants, and animals. Th-232 transitions by alpha decay. Its decay products emit alpha, beta, and gamma radiation in various combinations depending upon which decay product is being evaluated. Th-232 and its decay products can be an internal or external radiation hazard (ICRP 2008; Johnson et al. 2012). The use of Th-232 in calibrating radiation detection equipment and in commodity items, such as thoriated welding rods and night vision equipment were the primary reasons it was identified as an ROC at HPNS (USN 2004).

Uranium-235

U-235 has a radioactive half-life of 7×10^8 years and is a naturally occurring radionuclide. U-235 accounts for 0.72 wt% of natural uranium with the remaining fractions consisting of U-238 at 99.27 wt% and U-234 at 0.006 wt%. Natural uranium is present in low amounts in rocks, soil, water, plants, and animals. Uranium and its decay products contribute to low levels of natural background radiation in the environment. U-235 transitions by alpha decay. Its decay products emit alpha, beta, and gamma radiation in various combinations depending upon which decay product of the U-235 decay series is evaluated. U-235 is primarily an internal radiation hazard if ingested or inhaled (ICRP 2008; Johnson et al. 2012). Studies of the chemical and physical characteristics of U-235 were carried out at HPNS due to its important role in nuclear fuel (USN 2004). Such studies included the chemical separation of U-235 samples irradiated at Lawrence Livermore National Laboratory, and animal research was also conducted to evaluate potential health effects from exposure to U-235, particularly highly enriched uranium in U-235. The potential for the presence of U-235 contamination at on-site laboratories was a primary reason it was identified as an ROC at HPNS (USN 2004). U-238 was not included as an ROC since results of the site investigations did not identify concentrations above risk screening criteria used by the USEPA and the Navy, and the majority of sampling results during site investigations were not statistically different from background.

Gross alpha and gross beta in airborne particulates

From 2005 to 2014, sampling of airborne radioactivity occurred during remediation activities to collect particulate matter, which was subsequently analyzed for gross alpha and gross beta activity. These samples were compared to the DAC to assess the effectiveness of dust control measures used during remediation, to demonstrate compliance with regulated occupational dose limits, and to evaluate any loss of potentially contaminated dust from the site.

Alpha particles are not sufficiently energetic to penetrate the skin and are not a concern for external exposure for this risk assessment but can pose a potential concern if inhaled or ingested (ICRP 2008). Beta particles are also primarily a concern if inhaled or ingested (ICRP 2008) but can be an external exposure hazard if particles have sufficient energy to penetrate to underlying live dermal tissue.

Background radioactivity in air at the HPNS site

In 1991, a survey was conducted of long-lived airborne gross alpha and beta particles in air near IR sites IR-01, IR-02, and IR-05 (PRC Environmental Management 1992). Sample locations were selected as prescribed in USEPA report USEPA-560/5-86-017. The study concluded that gross alpha activity was not present at significant concentrations, but that gross beta activity was present at significant concentrations both on- and off-site. Importantly, the study showed that on- and off-site gross beta levels were within one standard deviation of each other, meaning that there was no statistically significant difference between on- and off-site gross beta activity, and noted that beta activity on-site was similar to typical background locations throughout the United States (PRC

Environmental Management 1992), where off-site monitoring locations were generally upwind of HPNS.

Relevance of naturally occurring radioactive material (NORM) at HPNS

All soils and underlying bedrock contain naturally occurring radionuclides, with the identity of the radionuclides and their activity concentrations varying with local geology. Additionally, the presence of radionuclides in soils can be attributed to global fallout and deposition following release from nuclear weapons testing or nuclear power plants (ICRP 2008; Johnson et al. 2012). Numerous detailed presentations and discussions of releases from nuclear weapons testing or nuclear reactors accidents and their associated global fallout have been published (Beck and Bennett 2002; Whicker and Pinder 2002; Renaud and Louvat 2004; Moroz et al. 2010; Bouville 2020; Simon et al. 2022). Distinguishing between background concentrations and those attributable to sources released on-site is crucial in accurately characterizing the incremental cancer risks that may be attributable to any contaminated site.

Numerous government guidance documents, such as the Multi-Agency Radiation Survey and Site Investigation Manual (MARSSIM) and USEPA Remedial Investigation/Feasibility Study (RI/FS) recommend that background characterizations be conducted as part of the remedial design prior to remediation (U.S. Department of Defense [USDOD, USDOE, USEPA, NRC] 2000; USEPA 1989). A recent study, Brown (2021) described the relationship between terrestrial background and remedial criteria made the following observations:

> The potential variability of NORM radionuclides in the soil and rocks can be significant, even over relatively short distances or depths due to factors such as geology, hydrology, and geochemistry.

> Particularly when the remedial action criteria are within the statistical range of local terrestrial background or less, it is difficult to distinguish between impacted materials (i.e. "radioactive waste") from natural non-impacted material. This can result in potentially unnecessarily high costs associated with the management of what is in fact 'just NORM.'

As is clear from Brown's analysis, proper characterization of the site prior to remediation is necessary to allow for consideration of the background concentrations when establishing the soil cleanup criteria. The objective of all cleanups is to limit the incremental cancer risk due to radionuclide exposure to the acceptable risk criteria of 3×10^{-4} (National Contingency Plan [NCP] 1990).

The estimated lifetime cancer risks for adult residents exposed to background soil concentrations of ROCs within the San Francisco Bay Area are presented in Table 6. This table shows that radionuclides in soils in the Bay Area pose an estimated cancer risk of about 2.4×10^{-4}, which is primarily attributable to a combination of NORM, specifically Ra-226 and Th-232.

The Navy has acknowledged that an excessive cleanup was conducted at HPNS (USN 2018). For example, in its draft Parcel G retesting work plan, dated 15 June 2018, the Navy stated:

> The previous work relied on a quicker, less accurate method for analyzing radium-226 (226Ra). This method was known by stakeholders at the time to be biased high. A large amount of soil (estimated 80 percent) was likely mischaracterized as contaminated. (Argonne National Laboratory 2011)

> The RGs [remedial goals] used previously are within background ranges. Therefore, soil that was considered contaminated could have been attributable to naturally occurring radioactivity or anthropogenic fallout. (Argonne National Laboratory 2011; USN 2018)

ROCs in soils at HPNS compared to guidance values

HPNS remedial goals for ROCs were originally developed in 2006 and were recently confirmed by the Navy to be protective of human health based on updated RESRAD-ONSITE dose model results (USN 2020a). Table 7 presents calculated doses based on HPNS remedial goals for the eight ROCs. This table provides dose/activity values, which represent the dose (in mrem/y) per unit soil activity (in pCi/g). These dose/activity values were calculated using the RESRAD-ONSITE model based on a residential use scenario.

At the time the HPNS remedial goals were developed, the USEPA annual dose limit for radioactive contaminated sites was 15 mrem/y, which corresponded to a risk of 3×10^{-4} (Brown 2021). However, in 2014, the USEPA indicated that the allowable net dose from post-remediation soil sources was to be set at 12 mrem/y (USEPA 2014). This dose level corresponds to the same incremental cancer risk of 3×10^{-4} as a result of model parameters (Brown 2021; USEPA 2014).

Table 6. Radionuclide dose and lifetime incremental cancer risk for adult residents living in the San Francisco Bay Area exposed to background soil concentrations of the ROCs.

Radionuclide	Background UCL soil concentrations for ROCs (pCi/g)*	Dose equivalent (mrem/y)[†]	Cancer risks for ROC background concentrations in soil
Am-241	0.183	8.8×10^{-3}	8.0×10^{-8}
Co-60	0.045	2.9×10^{-3}	4.5×10^{-8}
Cs-137	0.095	7.2×10^{-2}	1.5×10^{-6}
Pu-239	0.288	1.3×10^{-2}	5.7×10^{-8}
Ra-226	0.652	3.6	8.3×10^{-5}
Sr-90	0.145	1.3×10^{-3}	1.6×10^{-8}
Th-232	0.802	6.4	1.5×10^{-4}
U-235	0.068	2.6×10^{-2}	5.9×10^{-7}
Total (all ROCs)		$1.01 \times 10^{+1}$	2.4×10^{-4}

Note that background concentrations of Th-232 and Ra-226 are the predominant drivers of the incremental cancer risk.
*To convert to SI units (Bq/kg) multiply pCi/g by 37.
[†]To convert to SI unit (mSv/y) multiply mrem/y by 0.01.

Table 7. Estimated doses of the eight ROCs at HPNS if the site was cleaned to remedial goals. The Nuclear Regulatory Commission's NUREG-1757 conservative screening goals for these radionuclides are also presented.

ROC	NUREG-1757 soil screening value (pCi/g)[*,†]	HPNS remedial goal (pCi/g)[‡]	Dose at remedial goal (mrem/y)[¶,§]	Dose/concentration activity (mrem/y per pCi/g)[‖]
Am-241	2.1	1.36	0.10	0.07
Co-60	3.8	0.036	0.29	8.03
Cs-137	11	0.141	0.25	1.77
Pu-239	2.3	2.59	0.16	0.06
Ra-226	0.7 + background	1 + background	5.94	5.94
Sr-90	1.7	0.331	0.01	0.03
Th-232	1.1 + background	1.69	13.45	7.96
U-235	8	0.195	0.08	0.41

[*]Nuclear Regulatory Commission 2006.
[†]Based on 25 mrem/y limit.
[‡]To convert to SI units (Bq/kg) multiply pCi/g by 37.
[¶]Radiation doses for HPNS remedial goals were calculated with RESRAD-ONSITE for a residential use scenario.
[§]To convert to SI units (mSv/y) multiple mrem/y by 0.01.
[‖]Dose/activity values represent the dose (in mrem/y) per soil activity (in pCi/g). These dose/activity values were calculated using the RESRAD-ONSITE model based on a residential scenario.

After the 2019 background soil survey conducted by the Navy, the HPNS remedial goals for the three most common ROCs – Cs-137, Ra-226, and Sr-90 – were set at 0.141, 1 + background, and 0.331 pCi/g, respectively (CH2M Hill Inc 2020). At these remedial concentrations, the respective radiation doses contributed by these three ROCs would be 0.25, 5.94, and 0.01 mrem/y, respectively.

The Cs-137 background concentration in soil measured in 2019 is higher than the 2006 remedial goal of 0.113 pCi/g. Unfortunately, the vast majority of remediation activities had already occurred at the time of the 2019 background study. Nonetheless, the 2019 off-site background value for Cs-137 (0.141 pCi/g) was selected as the new remedial goal and it has been used for remedial activities conducted since then (CH2M Hill Inc 2020). Therefore, any soil concentration above background would, by definition, result in a concentration above the remedial goal. This is generally considered a poor approach to site management; especially when there is large variability in site soils that are considered clean.

The U.S. Nuclear Regulatory commissions' (NRC) NUREG-1757 soil screening guideline values can be compared to the HPNS remedial goals (Table 7). These dose-based values were used to screen soils at nuclear facilities undergoing decommissioning (NRC 2006). The screening approach allowed sites that pose lower potential risks to demonstrate compliance through simpler yet conservative screening analyses, provided results of the unity rule are compliant and other NUREG-1757 site criteria for screening are met. The unity rule, if correctly applied as recommended by MARSSIM guidance (NUREG 1575) and NUREG 1757 decommissioning guidance, generally means the measured average concentration for each radionuclide of concern within a survey unit shall be less than its respective dose-based cleanup criteria and the summation of the ratio of concentration to cleanup goal shall be less than or equal to one. If this screening approach had been used at HPNS, then the NUREG-1757 screening values could have been adjusted down to meet the USEPA's 12 mrem/y limit, but that was not the approach used by the Navy and the USEPA.

While some NUREG-1757 criteria were similar to the HPNS remedial goals, the Cs-137 NUREG-1757 criterion of 11 pCi/g is approximately 80 times higher than the HPNS remedial goal of 0.141 pCi/g. Even accounting for the fact that

NUREG-1757 criteria are based on a 25 mrem/y dose limit, rather than the USEPA's current 12 mrem/y limit, this illustrates how conservative (i.e. protective) the remedial goal for Cs-137 was at the HPNS site.

Figure 11 shows the cleanup levels at HPNS for Cs-137, Sr-90, and Ra-226, which were the three main ROCs at the site, compared to cleanup levels at the Brookhaven National Laboratory (BNL) site. The remedial goals at BNL assumed that public access to the site would be restricted for 50 years after cleanup (Meinhold et al. 1996). Therefore, the values presented in this figure represent the concentrations of ROCs after 50 years of decay from the BNL remedial goals. Nonetheless, the BNL remedial goals are significantly higher (i.e. less stringent) than those implemented for the same radionuclides at HPNS.

The comparison of BNL and HPNS remedial goals illustrates that not only do USEPA cleanup guidelines for soils vary amongst sites, but the comparison also illustrates that cleanup values set by the USEPA, DOE, and DoD can vary significantly with sites, radionuclides, and over time (Paustenbach et al. 1992; Nieuwenhuijsen et al. 2006; Brown 2021). Further, the goals at HPNS were established as part of a negotiation between the Navy and the USEPA, which resulted in the agreement upon highly protective remedial goals.

Exposure assessment

Conceptual site model and exposure pathways

A conceptual site model (CSM) was developed to account for the extensive site characterization data for radionuclides; physical and environmental features of the site; the history of radionuclide uses and environmental release, and current and future uses of the site and of adjoining lands (Figure 12). This diagram identifies the contaminated media, fate and transport processes, receptor populations, and exposure pathways for HPNS.

The exposure pathways and exposure factors used in this risk assessment (Figure 12) are consistent with those used by the Navy's contractor and the USEPA when they evaluated the health-protectiveness of the HPNS remedial goals for soil (Battelle 2019). These pathways included external whole-body exposure from gamma-emitting ROCs in surface and subsurface soil, inhalation of ROCs in resuspended surface and subsurface

Figure 11. The remedial goals at HPNS for the radionuclides Ra-226, Cs-137, and Sr-90 in soil were more stringent than land use requirements at Brookhaven National Laboratory (BNL), New York. The BNL soil cleanup levels shown in the figure reflect an adjustment to account for a 50-year restriction of access to the site – during this time, any ROCs present on the site would have decayed beyond their initial remedial goals.

Figure 12. Conceptual site model (CSM) of relevant exposure pathways at HPNS. Land use deed restrictions or covenants to restrict use of property (CRUPs) will limit land use and activities including placing restrictions on homegrown produce. Furthermore, there will be no grazing animals, fish harvesting, or drinking of groundwater at HPNS. Thus, the only potential source of exposure to the ROCs is from the soil (DTSC 2000; USN 2020a).

soil, and incidental ingestion of ROCs in surface and subsurface soils (Figure 12). The dermal absorption of radionuclides, which have low permeability constants, was not considered an important route of uptake and, in other assessments; it is nearly always significantly less than 1% of the risk (Integrated Risk Information System [IRIS] 1989). Therefore, dermal uptake of radionuclides was not quantified in this risk assessment. The complete and incomplete exposure pathways are denoted in the CSM with either a plus or minus sign (Figure 12).

All of the ROCs that exist in the soil at HPNS are present as nonvolatile ionic species or as inorganic compounds. Given their environmental stability, and because the water-soluble species would have entered the groundwater underlying HPNS years ago, the nonvolatiles will remain in surface soils unless entrained in dust generated by wind across the soil surface and/or mechanical disturbance. Subsurface soils are not subject to wind-generated resuspension, but mechanical activities, such as excavation or trenching can generate dust. All of these transport mechanisms could result in human exposure due to inhalation and/or incidental ingestion of ROCs adsorbed to soil particulates and were considered in this risk assessment. On-site contractors used dust suppression methods to eliminate or

maintain airborne dust concentrations at safe levels and used confirmation monitoring to check airborne dust (particulate) concentrations on a daily basis (USN 2004).

Transport mechanisms at HPNS that were not considered in this risk assessment include the migration of radionuclides from soil to groundwater and the uptake of ROCs in food that may be grown on site soils. Omission of groundwater transport in this risk assessment is standard practice when groundwater is shallow, tidally influenced, and not potable, similar to conditions found at the HPNS site (USN 2004). Further, both the use of groundwater and cultivation of homegrown produce are precluded at HPNS by institutional controls (IC) jointly developed by the Navy and the California Department of Toxic Substances Control [DTSC] (2000).

These ICs will be implemented in the form of land use deed restrictions (Quit Claim Deeds) or Covenants to Restrict Use of Property (CRUPs), either or both of which will limit land use and activities (DTSC 2000). For example, the Navy has stipulated that CRUPs will limit homegrown produce by future on-site residents to raised beds with impermeable bottoms and sides to prevent contact and/or uptake of contaminants from site soils (USN 2020a).

Sediment-related exposure pathways are not considered in this risk assessment because the underwater portion of HPNS (Parcel F) is currently undergoing characterization. Given the very low concentrations of ROCs in the surface soil, it seems unlikely that the sediments in Parcel F will be significantly contaminated above background. While initial data indicate that sediments are not a concern for human populations, the assessment of potential exposures to Parcel F sediments will be completed by the Navy once comprehensive data for the parcel becomes available (ITSI Gilbane Company and SAIC 2018).

Radiation badges (i.e. radiation dosimeters) were worn by certain on-site workers during the remediation activities to monitor and record workers' potential radiation exposures. These badges were designed to detect external gamma radiation. Workers assigned a badge were typically those individuals with the greatest potential to be exposed to radiation. According to Section 7.5 of the Remedial Action Completion Reports (RACRs) for each of the parcels/sites evaluated during the base-wide TCRA, "[n]o personnel dosimetry badges processed identified a gamma dose above the background level" (Aptim Federal Services 2020; Engineering/Remediation Resources Group Inc. [ERRG] 2012; Shaw Environmental & Infrastructure 2014; Tetra Tech EC 2007a, 2007b, 2007c, 2011a, 2011b, 2012a, 2012b, 2016a, 2016b). For this reason, gamma radiation exposure due to on-site soils was considered negligible in this risk assessment for remediation workers or persons in the surrounding community. However, external gamma radiation exposures were considered when characterizing risks for on-site residents due to their increased exposure times to potentially impacted soils.

Exposure for on-site residents

For future on-site residents, the exposure parameters included inhalation rate, incidental soil ingestion rate, fraction of time spent indoors and outdoors, and exposure duration (Table 5). Exposure parameter values used are consistent with those used by the Navy's contractor and the USEPA in the evaluation of the health-protectiveness of the HPNS remedial goals (Battelle 2019).

The same exposure parameters were also applied to the pre-remediation radiation levels to assess the exposures that may have been experienced by hypothetical on-site residents before remediation.

Exposure for on-site tenants/workers

For the nonresidential on-site tenants/workers, which includes people who worked in various occupations at HPNS, the exposure parameters incorporated in the analysis included inhalation rates, soil ingestion rates, fraction of time spent indoors and outdoors, and exposure duration periods (Table 5). These input parameters were selected to be conservative in order to be applicable to a wide variety of tenants (i.e. police officers, office workers, construction workers, and artists) that worked at HPNS and to encompass the variety of activities (both indoor and outdoor, including afterhours recreation) they may have conducted on-site.

Off-site residents

Given the distance between the site and the nearest residents, the fact that access to the site was restricted prior to and during remediation, and the fact that multiple years of on-site worker dosimeter data showed that all exposures were within background levels, it was concluded that potential gamma exposures to off-site residents would not be different from background levels.

Because the only plausible exposure pathway for off-site residents was inhalation of fugitive dust from the site, air sampling data collected during remediation between 2005 and 2014 and wind data from the same time period were assembled to assess any risks the site may have posed to this population during remediation efforts.

Pre-remediation concentrations of ROCs in soil

Radiological soil survey reports identified which ROCs were present in each of the 1309 soil survey units included in the HPNS soil sample database. Of the 1309 soil survey units, 1.1% had two ROCs, 72.1% had three ROCs, 19.5% had four ROCs, 6.2% had five ROCs, and 1.0% had six ROCs. Only one survey unit had all eight ROCs identified.

Cs-137 and Ra-226 were identified to be applicable as ROCs in the soil of all 1309 survey units. Sr-90 was applicable as an ROC in 1287 survey units. The remaining five ROCs, in decreasing order of frequency of being identified as applicable in soil survey units due to related site operations, were Pu-239 ($n = 343$ surveys units), U-235 ($n = 37$ survey units), Am-241 ($n = 34$ survey units), Th-232 ($n = 29$ survey units), and Co-60 ($n = 17$ survey units).

Table 8 presents the net UCLs calculated for each applicable ROC in soil for each of the parcels in the pre- and post-remediation data sets. This table shows that four ROCs (i.e. Am-241, Co-60, Pu-239, and Th-232) were determined to be at background (i.e. net UCL of zero) for all applicable parcels/sites. The net UCL for Cs-137 was only above background in one of 10 of the

Table 8. Net UCLs for the eight ROCs in the pre- and post-remediation soil at HPNS, by parcel/site.

ROC	Parcel/site	Net UCL (pCi/g)		Remedial goal (pCi/g)
		Pre-remediation	Post-remediation	
Am-241	Parcel E: Base-wide TCRA	0*	0	1.36
	Parcel G	0	0	
Co-60	Parcel B: Base-wide TCRA	0	0	0.0361
	Parcel E: Base-wide TCRA	0	0	
	Parcel G	0	0	
Cs-137	Parcel B: IR-07/18	0	0	0.141
	Parcel B: Base-wide TCRA	0	0	
	Parcel C	0	0	
	Parcel D-1	0	0	
	Parcel D-2	0	0	
	Parcel E: Base-wide TCRA	0.052	0	
	Parcel G	0	0	
	Parcel UC1	0	0	
	Parcel UC2	0	0	
	Parcel UC3	0	0	
Pu-239	Parcel B: IR-07/18	0	0	2.59
	Parcel B: Base-wide TCRA	0	0	
	Parcel C	0	0	
	Parcel D-1	0	0	
	Parcel E: Base-wide TCRA	0	0	
	Parcel G	0	0	
Ra-226	Parcel B: IR-07/18	0.039	0	1 + background
	Parcel B: Base-wide TCRA	0.08	0	
	Parcel C	0.205	0	
	Parcel D-1	0	0	
	Parcel D-2	0.216	0.095	
	Parcel E: Base-wide TCRA	0	0	
	Parcel G	0.154	0	
	Parcel UC1	0.069	0	
	Parcel UC2	0.144	0.046	
	Parcel UC3	0	0	
Sr-90	Parcel B: IR-07/18	0.02	0.009	0.331
	Parcel B: Base-wide TCRA	0	0	
	Parcel C	0	0	
	Parcel D-1	0.042	0	
	Parcel D-2	0	0	
	Parcel E: Base-wide TCRA	0.147	0	
	Parcel G	0	0	
	Parcel UC1	0.105	0.008	
	Parcel UC2	0.135	0.077	
	Parcel UC3	0.063	0.027	
Th-232	Parcel D-1	0	n/a[†]	1.69
	Parcel G	0	0	
U-235	Parcel E: Base-wide TCRA	0	0.015	0.195
	Parcel G	0	0	

Remedial goals at HPNS are shown for comparison.
*Negative net UCLs were set to zero; [†]Th-232 was not analyzed.

parcels/sites for the pre-remediation data and was not above background in any parcels/sites for the post-remediation data (Table 8).

Ra-226 had a net UCL above background soils in seven of ten pre-remediation parcels/sites, and in two of ten post-remediation parcels/sites. Sr-90 was above background in six of ten pre-remediation parcels/sites, and in four of ten post-remediation parcels/sites. U-235 was only found to be slightly above background in the Parcel E base-wide TCRA post-remediation dataset. The maximum net UCL for any ROC in either the pre- or post-remediation datasets was Ra-226 at 0.216 pCi/g (Table 8).

In the pre-remediation soil dataset, only 7.8% of all soil samples had an ROC that exceeded its remedial goal. For the pre-remediation soils data, Ra-226 had the most remedial goal exceedances ($n = 1,138$; 4.5%), and only three of these samples exceeded more than three times the remedial goal, a value which can be considered to represent the range of variability in the background soils. Cs-137 had the second-highest number of remedial goal exceedances ($n = 698$; 2.7%), followed by

Sr-90 ($n = 93$), Co-60 ($n = 55$), U-235 ($n = 3$), and Th-232 ($n = 2$). Neither Am-241 nor Pu-239 exceeded their remedial goals in any of the 50,000 soil samples collected at the site.

Additionally, Figure 13 shows the percentage of soil samples in the pre- and post-remediation datasets that were below the detection limit. Between 37 and 96% of samples were non-detects depending on the ROC in question, with more non-detects in the post-remediation dataset than the pre-remediation dataset. Am-241 was least frequently detected in both the pre- and post-remediation datasets, Th-232 was most frequently detected in the pre-remediation dataset (63%), and Ra-226 was most frequently detected in the post-remediation dataset (59%). It should be noted that for the majority of the ROCs, the percentage of non-detects in the pre- and post-remediation datasets did not differ significantly. Co-60 had the largest difference, with the post-remediation dataset having 17% more non-detects than the pre-remediation dataset, whereas Ra-226 and Am-241 differed by just 1 and 2%, respectively.
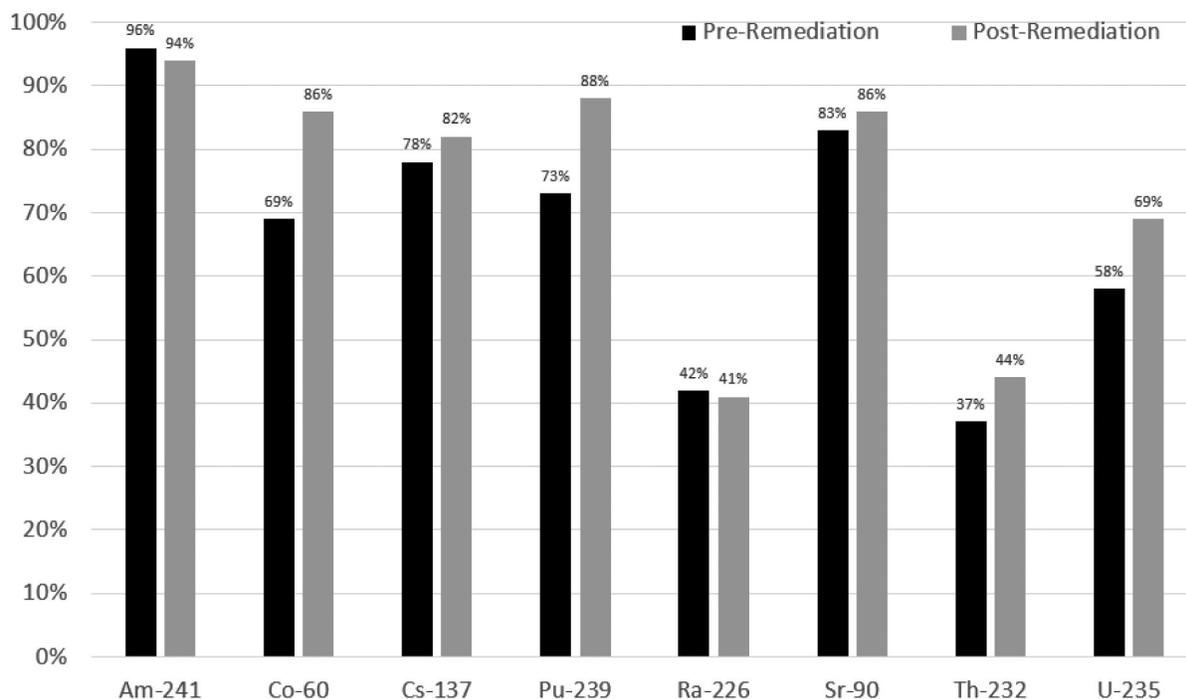
Figure 13. Percentage of non-detects in soil for the eight ROCs identified at HPNS in the pre- and post-remediation datasets.

Post-remediation concentrations of ROCs in soil

With the exception of Ra-226 and Sr-90, post-remediation soil concentrations are nearly identical to the pre-remediation values (Table 8). There was no net change in the pre- and post-remediation UCLs for Am-241, Co-60, Pu-239, or Th-232, and only one insignificant change each for Cs-137 and U-235. In parcel E, the net UCLs pre- and post-remediation for Cs-137 were 0.052 and 0, respectively, and for U-235, the pre- and post-remediation UCLs were 0 and 0.015, respectively. Figure 14 compares the pre- and post-remediation UCLs for Ra-226, which indicates that the pre-remediation Ra-226 net UCLs were larger than the post-remediation UCLs. For Ra-226, this is primarily because post-remediation soil samples were typically analyzed in the off-site laboratory, which used a more precise analytical method with lower detection limits than was used for the pre-remediation soil samples at the on-site laboratory (USN 2018).

This high bias in the pre-remediation Ra-226 net UCLs is consistent with the Navy's statement that 80% of remediated soils were likely mischaracterized as contaminated because of the use of this on-site laboratory screening method to reduce turn-around time for making remedial decisions in the field (USN 2018).

The concentrations of Sr-90 in pre-remediation soils were marginally higher than the post-remediation soil concentrations, as can be seen in Table 8. Differences in the Sr-90 pre- and post-remediation datasets can be explained by the effectiveness of remediation efforts, possible differences in analytical techniques, or some combination thereof.

Analysis of wind patterns around HPNS

The wind data, which was collected from 2005 to 2012, shows that the typical wind direction blew over the HPNS site predominantly from the north-west and west-northwest directions, away from the populated neighborhoods nearest the site (Figure 15). It is important to note that this figure shows the spokes of the wind rose in the direction from which the winds originate. This figure is supported by the findings of the Navy's Technical Liaison for HPNS, Dr. Kathryn Higley, who presented similar data to the Hunters Point Citizens Advisory Committee in October 2021 (Higley 2021).

Risk characterization

Risk characterization for this site involved calculating doses and separate incremental cancer risks for key populations for the relevant routes of exposure and estimated time spent on-site. It should be noted that all incremental cancer risks calculated in this assessment are specific to adult receptors, as children were not generally permitted access to the site prior to remediation, and lifetime risks for children on-site post-remediation would be comparable to the risk values presented.

The USEPA has identified the range of acceptable incremental cancer risk for contaminated sites to be between 10^{-4} and 10^{-6} (NCP 1990). If the population is small, such as 1000 persons, even risks as high as 1 in 1000 have been deemed acceptable (Figure 16). One reason for considering these cancer risks *de minimis* is that approximately 40% of Americans will develop cancer in their lifetime (National Cancer Institute [NCI] 2020). Thus, it is generally accepted that controlling risks at even the 1 in 10,000 level would not significantly adversely impact an individual's overall risk of developing cancer (e.g. 40.0 *vs.* 40.01%).

Despite the fact that there was likely to be a relatively small population who would live on this site, the remedial goal for incremental cancer risk was set at an unusually low level. Beyond this being a small incremental risk, most members of the public are not aware that the LNT model, and many other dose extrapolation approaches for estimating the

Figure 14. Pre- and post-remediation net upper confidence limits (UCLs) of the mean/median soil concentration by parcel/site for Ra-226. Ra-226 was identified as the primary contributor of site-wide radiological risk. All parcels/areas have net UCLs for all radionuclides below 0.25 pCi/g, and there was a significant reduction between pre- and post-remediation net UCLs for Ra-226 in soil.

Figure 15. Wind rose depicting data collected at HPNS from 2005 to 2012. These data show that the wind blows predominantly away from the Bayview Hunters Point community and toward the San Francisco Bay. The spokes of the wind rose show the direction from which the wind originates.

risk of carcinogens, are known to significantly overestimate the true risk. Often the overestimation can be 10- to 100-fold greater than the true risk at low doses (Wolf and Butterworth 1997). For example, an evaluation of methylene chloride indicated that low-dose models, such as the LNT, overpredict the true risk by a factor of at least 100 (Clewell 1995).

When characterizing risk, scientists are regularly asked to put risks into context. Often, they will say that the risk of

Figure 16. Effect of individual vs. population risk on chemical carcinogen regulation. This plot presents the ranges of individual risk levels inherent in various regulatory decisions as a function of the number of exposed persons. Note that when the number of exposed persons is relatively small, the allowable level of exposure increases (Travis et al. 1987). Historically, clean-up levels have been set such that the goal is that less than one person within the exposed community can theoretically be expected to develop cancer after 70 years of exposure. Of the 79 regulatory decisions that this plot addresses, it shows that when the number of estimated cancers per year in the population exceeds 10–100, there is usually regulatory action. When the number of cancers per year predicted by modeling is on the order of 10, there is sometimes regulatory action. When the number of model predicted cancer cases was less than 10, it was never regulated, especially when the exposed population was small. This plot may not reflect decisions made in more recent years.

getting struck by and killed by lightning is about one in one million; this is considered inconsequential, and thus, generally deemed "safe" by most persons (Lowrance 1976). Similarly, the risk of being killed driving 80.5 km is also about one in one million (Corn 1980); however, unlike the risks due to lightning and driving which are based on physical data, the risks due to radiation exposures, as calculated in this risk assessment, are estimates (i.e. theoretical risks) that are meant to not underestimate the true risk and do not necessarily represent fatal risks.

In addition to soil sampling and remediation, a durable cover consisting of either asphalt with an underlying gravel base or soil ranging from two to three feet in depth, was installed at HPNS at parcels B, C, D-1, G, UC1, UC2, and UC3. It will be maintained by the Navy for the foreseeable future (USN 2019). A 2-foot clean soil cover was also placed across the IR-07/18 site after remediation. While the gravel/asphalt durable cover was primarily constructed to prevent human exposure to residual metals that remained in the soils, the cover had the added benefit of preventing exposure to any ROCs which may have remained in soil after the base-wide TCRA w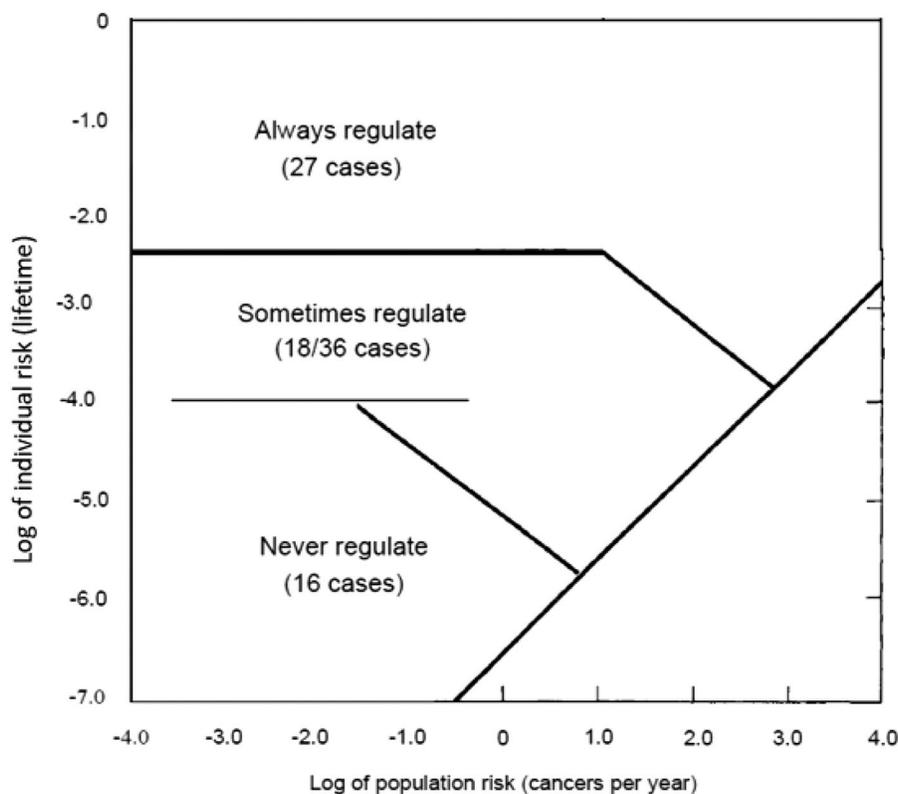as completed. To quantify the effects of this durable cover, the risk was characterized in scenarios both with and without the presence of the protective covers.

In order to estimate the risk to persons on-site, RESRAD-ONSITE modeling with 95% UCL net concentrations for each ROC were used to evaluate three scenarios: 1. Pre-remediation, no durable cover; 2. Post-remediation, no durable cover; and 3. Post-remediation, durable cover. When relevant,

parameters, including cover thickness, density, and area, were input into the RESRAD-ONSITE model to account for the durable cover in the calculation of radiation dose and risk. It should be noted that the risk values for each scenario were calculated using the UCL values which are likely to be conservative (i.e. overestimate true risks). The results are presented below.

Scenario 1 – pre-remediation, no durable cover, nonresidential tenants/on-site workers, and theoretical on-site residents

In this exposure scenario, the predicted cancer risks for pre-remediation were only calculated for the no-cover scenario, as prior to remediation, HPNS had not been fully covered with an added layer of soil or another durable cover material.

Before remediation, the base-wide incremental cancer risk for a nonresidential on-site worker was estimated to be 1.3×10^{-6} (Table 9). For a theoretical on-site resident at pre-remediation conditions, the base-wide incremental cancer risk would have been 3.2×10^{-6} (Table 10). These estimated incremental cancer risks are approximately 230-fold and 100-fold less, respectively, than the cumulative risks associated with the ROC remedial goals (3×10^{-4}). These low-risk values, even prior to remediation, show that incremental cancer risks to theoretical residents or workers on the site prior to remediation would not have exceeded regulatory limits.

Table 9. Pre-remediation risk for nonresidential tenants/on-site workers at HPNS, without durable cover*.

Parcel	Cancer risk	Contaminated portion of parcel (%)	Parcel-weighted cancer risk[†]	ROC contribution (%)
B	4.4×10^{-6}	3.20	1.4×10^{-7}	Ra-226: 100
C	1.2×10^{-5}	5.20	6.2×10^{-7}	Ra-226: 100
D-1	4.9×10^{-9}	9.12	4.5×10^{-10}	Sr-90: 100
D-2	1.2×10^{-5}	0.18	2.2×10^{-8}	Ra-226: 100
E	6.7×10^{-6}	10.99	7.3×10^{-8}	Cs-137: 97.7 Sr-90: 2.3
G	8.6×10^{-6}	3.45	3.0×10^{-7}	Ra-226: 100
UC1	3.7×10^{-6}	0.64	2.4×10^{-8}	Ra-226: 99.7 Sr-90: 0.3
UC2	7.7×10^{-6}	0.42	3.3×10^{-8}	Ra-226: 99.8 Sr-90: 0.2
UC3	1.7×10^{-8}	1.23	2.1×10^{-10}	Sr-90: 100
IR-07/18	2.2×10^{-6}	4.39	9.7×10^{-8}	Ra-226: 99.9 Sr-90: 0.1
Pre-remediation Site-wide[‡]	–	38.82	1.3×10^{-6}	–

*Table shows RESRAD-ONSITE-calculated risks at HPNS for all parcels without protective soil covers, as well as risks for the total area at HPNS. The risk estimates represent the incremental cancer risk attributable to the 95% UCL ROC activity concentrations above background.
[†]Parcel-weighted cancer risk was calculated by multiplying the parcel-specific risks by the ratio of the area of the surveyed portion of the parcel to the area of the total on-land portion of HPNS.
[‡]Pre-remediation site-wide risks were calculated by summing parcel-weighted cancer risks across all parcels.

Table 10. Pre-remediation risk for theoretical on-site residents at HPNS, without durable cover*.

Parcel	Cancer risk	Contaminated portion of parcel (%)	Parcel-weighted cancer risk[†]	ROC contribution (%)
B	1.1×10^{-5}	3.20	3.5×10^{-7}	Ra-226: 100
C	2.9×10^{-5}	5.20	1.5×10^{-6}	Ra-226: 100
D-1	1.1×10^{-8}	9.12	1.0×10^{-9}	Sr-90: 100
D-2	2.9×10^{-5}	0.18	5.2×10^{-8}	Ra-226: 100
E	1.7×10^{-6}	10.99	1.9×10^{-7}	Cs-137: 97.7 Sr-90: 2.3
G	2.1×10^{-5}	3.45	7.2×10^{-7}	Ra-226: 100%
UC1	9.4×10^{-6}	0.64	6.0×10^{-8}	Ra-226: 99.7 Sr-90: 0.3
UC2	1.9×10^{-5}	0.42	8.0×10^{-8}	Ra-226: 99.8 Sr-90: 0.2
UC3	1.7×10^{-8}	1.23	2.1×10^{-10}	Sr-90: 100
IR07/18	5.5×10^{-6}	4.39	2.4×10^{-7}	Ra-226: 99.9 Sr-90: 0.1
Pre-remediation site-wide[‡]	–	38.82	3.2×10^{-6}	–

*Table shows RESRAD-ONSITE-calculated pre-remediation risks at HPNS for individual parcels as well as risks for the total on-land portion of the site that has been remediated to date. The risk estimates represent the incremental cancer risk attributable to the 95% UCL ROC activity concentrations above background.
[†]Parcel-weighted cancer risk was calculated by multiplying the parcel-specific risks by the ratio of the area of the surveyed portion of the parcel to the area of the total remediated on-land portion of HPNS.
[‡]Pre-remediation site-wide risks were calculated by summing parcel-weighted cancer risks across all parcels.

Scenario 2 – post-remediation, no durable cover, nonresidential tenants/on-site workers, and future on-site residents

Scenario 2 evaluated the incremental cancer risk to future on-site workers and residents of the remediated HPNS site, based on post-remediation soil conditions prior to the placement of a durable cover in parcels B, C, D-1, G, UC1, UC2, and UC3.

For this scenario, the post-remediation site-wide incremental cancer risk was estimated to be 6.3×10^{-8} for future on-site residents (Table 11) and 2.6×10^{-8} for future on-site workers (Table 12). Incremental cancer risks for both future on-site workers and residents are greater than 4700- and 11,000-fold less than the remedial goal of 3×10^{-4} that was set by the USEPA for the HPNS site.

Scenario 3 – post-remediation, with durable cover, nonresidential tenants/on-site workers, and future on-site residents

Scenario 3 evaluated the incremental cancer risk to future on-site residents and workers of the remediated HPNS site, based on post-remediation soil conditions assuming that a durable cover is present in parcels/sites B, C, D-1, G, UC1, UC2, and UC3. To understand the impact of placing a durable cover on these parcels, RESRAD-ONSITE calculations were performed which accounted for either a soil or asphalt cover where one currently exists.

For this scenario, the site-wide incremental cancer risk was estimated to be 3.7×10^{-8} for future on-site residents (Table 13) and 1.6×10^{-8} for future on-site workers (Table 14). The durable cover reduced the site-wide incremental cancer risk approximately 2-fold. When the durable cover is considered, the risk to future on-site residents and workers at HPNS are more than 8100-fold and 17,000-fold less, respectively, than the level that the USEPA considers to be acceptable (3×10^{-4}).

Comparing pre- and post-remediation risk values

Figure 17 presents a comparison of the incremental cancer risks to future residents in the pre- and post-remediation scenarios. Additionally, Figure 18 presents a comparison of incremental cancer risks for on-site workers in the pre- and post-remediation scenarios. Based on review of these figures, it is apparent that when a durable cover is considered, the incremental cancer risks due to ROCs in the soil at HPNS are reduced and are well below those considered to be acceptable by the USEPA. In short, although the durable cover was not necessary from the standpoint of the human health risk attributable to ROCs, the addition of the cover provides extra assurance that the HPNS site would be deemed "safe" using any objective measures.

The estimated theoretical incremental cancer risks for on-site workers were consistently lower than the risks for future on-site residents which are often the case when conducting a human health risk assessment at sites similar to HPNS due primarily to lower occupancy times for on-site workers. It is clear from both figures that even prior to remediation, the risks posed by the site were significantly below the acceptable risk

Table 11. Post-remediation risk for on-site residents at HPNS, without durable cover*.

Parcel	Contaminated portion of parcel (%)	Cancer risk	Parcel-weighted cancer risk†	ROC contribution (%)
B	3.20	0	0	–
C	5.20	0	0	–
D-1	9.12	0	0	–
D-2	0.18	1.2×10^{-5}	2.2×10^{-8}	Ra-226: 100
E	10.99	1.4×10^{-7}	1.5×10^{-8}	U-235: 100
G	3.45	0	0	
UC1	0.64	2.1×10^{-9}	1.3×10^{-11}	Sr-90: 100
UC2	0.42	6.2×10^{-6}	2.6×10^{-8}	Ra-226: 99.7 Sr-90: 0.3
UC3	1.23	7.3×10^{-9}	9.0×10^{-11}	Sr-90: 100
IR-07/18	4.39	2.4×10^{-9}	1.1×10^{-10}	Sr-90: 100
Remediated site-wide‡	38.82	–	6.3×10^{-8}	

*Table shows RESRAD-ONSITE-calculated post-remediation risks at HPNS for parcels without a durable cover, as well as risks for the total remediated area at HPNS. The risk values represent the incremental cancer risk attributable to the 95% UCL of the ROC activity concentrations above background.
†Parcel-weighted cancer risk was calculated by multiplying the parcel-specific risks by the ratio of the area of the surveyed portion of the parcel to the area of the total remediated on-land portion of HPNS.
‡Remediated site-wide risks were calculated by summing parcel-weighted cancer risks across all parcels. Zero risk values mean net soil concentrations were zero or negative.

Table 12. Post-remediation risk for on-site workers/nonresidential tenants at HPNS, without durable cover*.

Parcel	Cancer risk	Contaminated portion of parcel (%)	Parcel-weighted cancer risk[†]	ROC contribution (%)
B	0	3.20	0	–
C	0	5.20	0	–
D-1	0	9.12	0	–
D-2	4.9×10^{-6}	0.18	8.8×10^{-9}	Ra-226: 100
E	6.4×10^{-8}	10.99	7.0×10^{-9}	U-235: 100
G	0	3.45	0	–
UC1	8.8×10^{-10}	0.64	5.6×10^{-12}	Sr-90: 100
UC2	2.4×10^{-6}	0.42	1.0×10^{-8}	Ra-226: 99.9 Sr-90: 0.01
UC3	3.0×10^{-9}	1.23	3.7×10^{-11}	Sr-90: 100
IR-07/18	1.0×10^{-9}	4.39	4.4×10^{-11}	Sr-90: 100
Remediated site-wide[‡]	–	38.82	2.6×10^{-8}	–

*Table shows RESRAD-ONSITE-calculated post-remediation risks at HPNS for parcels without a durable cover, as well as risks for the total remediated area at HPNS. The risk values represent the incremental cancer risk attributable to the 95% UCL of the ROC activity concentrations above background.
[†]Parcel-weighted cancer risk was calculated by multiplying the parcel-specific risks by the ratio of the area of the surveyed portion of the parcel to the area of the total remediated on-land portion of HPNS.
[‡]Remediated site-wide risks were calculated by summing parcel-weighted cancer risks across all parcels. Zero risk values mean net soil concentrations were zero or negative.

Table 13. Post-remediation risk for on-site residents at HPNS, with durable cover*.

Parcel	Cancer risk	Contaminated portion of parcel (%)	Parcel-weighted cancer risk[†]	ROC contribution (%)
B	0	3.20	0	–
C	0	5.20	0	–
D-1	0	9.12	0	–
D-2[‡]	1.2×10^{-5}	0.18	2.2×10^{-8}	Ra-226: 100
E[‡]	1.4×10^{-7}	10.99	1.5×10^{-8}	U-235: 100
G	0	3.45	0	–
UC1	1.1×10^{-12}	0.64	7.0×10^{-15}	Sr-90: 100
UC2	8.9×10^{-8}	0.42	3.8×10^{-10}	Ra-226: 99.99 Sr-90: 0.01
UC3	3.8×10^{-12}	1.23	4.7×10^{-14}	Sr-90: 100
IR-07/18	2.2×10^{-14}	4.39	9.7×10^{-16}	Sr-90: 100
Remediated site-wide[¶]	–	38.82	3.7×10^{-8}	–

*Table shows RESRAD-ONSITE-calculated post-remediation risks at HPNS for parcels with a durable cover, as well as risks for the total remediated area at HPNS. The risk estimates represent the incremental cancer risk attributable to the 95% UCL ROC activity concentrations above background.
[†]Parcel-weighted cancer risk was calculated by multiplying the parcel-specific risks by the ratio of the area of the surveyed portion of the parcel to the area of the total remediated on-land portion of HPNS.
[‡]Parcels E and D-2 post-remediation do not have durable covers.
[¶]Remediated site-wide risks were calculated by summing parcel-weighted cancer risks across all parcels.

Table 14. Post-remediation risk for on-site workers/nonresidential tenants at HPNS, with durable cover*.

Parcel	Cancer risk	Contamination portion of parcel (%)	Parcel-weighted cancer risk[†]	ROC contribution (%)
B	0	3.20	0	–
C	0	5.20	0	–
D-1	0	9.12	0	–
D-2[‡]	4.9×10^{-6}	0.18	8.8×10^{-9}	Ra-226: 100
E[‡]	6.4×10^{-8}	10.99	7.0×10^{-9}	U-235: 100
G	0	3.45	0	–
UC1	4.4×10^{-13}	0.64	2.8×10^{-15}	Sr-90: 100
UC2	3.5×10^{-8}	0.42	1.5×10^{-10}	Ra-226: 99.9 / Sr-90: 0.01
UC3	1.5×10^{-12}	1.23	1.8×10^{-14}	Sr-90: 100
IR-07/18	1.1×10^{-14}	4.39	4.8×10^{-16}	Sr-90: 100
Remediated site-wide[¶]	–	38.82	1.6×10^{-8}	–

*Table shows RESRAD-ONSITE-calculated post-remediation risks at HPNS for parcels with a durable cover, as well as risks for the total remediated area at HPNS. The risk values represent the incremental cancer risk attributable to the 95% UCL of the ROC activity concentrations above background. Parcels E and D-2 post-remediation do not have durable covers.
[†]Parcel-weighted cancer risk was calculated by multiplying the parcel-specific risks by the ratio of the area of the surveyed portion of the parcel to the area of the total remediated on-land portion of HPNS.
[‡]Parcels E and D-2 post-remediation do not have durable covers.
[¶]Remediated site-wide risks were calculated by summing parcel-weighted cancer risks across all parcels. Zero risk values mean net soil concentrations were zero or negative.

threshold; that is, safe prior to remediation using the USEPA criterion. This further emphasizes that the time, effort, and capital devoted to remediation efforts were largely excessive.

Off-site risks

To assess off-site risks, the concentration of airborne radioactivity at the HPNS site was evaluated by analyzing paired upwind and downwind air samples that were collected during TCRA remediation activities from 2005 to 2012. If the downwind samples were to show significantly higher radiation levels than their upwind counterparts, it could be concluded that remediation activities resulted in potential exposures to off-site residents. The opposite is also true: that is, if no statistical difference between upwind and downwind radiation was observed, it can be concluded that remediation activities did not result in potential exposures to off-site residents.

Summaries of the air data, by parcel, for alpha and beta air concentrations are presented in Tables 15 and 16, respectively. These tables show that for all of the parcels/areas at HPNS, there were no statistically significant differences between the measured upwind and downwind concentrations of airborne radioactivity. The average upwind alpha concentration was 4.3×10^{-13} µCi/mL, and the downwind average activity concentration was 6.0×10^{-13} µCi/mL, as presented in Table 17. The same table shows the gross beta data, for which the upwind average was 6.0×10^{-13} µCi/mL, and the downwind average was 6.2×10^{-13} µCi/mL (Table 17). Wilcox matched-pairs signed-rank analyses showed that neither the alpha or beta upwind and downwind sample sets were significantly different from one another.

The paired upwind:downwind air data were also compared to the 10% value of the most restrictive DAC, which is the level at which air monitoring and control are required to ensure proper worker safety. A DAC refers to the concentration of a given radionuclide in air which, if breathed by the reference employee for a working year of 2000 h under conditions of light work, results in an intake equal to the annual limit of intake (USNRC 2021a). A list of the DACs and effluent limits for each of the eight ROCs is included in Table 18. The most restrictive DACs were selected for comparison to average upwind and downwind alpha and beta air concentrations for each parcel/site and are presented in Tables 15 and 16, respectively. This analysis showed that for all but one parcel, the average alpha and beta air samples collected during remediation were below 10% of the applicable DAC values. This indicates that dust control measures were effectively implemented when needed during site remediation activities.

Based on all the available information, there are no data which indicate any measurable releases of airborne radiation during operations at HPNS. Results of dust swipe surveys conducted in 46 residences and 31 art studios on former Parcel A-1 concluded that none of the 229 dust swipe results were above the trigger level (i.e. the minimum detectable activity) (CDPH 2019a). Further, available documents indicate that the on-site incinerator did not process radiologically contaminated materials (USN 2004). In brief, because the airborne ROC concentrations downwind of the site were not statistically

Table 15. Summary of results of ten years of airborne dust sampling data for alpha at the HPNS site.

Parcel	Number of pairs	Upwind alpha mean (μCi/mL)*	Downwind alpha mean (μCi/mL)	p	Significant difference (α = 0.05)	Applicable DAC (μCi/mL)†
B	340	4.4×10^{-13}	3.8×10^{-13}	0.110	NO	Ra-226 (3×10^{-10})
C	291	4.7×10^{-13}	4.5×10^{-13}	0.270	NO	Ra-226 (3×10^{-10})
D	15	3.7×10^{-13}	3.4×10^{-13}	0.600	NO	Pu-239 (3×10^{-12})
D-1	968	2.8×10^{-13}	2.6×10^{-13}	0.230	NO	Pu-239 (3×10^{-12})
D-2	15	7.3×10^{-13}	6.2×10^{-13}	0.960	NO	Ra-226 (3×10^{-10})
E	1759	5.1×10^{-13}	5.3×10^{-13}	0.680	NO	U-235 (2×10^{-11})
E-2	304	7.2×10^{-13}	9.0×10^{-13}	0.090	NO	Ra-226 (3×10^{-10})
G	183	2.0×10^{-13}	2.2×10^{-13}	0.490	NO	Ra-226 (3×10^{-10})
IR-07/18	388	3.5×10^{-13}	3.3×10^{-13}	0.800	NO	Ra-226 (3×10^{-10})
UC1	42	3.4×10^{-13}	2.9×10^{-13}	0.080	NO	Ra-226 (3×10^{-10})
UC2	34	4.2×10^{-13}	3.1×10^{-13}	0.002	N/A‡	Ra-226 (3×10^{-10})
UC3	19	1.5×10^{-13}	1.5×10^{-13}	0.290	NO	Ra-226 (3×10^{-10})

The upwind and downwind alpha radiation data are not statistically different. Thus, nearby residents would not have been exposed to airborne dust containing radiation above background.
*To convert to SI units (Bq/mL) multiply μCi/mL by 3.7×10^{4}.
†The most restrictive DAC selected for comparison to the average upwind and downwind air data concentrations for each parcel is the alpha-emitting ROC detected in soil above background at least 1% or more of the time prior to or during remediation.
‡It is noteworthy that for UC2 the alpha concentration downwind is lower than the upwind concentration. This further shows that there was no exposure for off-site residents.

Table 16. Summary of results of 10 years of airborne dust sampling data for beta at the HPNS site.

Parcel	Number of pairs	Upwind beta mean (μCi/mL)*	Downwind beta Mean (μCi/mL)	p	Significant difference (α = 0.05)	Applicable DAC (μCi/mL)†
B	340	5.8×10^{-13}	5.6×10^{-13}	0.190	NO	Sr-90 (2×10^{-9})
C	291	6.8×10^{-13}	6.5×10^{-13}	0.800	NO	Sr-90 (2×10^{-9})
D	15	4.5×10^{-13}	4.3×10^{-13}	0.420	NO	Sr-90 (2×10^{-9})
D-1	968	4.0×10^{-13}	3.7×10^{-13}	0.270	NO	Sr-90 (2×10^{-9})
D-2	15	1.1×10^{-12}	9.7×10^{-13}	0.780	NO	Sr-90 (2×10^{-9})
E	1759	7.1×10^{-13}	7.4×10^{-13}	0.890	NO	Sr-90 (2×10^{-9})
E-2	304	9.7×10^{-13}	1.2×10^{-12}	0.220	NO	Sr-90 (2×10^{-9})
G	183	2.9×10^{-13}	3.2×10^{-13}	0.970	NO	Sr-90 (2×10^{-9})
IR-07/18	388	4.8×10^{-13}	4.6×10^{-13}	0.430	NO	Sr-90 (2×10^{-9})
UC1	42	5.8×10^{-13}	5.0×10^{-13}	0.060	NO	Sr-90 (2×10^{-9})
UC2	34	7.2×10^{-13}	5.4×10^{-13}	0.001	N/A‡	Sr-90 (2×10^{-9})
UC3	19	1.8×10^{-13}	2.1×10^{-13}	0.950	NO	Sr-90 (2×10^{-9})

The upwind and downwind beta radiation data are not statistically different. Thus, nearby residents would not have been exposed to airborne dust containing radiation above background.
*To convert to SI units (Bq/mL) multiply μCi/mL by 3.7×10^{4}.
†The most restrictive DAC selected for comparison to the average upwind and downwind air data concentrations for each parcel is the beta-emitting ROC detected in soil above background at least 1% or more of the time prior to or during remediation.
‡It is noteworthy that for UC2 the beta concentration downwind is lower than the upwind concentration. This further shows that there was no exposure for off-site residents.
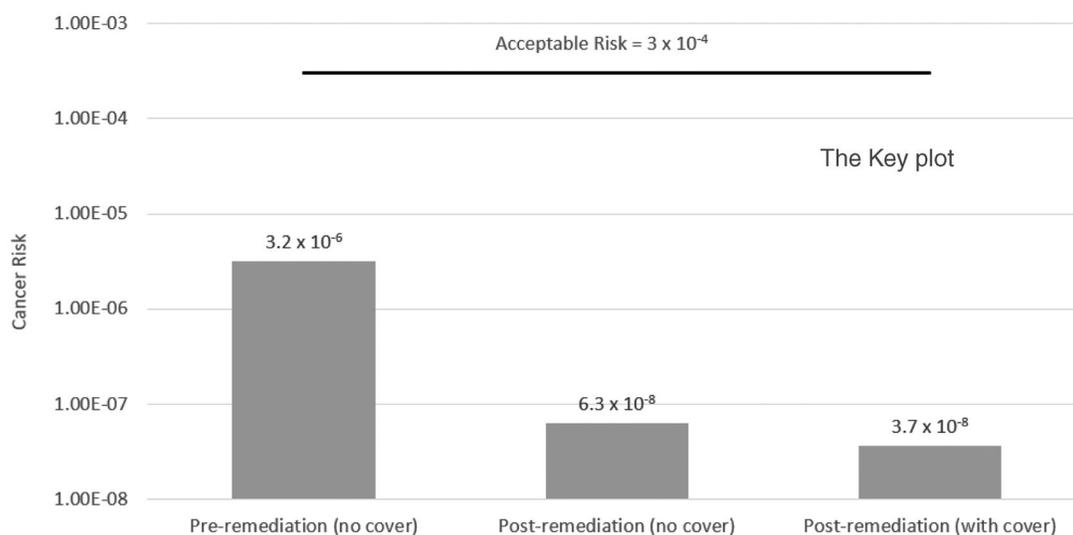
Figure 17. Site-wide pre- and post-remediation estimated incremental cancer risks for future on-site residents. The acceptable risk presented by the line at the top of the figure reflects the acceptable levels of incremental risk for this site (3×10^{-4}) as established by USEPA (2014).
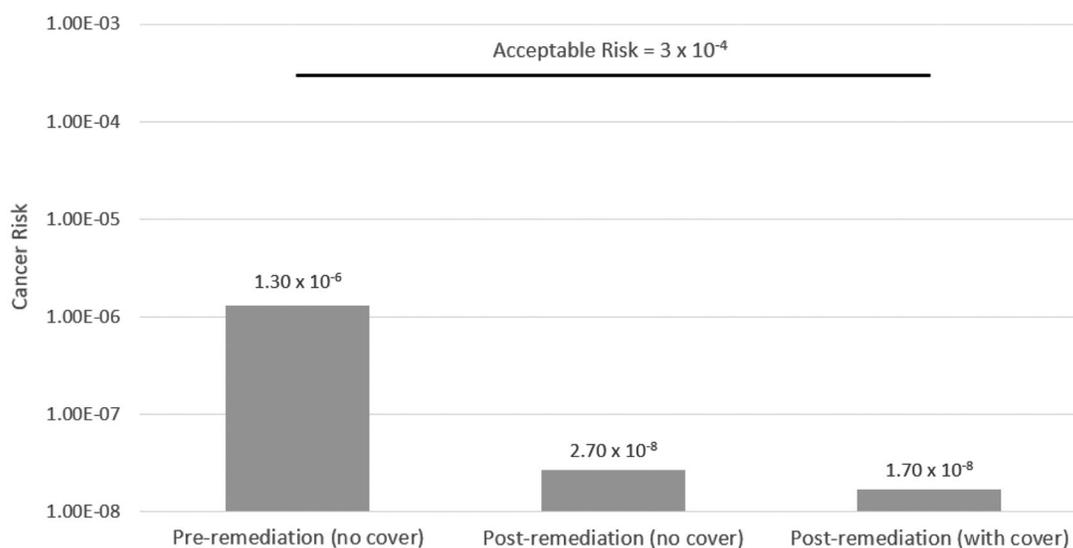

Figure 18. Site-wide pre- and post-remediation estimated incremental cancer risks for nonresidential tenants or on-site workers. The acceptable risk presented by the line at the top of the figure reflects the acceptable levels of incremental risk for this site (3×10^{-4}) as established by USEPA (2014).

Table 17. Average alpha and beta concentrations ($\mu Ci/mL$)* for upwind and downwind airborne dust samples collected from 2005 to 2014 at HPNS.

Radiation type	Upwind concentration ± SD ($\mu Ci/mL$)	Downwind concentration ± SD ($\mu Ci/mL$)	Statistical difference? (p value < 0.05)[†]
Alpha	$4.3 \times 10^{-13} \pm 1.0 \times 10^{-12}$	$6.0 \times 10^{-13} \pm 1.3 \times 10^{-13}$	No
Beta	$6.0 \times 10^{-13} \pm 1.3 \times 10^{-13}$	$6.2 \times 10^{-13} \pm 1.3 \times 10^{-13}$	No

These data include contributions from radon and thoron short-lived decay products, which are not relevant when evaluating potential exposures to ROCs during HPNS remediation because they rapidly decay.
*To convert to SI units (Bq/mL) multiply $\mu Ci/mL$ by 3.7×10^4.
[†]Based on Wilcox matched-pairs signed-rank testing.

different than those present in the upwind samples, it can be concluded that off-site residents have not been exposed to radionuclides from the site due to remediation activities.

Sensitivity analysis of the plausible impact of soil sample substitution

Using the sensitivity analysis approach discussed in the methodology section, even if the upper 95% confidence limit for the upper 95th percentile of the distribution of concentrations (UTL) for the soil samples was substituted into the RESRAD model for 100% of the samples, the incremental cancer risk was found to be 9.2×10^{-6} for on-site residents (Table 19) and 3.6×10^{-6} for on-site workers (Table 20). These incremental cancer risks would not exceed the acceptable level (increased individual risk of 3×10^{-4}) (NCP 1990).

In short, it is implausible that potentially compromised samples would have had an impact on the conclusion that

Table 18. Derived air concentrations (DACs) for occupational exposures and effluent concentration limits for HPNS ROCs*.

Radionuclide	DAC (µCi/mL)[†]	Effluent Limit (µCi/mL)[†]
Ra-226	3×10^{-10}	9×10^{-13}
Th-232	5×10^{-13}	6×10^{-15}
Pu-239	3×10^{-12}	2×10^{-14}
U-235	2×10^{-11}	6×10^{-14}
Sr-90	2×10^{-9}	6×10^{-12}
Cs-137	6×10^{-8}	2×10^{-10}
Am-241	3×10^{-12}	2×10^{-14}
Co-60	1×10^{-8}	5×10^{-11}

*10 CFR 20, Appendix B, Tables 1 and 2.
[†]To convert to SI units (Bq/mL) multiply µCi/mL by 3.7×10^4.

Table 19. Post-remediation risk for on-site residents at HPNS, with durable cover (calculated with UTLs for sensitivity analysis)*.

Parcel*	Cancer risk	Contaminated portion of parcel (%)	Parcel-weighted cancer risk[†]
B	3.3×10^{-6}	3.20	1.1×10^{-7}
C	1.2×10^{-6}	5.20	6.2×10^{-8}
D-1	7.0×10^{-7}	9.12	6.4×10^{-8}
D-2[‡]	1.8×10^{-4}	0.18	3.2×10^{-7}
E[‡]	7.7×10^{-5}	10.99	8.4×10^{-6}
G	6.7×10^{-6}	3.45	2.3×10^{-7}
UC1	1.3×10^{-6}	0.64	8.3×10^{-9}
UC2	1.8×10^{-6}	0.42	7.6×10^{-9}
UC3	1.2×10^{-6}	1.23	1.5×10^{-8}
IR-07/18	1.4×10^{-7}	4.39	6.2×10^{-9}
Remediated site-wide[¶]	–	38.82	9.2×10^{-6}

*Table shows RESRAD-ONSITE-calculated post-remediation risks at HPNS for parcels with a durable cover, as well as risks for the total remediated area at HPNS. The risk estimates represent the incremental cancer risk attributable to the 95% UTL ROC activity concentrations above background.
[†]Parcel-weighted cancer risk was calculated by multiplying the parcel-specific risks by the ratio of the area of the surveyed portion of the parcel to the area of the total remediated on-land portion of HPNS.
[‡]Parcels E and D-2 post-remediation do not have durable covers.
[¶]Remediated site-wide risks were calculated by summing parcel-weighted cancer risks across all parcels.

Table 20. Post-remediation risk for on-site workers/nonresidential tenants at HPNS, with durable cover (calculated with UTLs for sensitivity analysis)*.

Parcel*	Cancer risk	Contaminated portion of parcel (%)	Parcel-weighted cancer risk[†]
B	1.3×10^{-6}	3.20	4.2×10^{-8}
C	5.0×10^{-7}	5.20	2.6×10^{-8}
D-1	2.7×10^{-7}	9.12	2.5×10^{-8}
D-2[‡]	7.2×10^{-5}	0.18	1.3×10^{-7}
E[‡]	3.0×10^{-5}	10.99	3.3×10^{-6}
G	2.3×10^{-6}	3.45	8.1×10^{-8}
UC1	5.3×10^{-7}	0.64	3.4×10^{-9}
UC2	7.1×10^{-7}	0.42	3.0×10^{-9}
UC3	4.8×10^{-7}	1.23	5.9×10^{-9}
IR-07/18	3.5×10^{-8}	4.39	1.5×10^{-9}
Remediated site-wide[¶]	–	38.82	3.6×10^{-6}

*Table shows RESRAD-ONSITE-calculated post-remediation risks at HPNS for parcels with a durable cover, as well as risks for the total remediated area at HPNS. The risk estimates represent the incremental cancer risk attributable to the 95% UTL ROC activity concentrations above background.
[†]Parcel-weighted cancer risk was calculated by multiplying the parcel-specific risks by the ratio of the area of the surveyed portion of the parcel to the area of the total remediated on-land portion of HPNS.
[‡]Parcels E and D-2 post-remediation do not have durable covers.
[¶]Remediated site-wide risks were calculated by summing parcel-weighted cancer risks across all parcels.

incremental cancer risks on-site and off-site at HPNS did not exceed the acceptable level.

The linear no threshold model

Virtually all risk assessments which are intended to characterize possible cancer risk tend to be overly conservative – that is, they are generally believed to overestimate the true cancer risks. This is partially due to the use of a linear no threshold (LNT) dose-response model for estimating radiological risks at low doses. A variation of this model was adopted by the radiological health community in the late-1970s (Crump et al. 1976; Fabrikant 1980). For the information at the time, it seemed logical that the response, even in the low dose region, was linear with no clear threshold where the dose was expected to yield no carcinogenic response.

Later, the Biological Effects of Ionizing Radiation VII (BEIR VII) report stated that the LNT model " … provided the most reasonable description of the relation between low-dose exposure to ionizing radiation and the incidence of solid cancers that are induced by ionizing radiation" (NRC 2006). That report also stated that "At doses less than 40 times the average yearly background exposure (100 mSV [10,000 mrem]), statistical limitations make it difficult to evaluate cancer risk in humans" (NRC 2006).

Regarding their use of the LNT model in the BEIR VII report, the committee stated that " … the health risks of ionizing radiation, although small at low doses, are a function of dose … [and that] the occurrence of radiation-induced cancers at low doses will be small" (NRC 2006). It is important to recognize that from the time the LNT model was used to predict the possible cancer risks of radiation, there has been some level of uncertainty about the accuracy of the model, but, for policy reasons, it was adopted because it was unlikely to underpredict the true risks.

Similarly, the Health Physics Society (HPS), an organization of radiation protection professionals associated with characterizing the hazards of radionuclides, has stated that the risks due to radiation are not statistically different than zero for doses of about 10,000 mrem above background radiation levels (HPS 2013). The society's position statement notes:

> Radiological risk assessment, particularly for radiogenic cancer, currently is only able to demonstrate a consistently elevated risk in the intermediate- and high-dose groups of the studied populations. Cancer and other health effects have not been observed consistently at low doses (<0.1 Gy), much less at even lower doses (<0.01 Gy) typical of most occupational and environmental exposures. (HPS 2013)

Over the past 50 years, the LNT approach has been embraced by some radiation scientists and rejected by others (Abelquist 2019; Brown 2021; Golden 2019; Golden et al. 2019; NRC 2006). In recent years, for non-genotoxic chemicals rather than radiation, many scientists believed that low dose linearity was biologically implausible and, even for ionizing radiation, many have come to doubt that risks are linear in the low dose region (Abelquist 2019; Scott 2018; USEPA 2012). The USEPA has long held that the risks estimated by their models are likely overestimates of the actual risks at low doses and that the true risk may often be zero (USEPA 1995).

Even though the cleanup levels for the soil at this site were based on the model predicted (i.e. theoretical) cancer risks, with the goal of preventing a total incremental cancer

risk for persons to be less than 3×10^{-4}, one must recognize that the selection of a target risk and use of the low dose model are based primarily on regulatory policy. The regulators were aware that the established remedial goals were so low as to be considered "safe" using virtually any definition of the term, and the model and the target risk were considered to represent a reasonable and highly health protective goal that could be agreed upon by the community. It was never believed that the LNT or any other model could accurately predict the cancer risk at HPNS, nor that 3×10^{-4} was the true target cancer risk not to be exceeded. It should be noted again that, except for Ra-226, the remedial goals established for HPNS did not account for background contributions for the remaining ROCs which is against all scientific guidance and applicable regulations intended for decommissioning a radiological site.

Uncertainty analysis for the risk assessment

The data for this site and the analytical approach do not lend themselves to a quantitative uncertainty analysis. All the statistical evaluations indicate that the soil concentrations of radionuclides both before and after remediation were quite low. The number of samples (both soil and air) was sufficiently high that it is extremely unlikely that there is significant uncertainty around the mean concentration of any radionuclide.

It is recognized that quantitative uncertainty analysis has been a topic of interest for 30+ years in the field of health risk assessment (McKone and Bogen 1991; Morgan 1998). The interest generally surrounds the use of environmental fate and transport models, as well as differences in the plausible exposure parameters related to the intake of various media by humans or non-human receptors (Fries and Paustenbach 1990; Finley and Paustenbach 1994; Paustenbach 2000; Linkov and Burmistrov 2003, 2005; Paustenbach and Madl 2023). For example, there was much debate for nearly 30 years about the estimates of the amount of soil ingested by children ages 0–2 and 2–6 (Paustenbach and Langner 1986). Since ingestion as a route of exposure drove soil cleanup at hundreds of sites from 1975 to 2015, many different models for characterizing uncertainty around this important exposure pathway were proposed (Calabrese et al. 1996; von Lindern et al. 2016).

Other exposure pathways that have undergone scrutiny include the amount of soil eaten by cows, turkeys, and deer, the amount of catfish consumed by the human population, and dozens of other routes of exposures to long-lived chemicals like dioxins and furans (Paustenbach 2002; Scott et al. 2009). As discussed previously, none of these are applicable to the HPNS site.

Methods for identifying the optimal cleanup strategy

As scientific methods have advanced over the past 15 years for estimating intake of chemicals *via* various exposure pathways and predicting the risk of low-dose exposures, opportunities to identify the most cost-effective approach for achieving desired site remediation have expanded (Peters et al. 1998; Tompson et al. 1998). During the 1990s and early 2000s, the laptop computer and a myriad of software packages introduced models for low-dose risk and exposure analyses (Higgins et al. 2019; Chatzidiakou et al. 2020). As a result, both the regulatory community and risk assessors expected better decisions regarding remediation efforts and cleanup goals; however, several nonscientific factors, such as the environmental stigma attached to contaminated sites, hampered the effectiveness of incorporating new computing technologies into decision making (Wiltshaw 1998; Zhuang et al. 2016). Decision-making was further hindered by the distrust toward elected officials, regulatory agencies, and the regulated community felt by various stakeholders, who often did not feel part of the decision-making process (Weibel et al. 2020).

Fortunately, it is possible that the general risk assessment approach and the support of decision makers may evolve so that better decisions can be made in the coming years. For example, data-driven and risk-based approaches, which once resulted in conservative goals and high costs, can now be combined with decision-analyses techniques so that remedial alternatives can objectively be compared. A combination of these approaches promotes the selection of remediation measures that are appropriate given the risk tolerance of stakeholders and relevant regulatory standards (Linkov et al. 2014).

Another approach by which risk management and remedial efforts may be improved is the implementation of adaptive management. It is a common misconception that aggressive and expensive remediation strategies are the only way to mitigate human health and environmental damages. As has been discussed by Foran et al. (2015) and Convertino et al. (2013), adaptive management strategies allow remedial efforts to begin with less aggressive measures and then transition to more aggressive efforts (as needed) in order to achieve the desired response (Convertino et al. 2013; Foran et al. 2015). It has been stated that this approach is, "a way to change or update courses of action based on emerging information to improve the outcome and reduce the uncertainty" (Foran et al. 2015). Not only might this approach result in cost savings, but its application can also reduce the time, labor, and resources required in remediation efforts.

Risk communication

Most risk assessments of contaminated sites would not be complete without a discussion of how risk communication is an essential complement to the scientific and remedial work. This risk assessment is no exception – the importance of stakeholder involvement at the HPNS site was as important at this site as most former military or government run sites.

As recently described by Lowrie et al. (2021) over $500 billion have gone toward cleanup of large, contaminated sites owned and/or operated by the U.S. Federal Government over the past 30 years. Nevertheless, some stakeholders worry that even after remediation, there are remaining risks that are worthy of concern. Research has indicated that communication regarding the remediation of these sites has been generally lacking and has often resulted in dissatisfied stakeholders (Charnley and Elliot 2002; Lowrie et al. 2021).

The situation at HPNS is not unlike that described by Lowrie et al. (2021), and similar cases described by other authors who have written on this issue. At least four other studies have been conducted regarding the importance of communication in the remediation process (Chess et al. 1995; Lofstedt 2006; Lyytimaki et al. 2011; Dietz 2013). The historical work on risk communication and perception by Slovic is informative (Kunreuther and Slovic 1996; Slovic 2000, 2002; Slovic and Peters 2006). Since the 1990s, the USEPA has been aware of the challenges in discussing risks due to background concentrations in the environment in communicating with stakeholders (Fowle and Dearfield 2000; USEPA 1997a, 2002, 2018).

The importance of establishing a comprehensive communication plan before beginning site characterization or remediation efforts cannot be overstated. Communication must be multifaceted, and the process should allow for input from potentially affected communities, and as such, a communication plan should include frequent public meetings as well as routine written communications of various forms. It has been stated that, "Public participation in any decision-making process is specific to time, site, and issue. The outcome of a particular participatory process serves only to set context for the assessment in question, not to establish precedent for all assessments" (Turnley 2002).

Questions that arise from within the community need to be quickly, thoroughly, and transparently addressed. Experience has shown that when the community is not involved from the time it is decided that the site should be remediated until the site closure occurs, the stakeholders generally believe that the site was not properly remediated. When this occurs, there can be public demonstrations, lawsuits, and much unfavorable press. The result is often that tens or hundreds of millions of dollars of additional work are piled on top of already expensive cleanup with little or no improvement in protection of public health.

Risk communication could have been better at HPNS just as it could have been at many similar former government sites. For example, in January 2020, an independent panel of scientists from the University of California, San Francisco (UCSF) and the University of California, Berkeley (UCB) issued a report regarding the radiation testing protocols that were being used at the HPNS site (Balmes et al. 2020). Among their findings was that:

> … the committee became aware of the need to improve communications with stakeholders, especially current residents of Parcel A and people living in the Bayview neighborhood. The depth of mistrust toward the US Navy, and increasingly, other government agencies involved, should not be underestimated. Every effort should be made to encourage the Navy to fully inform and engage the community during all stages of the retesting and remediation process. Community access to qualified independent experts would be helpful in this regard. An additional challenge is created by the information communicated to the public by the Navy in flyers with wording such as "no risk to human health" (rather than "no radioactivity detected above baseline levels"). Rather than minimizing risk, the committee advises that public information about risk should be conveyed in a way that is consistent with what the data actually show. (Balmes et al. 2020, p. 6)

When risk communication is properly executed, there is a higher probability that the community will accept the outcome and there is a much lesser likelihood that litigation will ensue. Numerous examples of effective risk communications strategies along with outlined methods for improvement have been published (Covello et al. 2001; Petersen et al. 2002; Slovic 2002; Drew et al. 2003; Drew and Nyerges 2004; Walpole and Wilson 2023).

Conclusion

The HPNS site has been of significant concern to the surrounding community for decades. The community has focused on the history of radiological research at the site and the fact that the extent, distribution, and potential health effects of radioactive contamination at the site had not previously been evaluated. The results from this risk assessment should be helpful to all the various stakeholders who have an interest in the site.

This risk assessment's findings that there is no unacceptable incremental cancer risk to those working on the HPNS site and those living nearby are supported by a series of studies recently conducted by the CDPH and the San Francisco Department of Public Health (SFDPH) (Appendix 3). These studies have found that there was no radiation or health and safety risk to residents or tenants of Parcel A-1 as evaluated from site dust samples (CDPH 2019a) and no external gamma radiation hazards were observed following a gamma radiation survey of all accessible areas of former Parcels A-1 and A-2 (CDPH 2019b, 2019c). Additionally, the SFDPH concluded that Building 606, one of the buildings leased out to on-site tenants, had no potential health hazards associated with former operations at HPNS (SFDPH 2019). The studies also documented no excess cancer cases (for 11 types of cancer) for the period 2008–2012 in female residents of Bayview Hunters Point compared to the greater Bay Area. An increase in lung cancer cases in men was observed along with an increased prevalence of smoking (SFDPH and University of California San Francisco 2019). Additionally, the Navy's Community Technical Liaison for HPNS, Dr. Kathryn Higley, a professor of nuclear engineering at the University of Oregon, has observed that the "…[r]emaining radiological signature across HPNS is so low, it takes a huge effort to even detect its presence" (USN 2019).

For many of the soil samples collected prior to remediation, results were non-detect for some of the eight ROCs. RESRAD-ONSITE analyses of pre-remediation risks indicated that the risks were within acceptable levels, and at 3.2×10^{-6} for theoretical on-site residents (Table 10), they were just above the generally accepted *de minimis* risk threshold of 1×10^{-6} (NCP 1990; Till and Grogan 2008).

The post-remediation risks due to soil ROCs without the existing durable cover are at a level (6.3×10^{-8}) that would be considered negligible according to virtually all regulatory and non-regulatory guidelines in the United States. When the durable cover is taken into account, the incremental radiological risk of 3.7×10^{-8} is more than 18,000-fold less than the radiation risks attributable to background soils in the San Francisco Bay area (2.4×10^{-4}).

Ultimately, this risk assessment concluded that there was no unacceptable increased cancer risk from radiation to on-site workers or residents or to off-site residents from soil or airborne dust associated with activities prior to, during, or after the remediation activities at the HPNS site.

Acknowledgments

Declaration of interest

The research surrounding this manuscript, as well as general consulting services, were funded by Tetra Tech EC, Inc. (TtEC), which is a national firm that has conducted hundreds of cleanups at sites owned by the government and the private sector. TtEC was one of the contractors that performed work at the Hunters Point Naval Shipyard (HPNS) site. TtEC is among several contractors involved in litigation associated with HPNS, including (1) Bayview Hunters Point Residents v. Tetra Tech EC, Inc., et al., (2) Kevin Abbey, et al. v. Tetra Tech EC, Inc. et al., (3) Linda Parker Pennington, et al. v. Tetra Tech EC, Inc., et al., and (4) The United States of America ex rel., Arthur R. Jahr, III, et al., Anthony Smith, & Donald K. Wadsworth et al., v. Tetra Tech EC, Inc. et al. Allegations have been made about the adequacy of the site clean-up, as well as claims of personal injury due to historical exposure to chemicals and radionuclides at the site.

The purpose of the risk assessment was to share information with stakeholders regarding the history of the site, the remediation activities, and the radiological health risks to workers and the community prior to and after remediation. No comprehensive or similar evaluation had been conducted or shared with stakeholders previously. This risk assessment illustrates how to conduct a risk assessment of a radiologically contaminated site, focusing on the importance of conducting a thorough pre-remediation risk assessment, understanding the background concentration of radionuclides in soil, establishing a sampling plan focused on obtaining an understanding of the plausible health risks, conducting a post-remediation assessment, and the role of risk communication with stakeholders. It should help others formulate their approach to assembling and analyzing data at similar former military sites.

This manuscript was the work of Paustenbach and Associates and Dr. Robert Gibbons but, due to the complexity of the issues addressed here, they relied on reports by many site contractors to conduct this analysis (as is customary). Dr. Gibbons is a professor of statistics and was responsible for statistical data analysis. He was not compensated by the University of Chicago for his work on the risk assessment but was compensated by TtEC. Paustenbach and Associates have been consultants to TtEC on this site since 2019. Neither Paustenbach and Associates nor Dr. Gibbons, have been retained by or done any work for any other party but TtEC regarding the HPNS site and they have not consulted in the past with any other party in this litigation.

With respect to the involvement of TtEC and their legal counsel:

1. The paper was proposed by Dr. Paustenbach. Neither TtEC's counsel or TtEC's management requested that this manuscript be prepared or published.

2. At the request of the authors, TtEC's lawyers offered input on an earlier draft of the paper. As is customary, these precautions were taken to ensure the accuracy of facts and avoid inadvertent disclosure of confidential information. TtEC's management and TtEC's lawyers did not read this manuscript prior to publication.

3. Only the authors were aware of all the changes that were required to satisfy the six peer reviewers.

4. Drs. Gibbons and Paustenbach, if there is a trial for this litigation, are likely to provide expert testimony on behalf of TtEC. They will be compensated for their time in a standard and customary manner for this type of litigation.

Paustenbach and Associates paid the publisher $4000 for this manuscript to be open access. It is not known whether TtEC will reimburse them.

The authors are solely responsible for the content of this manuscript.

Supplemental material

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Appendix 1. Historical radiological investigations and remedial activities

The HPNS property was added to the Superfund National Priorities List (NPL) in 1989 pursuant to the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA), as amended by the Superfund Amendments and Reauthorization Act of 1986. This appendix presents a summary of radiological investigations and remedial activities that have been conducted at HPNS. The extensive organic and metals contamination at HPNS, which was the main driver for the site being listed on the NPL, is described in various site reports.

History of pre-CERCLA site investigations and remediation (1946–1980)

Since the beginning of radiological operations at HPNS in 1946, various entities and regulatory agencies have conducted radiological investigations and removal actions to assess and remove residual general radioactive material (G-RAM) resulting from these operations. These early radiological investigations and surveys are described in detail in the 2004 Historical Radiological Assessment Report and are listed in Table 1.1 below. As shown in Table 1.1, the Navy conducted a series of radiological surveys and remedial actions as part of its decommissioning of various buildings at HPNS, and there was regulatory oversight for much of this period.

Phase I radiological investigation (1991)

The Phase I radiological investigation at HPNS was conducted by PRC Environmental Management (1992). It consisted of two components: 1) An airborne survey of baseline alpha/beta radiation prior to remedial investigations and remedial actions, with monitoring locations included in current Parcels A, D-1, D-2, E, E-2, G, and UC3; and 2) Surface Contamination Radiation Surveys (SCRS) of soils to identify potential surficial radiological sources.

The 1991 air survey concluded that airborne particulate alpha and beta levels were similar to San Francisco Bay Area background. According to a 1992 report by PRC Environmental,

> The gross alpha and gross beta airborne particulate concentrations measured at [HPNS] during this study are well below the limiting values for ambient air … The values reported … were typical of background levels observed at many locations in the United States. (PRC Environmental Management and Normandeau Associates 1992).

The SCRS identified several hundred surface gamma anomalies, including gamma-emitting point sources (e.g. discarded deck markers, chips of slag) within the upper six inches of soil at IR-02 (mainly at the IR-02 Northwest area, otherwise referred to as the Bay Landfill). The anomalies were considered an insignificant health hazard to on-site workers due to the depth at which most of the devices or slag were buried and the controls put in place (e.g. fencing) to restrict unauthorized persons from entering the site.

The locations of gamma surface anomalies are shown in Figure 1.1. Over 300 radium-containing devices were discovered at IR-02 in an area of 600 ft by 600 ft. The report stated that during routine maintenance operations on Navy ships and submarines, unserviceable radium-containing devices were removed and disposed of in the IR-01 and IR-02 landfills (PRC Environmental Management 1996).

> The results of the SCRS indicated that (1) that no mixed fission products were detected; (2) radioisotopes other than ^{226}Ra were measured to be within expected background levels in soil samples collected and analyzed; and (3) ^{226}Ra-containing materials are present at the IR-01 and IR-02 landfills, and, to a minor extent, at IR-07 and PA-18 [a/k/a IR-18]. (PRC Environmental Management 1992)

Phase II radiological investigation (1993)

PRC conducted field activities for the Phase II radiological investigation between January and July 1993. This included the excavation of a total of forty-two test pits (15 ft long, 2 ft wide, at least 8 ft deep) and three trenches (100 ft long, 2 ft wide, at least 8 ft deep in parcels IR-01/21, IR-02, and IR-07/18). Most of the test pits and all three trench excavations were done in the IR-02 Northwest area (Bay Landfill). A total of 111 radium-containing devices were found in subsurface soils in twelve test pits and two trenches. Eighty-seven percent of these devices were found in the upper six feet of soil, with the deepest device found at 9 feet below ground surface. Point sources included illuminators, ship instruments, and dials with radioactivity of approximately 1 μCi each (Tetra Tech EC 2007a, 2007b).

Phase III radiological investigation (1996–1997)

Tetra Tech EM Inc. (TtEMI) conducted the Phase III Radiological Investigation with a goal of the eventual release of all buildings and sites in Parcel D and E for unrestricted use. It included surveys at the former NRDL and formerly used defense (FUD) sites (Buildings 351A, 506, 507, 508, 509, 510, 510A, 517, 529, and 707 including the concrete pad area in Parcel E). In addition, surveys were conducted of a low-level radioactive waste (LLRW) storage tank vault at Building 364 in Parcel D, in IR-02 where surfaces were previously inaccessible during the SCRS and tidal/intertidal areas in Parcel E, which the USEPA did not previously survey in 1989. Buildings 351A, 507, 508, 510, and 510A were cleared and released for unrestricted use, while further investigation in Buildings 364, 509, 517, and 707 and the concrete pad was advised. A buried potential point source was discovered behind Building 529 and recommended for removal, while no radioisotopes were detected at the former Building 506 location (TtEMI 1997; USN 2004).

Phase IV radiological investigations (1998–1999)

Relative to the first three radiological investigation phases, Phase IV was a smaller investigation. Phase IV was conducted by TtEMI in 1999 and focused on two areas where anomalies had been previously found:

- The Peanut Cesium Spill area near Building 364, which was previously excavated and sampled by Allied Technology Group (ATG) between 1993 and 1994.
- At the Building 707 concrete pad previously used for drum storage, where several anomalies were detected during the Phase III investigation.

It was determined that neither area (the Peanut Cesium Spill area nor Building 707 pad) posed an unacceptable risk to human health or the environment. The contractor estimated that the maximum incremental cancer risk at these two sites was 1.2×10^{-5}. While it was concluded that there was no unacceptable risk to human health as calculated by RESRAD, CERCLA removal actions were performed at both locations as a conservative measure and to accelerate the property transfers for Parcels D and E for industrial reuse without further consideration of residual radioactivity in property lease, transfer, or land use decisions (TtEMI 2000).

Phase V radiological investigations (2002–2003)

More than 60 Phase V radiological investigations were performed at HPNS at buildings and other areas at HPNS. These investigations involved building interior surveys and soil site surveys. Table 1.2, below, presents a summary of the Phase V investigations by location and action.

Landfill TCRAs (2005–2007)

Several radiological TCRAs were conducted in areas of Parcels E and E-2 between 2005 and 2007, including IR-02 Northwest, the PCB Hot Spot,

Table 1.1. Pre-CERCLA radiological surveys and remedial activities.

Time period	Pre-CERCLA radiological surveys and studies
1946–1948	Radiological Safety Section (RSS) and NRDL surveys and decontamination of Operation Crossroads ships and drydocks
1955	NRDL surveys to decommission NRDL buildings at HPNS
1969	NRDL survey for the disestablishment of the NRDL
1969–1970	Atomic Energy Commission (AEC) survey to verify NRDL's survey results and release buildings for reuse
1974	HPNS survey for base closure
April 1978	LFE Environmental Analysis Laboratories, Inc. (LFE) survey of Building 815
July 1978	RASO survey of Building 815 to confirm LFE survey findings
September 1978	RASO survey of former NRDL buildings
1979	RASO resurvey of Buildings 364, 815, and 816
1986	USEPA harbor survey at Naval Nuclear Propulsion Program (NNPP) request

The Naval Radiological Defense Laboratory (NRDL), Navy contractors, regulatory agencies, and the Radiological Affairs Support Office (RASO) have conducted radiological surveys and studies to evaluate residual radioactive contamination and risks from radiological operations at HPNS through the years (Tetra Tech EC Inc 2006; United States Navy [USN] 2004)
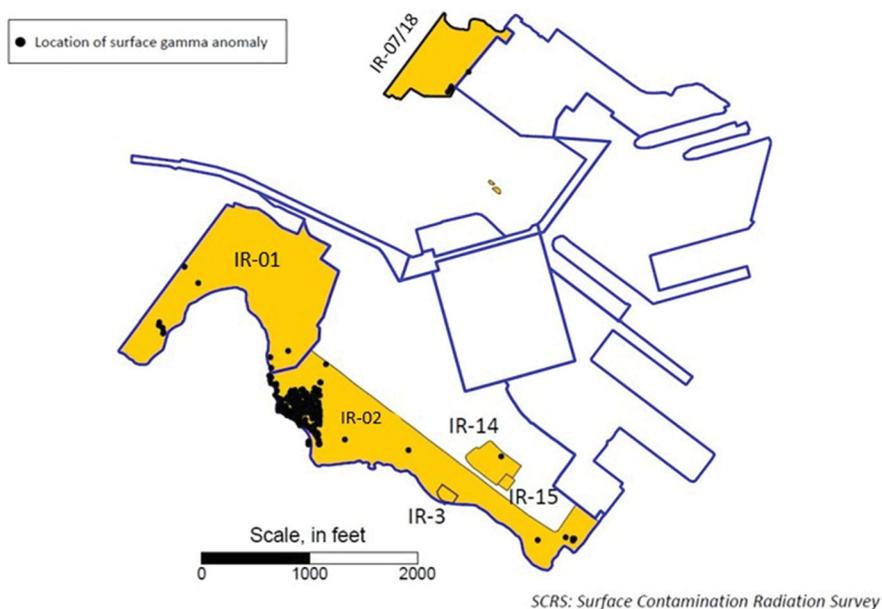

Figure 1.1. 1991–1992 PRC Phase I SCRS Gamma Surface Anomaly Locations. The SCRS identified several surface gamma anomalies, including gamma-emitting point sources (e.g. deck markers) within the upper six inches of soil at IR-02 (mainly at the IR-02 Northwest area, otherwise referred to as the Bay Landfill).

and the Metal Debris Reef/Metal Slag Area. A soil cover was installed at IR-02 Northwest to mitigate risk from any remaining residue below the bottom of the excavated soil.

Base-wide TCRA (2006–2017)

The base-wide TCRA resulted in the collection of tens of thousands of soil samples from current and former buildings, piers, and ship berths, in trench survey units which ranged from approximately one foot to 20 feet in depth, and in excavated soil survey units that were spread out in radiological screening yards after trenches were excavated to support the removal of storm drain and sanitary sewer piping.

One of the main objectives of the base-wide TCRA was the removal of approximately 25 miles of drain and sewer piping because of suspected contamination. There were over 1000 local survey units sampled as part of this removal, with mass removal and disposal occurring where soil exceeded HPNS remedial goals for the ROCs.

In addition to soil sampling and remediation, a durable cover consisting of either asphalt with an underlying gravel base, or a soil cover ranging from two to three feet in depth, was constructed at HPNS in Parcels B, C, D-1, G, UC1, UC2, and UC3. A durable cover will also be constructed

at Parcel E upon completion of remaining soil remediation activities. While this durable cover was or will be primarily constructed for the purpose of preventing human exposure to residual metals that remained in soils, the cover has the added benefit of preventing exposure to any ROCs which may have remained in soil after the base wide TCRA was completed.

IR-07/18 radiological remediation (2010–2012)

The IR-07/18 site underwent radiological remediation between 2010 and 2012. Remedial activities included:

- Removal of debris and sediment from the IR-07 shoreline to allow for construction of a revetment structure.
- Construction of a 1000 linear foot revetment structure along the entire shoreline of IR-07.
- Radiological survey and remediation of the top 12 inches of soil in the upland area of IR-07/18.
- Placement of a 2- or 3-foot-thick soil cover over IR-07/18 where ICs were required, and placement of a 2-inch asphalt layer on top of 4 inches of compacted base material in a small portion of IR-07 where ICs were not required.

Table 1.2. Phase V Action summary of radiological operation at HPNS by new world technologies.

Parcel/area	Action taken
A/Building 821	Class 3 surveys performed. Slightly elevated levels [of ROCs] found in drains. Class 1 surveys performed. No contamination found. Final status survey report submitted and finalized.
B/ Building 103	Class 3 surveys complete. Slightly elevated levels of Cs-137 found under building investigated and found to be below action levels. Final status survey report submitted to RASO.
B/Building 113 IR-42	Class 3 surveys complete. Gamma spectroscopy of concrete, firebrick, and hand kiln samples indicated NORM that did not exceed action levels. Firebricks and hand kiln disposed. Final status survey report submitted to RASO.
B/Building 113 A	Class 3 surveys complete. Thirteen elevated gamma scan locations investigated. NORM below background found. Final status survey report submitted to RASO.
B/Building 130 IR-24	Class 3 surveys complete. Eleven elevated gamma scan locations investigated. NORM below investigation level found and attributed to gravel. Final status survey report submitted to RASO.
B/Building 146 IR-23	Class 3 surveys complete. Twelve elevated gamma scan locations investigated. NORM below action level found. Historical research identified need for Class 1 survey. Report of actions completed submitted to RASO.
B/Drydock 6	Class 3 surveys complete. Ra-226 identified in samples within background range. Final status survey report submitted to RASO.
B/Drydock 6 Sediment	Sediment samples taken from the bottom centerline of drydock at 100-foot intervals along length of the drydock for gamma spectroscopy. Two of these samples were also processed by alpha spectroscopy. No contamination found. Results incorporated into Drydock 6 final status survey report.
C/Building 211	Formerly used for storage of LLRW by NWT. Class 1 and 2 surveys complete. Elevated levels found in area not used for LLRW storage. Report of actions completed submitted to RASO.
C/Building 214 IR-28	Class 3 surveys complete. No elevated levels found. Final status survey report submitted to RASO.
C/Building 224 IR-28	Class 3 surveys complete. Final status survey report submitted to RASO.
C/Building 241	Class 3 surveys complete. Elevated areas found. Firebrick and potassium nitrate removed. Class 1 and 2 surveys complete. No elevated levels found. Final status survey report submitted to RASO.
C/Building 253	Class 3 surveys complete on first through sixth floors. Contamination found and remediated on fifth and sixth floor. Class 1 survey conducted on fifth and sixth floors and roof with additional surveys found contamination throughout building, ventilation shafts, piping, manholes, and on ledge outside of building. Roof and parts of ventilation system remediated. Report of actions completed submitted to RASO.
C/Building 271	Class 3 survey complete. Radium contamination found. Characterization, remediation, and Class 1 complete. Final status survey report submitted to RASO.
C/Building 272	Class 3 survey complete. No contamination found. Final status survey report submitted to RASO.
C/Drydock 2	Seven radium devices found and removed. Class 1 and Class 2 surveys completed of areas with devices. Final status survey report submitted to RASO.
C/Drydock 3	Class 3 surveys complete. Eleven devices removed; Three were Ra-226. Class 1 and Class 2 surveys completed of areas with devices. Final status survey report submitted to RASO.
C/Drydock 4	Class 3 surveys complete. Eleven devices removed; One was Ra-226. Class 1 and 2 surveys completed of areas with devices. Final status survey report submitted to RASO.
D/Building 274 IR-35	Class 3 surveys complete. Investigated seven elevated gamma scan readings. Identified NORM that did not exceed action levels. Final status survey report submitted to RASO.
D/Building 313 Site IR-35	Class 3 surveys complete. Cs-137 contamination above action level found and remediated. Class 1 surveys complete. Final status survey report submitted to RASO.
D/Building 313 A Site IR-35	Class 3 surveys complete. Cs-137 and Eu-152 contamination slightly above action levels found and remediated. Contaminated manhole found (see D/Building 313 A Site Manhole). Class 1 survey complete. Final status survey report submitted to RASO.
D/Building 313 A Site Manhole	Discovered during remediation of Building 313 A site. Manhole no longer connected to any system. Water and sediment removed from manhole. Initial surveys and sampling found elevated readings in sediment and manhole. Sediment removed from manhole. Manhole removed. Class 1 surveys complete. Results incorporated into Building 313 A Site report.
D/Building 322 Site	Class 3 surveys complete. Found Cs-137 and Eu-152 slightly above action levels. Characterization, remediation, and Class 1 survey complete. Final status survey submitted to RASO.
D/Building 351 IR-34	Class 3 surveys complete. Second Class 3 surveys conducted as original background area (Building 411) determined to be impacted site. No contamination found. Final status survey report submitted to RASO.
D/Area Behind Building 351 between Buildings 323 and 324 IR-34	Class 3 surveys complete. Elevated Cs-137 found. Characterization and remediation complete. Class 1 surveys and review of data complete. Final status survey report submitted to RASO.
D/Building 351 A IR-34	Class 3 surveys complete. Contamination identified in crawlspace. See below. Final status survey report submitted to RASO.
D/Building 351 A Crawlspace	Contaminated pipe and soil removed and disposed. Class 1 surveys completed. NWT data review complete. Final status survey report submitted to RASO.
D/Building 364 IR-33	Continuation from prior interim project. Contamination found and remediated. Class 1 survey completed found elevated alpha and beta readings in Room 107 that require remediation. Results provided in report to RASO.
D/Building 364 Crawlspace	Continuation from prior interim project. Contaminated found and remediated. Class 1 survey completed. Final status survey report submitted to RASO.
D/Area behind Buildings 351 A and 364	Continuation from prior interim project. Characterization complete. Cs-137 contamination found and remediated. Investigated void space found at former Building 317 site and found no contamination. Class 1 survey identified additional area of contamination just outside of back steps from Building 351 A. Results reported to RASO in Building 351 A report.
D/Building 364 Trench	Continuation from prior interim project. Cs-137 contamination found. Additional pipe removed and disposed. Class 1 survey found additional elevated levels. Remediation and surveys complete. Results to be incorporated into Building 364 report.
D/Manhole between Building 364/365	Cs-137 contamination found when tracing pipes from Building 364. Scraped and disposed of loose sediment. Elevated levels remain. Manhole sampled. Characterization indicates elevated levels in some manholes and lines. Results to be incorporated into report on sanitary and storm drain systems.
D/Manhole and Sewer Line on Cochrane Street	Manhole surveyed. Contamination found and removed. Sewer lines surveyed. Elevated levels found in lines and manholes. Results to be incorporated into report on sanitary and storm drain systems.

Table 1.2. Continued.

Parcel/area	Action taken
D/Building 365 IR-33	Class 3 surveys complete. No elevated readings found. Final status survey report submitted to RASO.
D/Building 366 (Former Building 351B)	Class 1 surveys complete. Identified contamination in ventilation system and floor drains. Results provided in report to RASO.
D/Building 383	Class 3 surveys complete. No elevated readings found. Safe found containing night vision device with thoriated lens that is being used by San Francisco Police Department. Final status survey report submitted to RASO.
D/Building 411	Class 3 surveys complete. Slightly elevated radium levels found on second floor in two areas. Elevated radium levels investigated and found to be within release limits. Final status survey report submitted to RASO.
D/Gun Mole Pier with Berths 15, 16, 17, 18, 19, and 20	Class 3 surveys complete. Elevated readings found on GMP. Sediment had elevated levels of Cs-137. Remediated areas on GMP-B. Class 1 surveys of remediated areas complete. Final status survey report for selected areas submitted to RASO.
D/Former NRDL Site on Mahan Street	Class 3 surveys complete. Elevated levels of Cs-137 and Ra-226 found. Characterization complete. Elevated readings found. New map located indicating much larger area. Additional characterization complete and reviewed by RASO. Remediation complete. Class 1 surveys complete. Final status survey report provided to RASO.
E/Building 406	Class 3 surveys complete. Elevated levels of Ra-226 found. Characterization and remediation complete. Class 1 surveys complete. Required recounts completed. One area remains to be remediated where a source had leaked onto the wood framing. Results provided in report to RASO.
E/Building 414	Class 3 surveys complete. Included areas under gravel. No elevated levels found. Final status survey report submitted to RASO.
E/Building 506 Site IR-14	Class 3 survey of building footprint complete. No elevated levels found. Historical research indicates need for Class 1 survey of building footprint, and former underground waste tank location outside of building. Results provided in report to RASO.
E/Building 507 Site IR-38	Class 3 survey of building footprint complete. Elevated levels of radium found and remediated. Class 1 surveys of remediated area complete. Historical evidence indicates need for additional Class 1 surveys outside/adjacent to building footprint. Results provided in report to RASO.
E/Building 508 Site IR-38	Class 3 survey of building footprint complete. No elevated levels found. Historical evidence indicates need for Class 1 surveys of site and areas outside/adjacent to building footprint. Results provided in report to RASO.
E/Building 509 Site IR-38	Class 3 survey of building footprint complete. No elevated levels found. Historical evidence indicates need for Class 1 survey of site and areas outside/adjacent to building footprint. Results provided in report to RASO.
E/Building 510/510 A Site IR-14	Class 3 survey of building footprint complete. No elevated levels found. Historical evidence indicates need for Class 1 survey of site and areas outside/adjacent to building footprint. Results provided in report to RASO.
E/Building 517 Site IR-70	Class 3 survey of building footprint complete. No elevated levels found. Historical evidence indicates need for Class 1 survey of site and areas outside/adjacent to building footprint. Results provided in report to RASO.
E/Building 520 Site IR-14	Class 3 survey of building footprint complete. No elevated levels found. Historical evidence indicates need for Class 1 survey of building footprint. Results provided in report to RASO.
E/Building 529 Site IR-14	Class 3 survey of building footprint complete. Historical evidence indicates need for investigation of underground isotope storage facility and Class 1 survey of building footprint. Results provided in report to RASO.
E/Area around Buildings 506, 520, and 529 Sites	Class 3 survey complete. Elevated levels found near foundation of Building 520. Investigation of elevated levels found sand with radium contamination and piping system with cesium contamination. Results provided in report to RASO.
E/Building 701 Site	Class 3 surveys complete. No elevated levels found. Results provided to RASO.
E/Building 707 IR-39	Asbestos removal complete. Surveys complete. Results provided to RASO.
E/Building 707 Concrete Pad	Remediated 3 areas previously. Area mowed and debris removed. Surveys complete. Recounts conducted. Elevated cesium-137 levels found underneath concrete pad. Results provided to RASO.
E/Building 707 Triangle	Area mowed and debris removed. Grids complete. Innovative Technology Solutions, Inc.'s removal of soil from IR-01/21 complete. Surveys complete. Results provided to RASO.
E/Building 707 Drains	Mobilization complete. Started tracing lines. Obstructed lines prohibit surveys internal characterization surveys. Samples show piping to be contaminated. Results provided to RASO.
E/Building 708	Mobilization complete. Asbestos contractor work complete. Surveys complete. No contamination found. Results provided to RASO.
E/Building 810	Class 3 surveys complete. No elevated levels found inside of building. Class 1 survey required as a result of finding contamination on loading dock. Results provided to RASO.
E/Shack 79 Site	Class 3 surveys complete. No elevated levels found. Historical evidence indicates need for Class 1 survey of site. Results provided to RASO.
E/Shack 80 Site	Class 3 surveys complete. Elevated levels of Cs-137 found. Characterization and remediation complete. Class 1 and 2 surveys complete; located additional areas of cesium contamination. Results provided to RASO.
E/IR-01/21 (Includes South Gate Range)	Area moved and gridded. Surveys and sampling complete. Elevated areas identified. Results provided to RASO.
E/IR-04	Surveys complete on original boundary of site. Site boundaries expanded due to elevated readings at original boundary. Contamination found in railroad track areas. Results provided to RASO.

These investigations began in 2003 and consisted of scoping and Characterization Surveys, soil, and other sampling programs, remediations, Final Status Surveys, and sampling in various buildings at HPNS in accordance with MARSSIM guidelines. Each site was assessed for potential radionuclides of concern (ROCs) with surveys designed according to the MARSSIM area classification (Class 1, 2, or 3). The extent of the surveys depended upon the classification of the area (USN 2004)

Appendix 2. Calculation of UCLs and UTLs

Statistical methodology UCLs

The pre- and post-remediation datasets included 25,405 and 23,954 soil samples, respectively, across the ten parcels/sites.

The statistical analysis of these data consisted of two steps:

1. Tests of distributional form; and
2. Development of the parcel/site UCLs for the pre- and post-remediation datasets.

The 95% UCL provides a 95% upper limit for the on-site sample mean for each ROC. The 95% UCL will include the true population mean 95% of the time. Depending on the results of distributional testing and detection frequency, the 95% UCL could be based on a normal, lognormal, or gamma distribution, or a nonparametric alternative (Chebyshev's method).

The tests of distributional form were performed to select the best fitting parametric distribution so that the appropriate form of the UCL was used in the analysis. Ultimately, these were used in the risk assessment computations as the best estimate of the upper bound concentration for the on-site concentration for the parcel/site. To this end, the Shapiro–Wilk (SW) test was used for testing for normality and lognormality and the Empirical Distribution Function Kolmogorov–Smirnov (EDF KS) test was used for testing the fit of a gamma distribution.

These tests are the recommended tests in the USEPA program PRO-UCL. If the detection frequency is less than 50%, nonparametric methods for computing the 95% UCL were used (Chebyshev's method, per PRO-UCL). The same is true for the case when none of the three distributions adequately fit the data. Analyses were performed separately for the pre- and post-remediation datasets.

The aforementioned steps of statistical analysis are outlined below.

1. Test of Distributional Form
   a. Hierarchy: Normal, Gamma, Lognormal, and nonparametric
   b. Require at least 8 detections and detection frequency of 50% or greater (i.e. <50% non-detects) to test distribution
   c. Use detected concentrations only
   d. Use SW test for normal and lognormal
   e. Use EDF KS for gamma
2. Development of the UCL
   a. If no detects use the 95% nonparametric UCL for the median concentration.
   b. If <8 detects use the 95% nonparametric UCL for the median concentration.
   c. If 8 or more detects but a detection frequency of <50%, use the 95% nonparametric UCL for the mean concentration (Chebyshev's method).
   d. If the detection frequency is greater than or equal to 50% (i.e. <50% non-detects) use the 95% UCL for the mean of the best

fitting distribution, using the Kaplan–Meier estimator to adjust for censoring due to non-detects.

PRO-UCL was the statistical software used to conduct these analyses.

Statistical methodology UTLs

To characterize the high end of the concentration distribution, an upper 95% CL for the upper 95th percentile of the concentration distribution was calculated for each ROC. Note that this is statistically equivalent to computing a 95% confidence 95% coverage UTL. In other words, there is 95% confidence that 95% of all measurements drawn from this distribution will be below the UTL. Distributional testing was conducted to select the most appropriate parametric (normal, lognormal, and gamma) or nonparametric UTL for each ROC.

This statistical analysis consists of 2 steps:

1. Tests of distributional form; and
2. Development of the UTLs

The tests of distributional form were performed to select the best fitting parametric distribution so that the appropriate form of the UTL was used in the analysis. To this end, the SW test was used for testing for normality and lognormality and the EDF KS test was used for testing the fit of a gamma distribution. These tests are the recommended tests in the USEPA program PRO-UCL. If the detection frequency is less than 50%, nonparametric methods for computing the UTL were used. The same is true for cases when none of the three distributions adequately fit the data. In computing the sample mean, the Kaplan–Meier method was used to adjust for non-detects.

It can be noted that the test of distributional form and 95% UTLs are of no value when the number of detected concentrations is less than eight. When this is the case, the maximum concentration (which may be a detection limit) is presented.

Note that 59 samples are required to provide a 95% confidence 95% coverage nonparametric UTL. As such, in cases in which the total number of samples for a ROC is less than 59, there will be less than 95% coverage of the entire population. The same is not true for normal, lognormal, or gamma UTLs where the multiplier adjusts for the number of available measurements.

Development of the UTL

a. If no detections use the maximum detection limit.
b. If <8 detects use 95% confidence 95% coverage nonparametric UTL.
c. If 8 or more detects but a detection frequency of <50%, use 95% confidence 95% coverage nonparametric UTL.
d. If the detection frequency is greater or equal to 50% (i.e. <50% non-detects) use the 95% confidence 95% coverage UTL for the best fitting distribution.

Pro-UCL was the statistical software used to conduct these analyses.

Appendix 3. Additional studies

This Appendix provides details on the scope, methods, analyses, and conclusions of a number of studies conducted by other agencies pertaining to the HPNS site. These studies have used a range of methods including dust swipe sampling, gamma radiation surveys, cancer incidence analysis, visual inspection, radiological screening surveys, and air quality measurements, to examine whether there is evidence of increased exposure to radionuclides present at HPNS or in the surrounding community.

While this risk assessment utilized RESRAD-ONSITE modeling based on soil sampling results and a statistical analysis of air samples collected upwind and downwind of remediation efforts, the various approaches of these additional studies all lead to the same conclusion: there is no indication that ROCs at the HPNS site have contributed to an increased radionuclide exposure or to an elevated risk of adverse health effects. In 2019, several evaluations were conducted by the city of San Francisco and the California Department of Public Health (CDPH). These studies were performed in response to community concerns about residual radioactivity at the HPNS site.

"Hunters point naval shipyard, residential dust survey" by the California Department of Public Health (2019)

As stated in the report,

> The [Radiologic Health Branch] RHB was requested by some of the residents of Hunters Point to perform a dust survey of their homes and of the art studios. These residents and artists have concern that dust contaminated from previous radiological work performed by the Navy at Hunters Point Naval Shipyard may have been blown into their homes or the art studios. To ensure the health and safety of the residents at Hunters Point, RHB performed dust surveys for alpha and beta radiation in the homes and studios in areas where outside dust would most likely collect (i.e. window sills, HVAC Vents).

Surveys of such areas allow the analysis to understand $5-40$ years of deposition. The report continues,

> CDPH, over the survey period, conducted surveys in 46 residences and 31 art studios at Hunters Point Parcel A-1. In these 77 survey units, a total of 229 dust swipes were taken. None of the dust swipe results were above the trigger level (minimum detectable activity [MDA]) for either alpha or beta radiation that would require additional investigation. Note that, while the majority of readings were zero, there were some values above zero but below the MDA – these values are not statistically different than zero readings and do not indicate the presence of alpha or beta radiation. Lastly, all results were far below readings that would have indicated any unacceptable cancer risk from the dust.

In conclusion, no radiation or health and safety risk to the residents and artists was identified as a result of the survey (CDPH 2019a).

"Hunters point shipyard, parcel A-1 health and safety survey" by the California Department of Public Health (2019)

In 2019, CDPH staff performed a radiological survey to assess the health and safety of the public and the environment in Parcel A-1. This CDPH survey was limited to investigating ionizing radiation. The report states,

> The CDPH performed this health and safety survey to ensure that residents of Parcel A-1 [were] not exposed to unsafe levels of radiation. This radiation survey of accessible outdoor areas assessed the radiological health and safety of the public and the environment.

The CDPH concluded,

> In total, the radiation survey detected 110 anomalies with 64 from the walkover survey and 46 from the towed array system. All but one [was] determined to be NORM, namely potassium-40. The one exception was a Navy radium-containing deck marker. Upon completion of this radiation survey, no radiological health and safety hazards to the residents of Parcel A-1 were observed.

> The deck marker, which was buried under approximately 10 inches of soil, had a radiation reading of 0.09 mrem/hr on soil surface. Radium is a radioactive substance found in nature and is produced by the radioactive decay of uranium. The amount of radiation output by this deck marker would not have resulted in a health or safety hazard to anyone who happened to be at that spot previously, and radiation readings during and after removal indicated that there was no residual contamination in the soil (CDPH 2019b).

"Hunters point shipyard, parcel A-2 health and safety survey" by the California Department of Public Health (2019)

The CDPH Radiological Branch performed gamma radiation surveys of all accessible areas within Parcel A-2 at HPNS from October to November 2018 and released results in a CDPH report (CDPH 2019c). The survey was conducted by performing gamma-ray scans using highly sensitive, state-of-the-art instruments.

The report states,

> [A] gamma radiation survey of all accessible areas within Parcel A-2 where staff could remain safe while completing accurate and detailed surveys [was performed]. CDPH was able to survey close to 90% of Parcel A-2. This … survey, with isotopic identification performed at locations where elevated readings were detected, was the most effective and efficient method to determine if any sources of radiation from human activity were present and assessed the radiological health and safety of the public and the environment.

The CDPH concluded that no radiological hazards were presently observed at parcel A-2 and stated,

> In total, the radiation survey detected 113 anomalies, 11 from the walkover survey and 102 from the towed array system. All anomalies were determined to be naturally occurring radiological material (NORM), namely potassium-40. (CDPH 2019c).

"Cancer Incidence among residents of Bayview-Hunters point neighborhood, San Francisco, California, 2008 – 2012" by the San Francisco Department of Health (2019)

The San Francisco Department of Public Health (SFDPH) and the Greater Bay Area Cancer Registry (GBACR) at the UCSF conducted a cancer incidence analysis for the Bayview Hunters Point neighborhood for the period of $2008-2012$ after Bayview Hunters Point residents expressed concerns about cancer incidences due to the HPNS site undergoing remediation and restoration work (San Francisco Department of Public Health [SFDPH] and University of California San Francisco 2019).

This analysis offered insight into whether or not an excess of specific types of cancer (myeloma, thyroid, bladder, breast, lung, ovarian, colon, esophageal, stomach, liver, and lymphoma) have occurred in the Bayview and Hunters Point neighborhoods in San Francisco. According to the report,

… The number of cases observed in the designated area during a specified time period is compared to the number of cases expected to have occurred in the area given the number of persons who live there, and the rates of cancer in the Greater Bay Area. In this analysis, cancer registry data were used to determine whether an excess number of cancer cases were diagnosed in residents of the neighborhoods identified as Bayview and Hunters Point, given the expected occurrences of these cancers in the entire Greater Bay Area population. Eleven Census tracts were selected for analysis.

Because populations are enumerated at the census tract level only for decennial censuses, we examined cases diagnosed in the 5-year period surrounding the 2010 Census (2008-2012). Thus, cancer cases of all races/ethnicities and both sexes diagnosed among residents of the identified Census tracts, during the years 2008-2012 were obtained from the GBACR and served as the observed cases. For each cancer site evaluated, the observed number of cases were compared to an expected number of cases. Using the observed and the expected numbers of cases, a standardized incidence ratio (SIR) and 95% confidence intervals (CI) around the SIR were calculated for each cancer site.

The SIR is the ratio of the observed number of cases to the expected number of cases. A SIR greater than 1.0 indicates that more cases were observed than were expected and a SIR less than 1.0 indicates that fewer cancer cases occurred than were expected. The 95% confidence interval determines if the ratio is "statistically significant" (i.e. the difference between observed and expected is unlikely due to chance). The confidence interval assesses the stability of the SIR.

The observed number of cancer cases in persons residing in the Bayview and Hunters Point Census tracts from 2008 to 2012 are presented in Table [4-1]. The cancer sites listed can be linked to radiation exposure according to the American Cancer Society. Many of these sites have other risk factors as well, such as smoking. The total numbers for such cancers by sex are 182 in males and 305 in females. Among males and females, the total observed number of cancers did not differ from the total expected number (SIR = 1.10 for males, and SIR = 1.12 for females). For specific sites, the observed number of male lung cancers was 31% greater than expected (SIR = 1.31).

The number of observed cancer cases in the SFDPH report is presented in Table 3.1.
As reported by the area registry,

Cancer is a complex disease with many different causes, and the reasons why it affects some people and not others are still

Table 3.1. Observed number of cancer cases* in Bayview–Hunters Point Census tracts, by sex, 2008–2012.

Cancer site	Male	Female
Breast	<5	107
Lung	71	51
Colon	37	25
Uterine	NA	29
Thyroid	<5	20
Myeloma	7	8
Bladder	19	9
Ovary	NA	10
Esophageal	<5	<5
Stomach	6	12
Liver	22	11
Lymphoma	15	21
Radiation exposure-linked cancers combined	182	305

*Data are suppressed if the number of cases is less than 5.
NA: not applicable.

poorly understood for many cancers. Oftentimes, it is difficult for epidemiologists to provide answers regarding cancer concerns and perceived cancer clusters. This is, in part, because cancer is a very common disease. Approximately 1 in 2 people will develop some type of cancer in their lifetime, and this estimate continues to rise due to our aging population. A 'true' cancer cluster is rare and might typically involve, (1) more cases (of the same type or similar types) of cancer than expected in a group of people, geographic area and/or period of time, (2) a rare type of cancer, or (3) cases that appear in age groups that might not normally be associated with a certain cancer. Although most cancer clusters occur by chance, it is not uncommon for people to be concerned that cancer clusters are caused by an exposure that occurs or occurred in their environment. However, clusters that are proven to be associated with an environmental or occupational carcinogen are extremely rare. And these would not be identified solely by looking at cancer registry data.

Based on our analysis of cancer registry data, ***there is evidence of an excess number of lung cancer cases among males, but not females, in the Bayview-Hunters Point area of San Francisco between 2008 and 2012.*** There is not evidence of other cancers linked to radiation exposure among males or females. Additionally, there is not evidence of an excess number of all radiation-exposure linked cancers combined, among males or females.

While the findings cannot speak to radiation exposures experienced by the Bayview-Hunters Point residents, they do provide some evidence of an increased incidence of lung cancer, specifically among males. The greatest risk factor for lung cancer is a history of smoking. Data obtained from the ***500 Cities Project: Local Data for Better Health*** shows that some of the Census tracts in the Bayview-Hunters Point area have a higher prevalence of current smoking than in other areas of San Francisco, referencing data from 2016.

Future efforts by the GBACR to address the findings in this report include a second phase of analysis to evaluate lung cancer incidence in the Bayview-Hunters Point neighborhood during earlier time periods surrounding Censal years (1988-1992 and 1998-2002). In addition, any additional data found on smoking rates in this area will be evaluated further" (San Francisco Department of Public Health (SFDPH) and University of California San Francisco 2019).

"Comprehensive Health and safety site assessment report – crime lab and property control warehouse (building 606)" by the San Francisco Department of Public Health (2019)

This SFDPH survey was prompted by employee concerns of occupational exposures while working in the Crime Lab stationed at Building 606 at HPNS. The San Francisco Police Department (SFPD) has occupied building 606, an approximately 80,000 square foot, 2-story space, continuously since 1997.
The report states,

Visual inspection of the interior of Bldg. 606 office/lab spaces did not reveal any observable settled dust/particulate. Some settled dust was observed on the tops of the file cabinets, larger furniture items and on top of lockers in the men's and women's locker rooms. Visible dust and debris were present throughout the warehouse area. No notable odors were observed inside Bldg. 606.

The indoor air quality measurements, overall, were found to be equal to or lower than comparison outdoor levels. Measured indoor air quality parameters were within the normal ranges

according [to] the ANSI/ASHRAE guidelines pertaining to temperature, %RH, CO, and CO_2.

Particulate readings indoors were generally an order of magnitude lower than outdoor comparison readings. Inside Crime Lab/office areas, particle readings are ≤25% of outdoor particle levels. The areas/rooms supplied by HEPA filtered air were roughly ≤5% of outside comparison readings. The HVAC function and efficacy of filtration was confirmed with particle counts and compared to outside samples pre and post sampling. Property Control Warehouse particle readings were, on average, ≤50% of outdoor particle levels.

A radiological screening survey of building 606 was conducted and reported,

The radiological screening survey report concludes that the alpha/beta scans, the gamma scans, and swipe samples collected showed no indication of radiological contamination or other radiological concerns at Bldg. 606. The report indicated that from an occupational health perspective, the working environments at Bldg. 606 are no different than any other publicly-accessible location in the SF Bay Area. (San Francisco Department of Public Health [SFDPH] 2019)