Operational Topic

Facility construction activities can disturb confining layers creating pathways to deeper aquifers.

Monitoring and Remediation of Tritium Contamination in Groundwater at a New Jersey Nuclear Power Plant

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Abstract: *The New Jersey Department of Environmental Protection's (NJDEP) Bureau of Nuclear Engineering (BNE) has an ongoing program to monitor the concentrations of tritium in groundwater associated with leaks from nuclear power plants. Numerous monitoring wells are sampled on a routine basis to monitor the progress of licensee remedial activities and to ensure that off-site groundwater is not impacted by the leaks. The results of this program have demonstrated that off-site groundwater, including drinking water sources, have not been impacted by these leaks, and that ongoing remedial activities have successfully reduced the level of tritium contamination in on-site groundwater. An important lesson learned was that facility construction activities, such as building foundations, buried pipes and tunnels, cofferdams, and sheet piling, disturb confining layers, creating pathways to deeper aquifers. Proper plume characterization must include sampling in the formation to which the contaminant was released, as well as concurrent sampling of the underlying aquifers that were disturbed by facility construction. Health Phys. 128:227–232; 2025*

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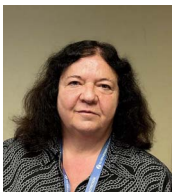
INTRODUCTION

Tritium, which has a half-life of 12.3 years, is a radioactive isotope of hydrogen and is represented by the chemical symbol H-3 or ^{3}H. It is produced in the atmosphere when cosmic rays collide with air molecules (US NRC 2019). As a result, tritium is found in very small amounts in surface water (lakes, streams, ocean), groundwater, and soil throughout the world. Tritium is also a byproduct of commercial nuclear power production and is commonly found in reactor coolant systems. Water containing tritium and other radioactive substances is released under controlled, monitored conditions, during normal operations at a nuclear power plant (US NRC 2019). Tritium emits a weak form of radiation that is a low-energy beta particle. Tritium radiation does not travel very far in the air (US NRC 2019). For this reason, the beta particles emitted by tritium are generally only considered to be hazardous if a significant quantity of tritium is, or has the potential to be, taken into the body through ingestion or absorption. The general public is exposed to extremely low radiation doses from tritium most often when people ingest tritiated water (HPS 2020). Once tritium enters the body it disperses relatively quickly in a uniform manner and settles in the soft tissue. Approximately 50% of tritium is removed through biological processes such as excretion within a month or so after ingestion. A small portion of the dose (~10%) from exposure to tritium comes from a small amount that the body retains as organically bound tritium (US NRC 2019). Organically bound tritium (tritium incorporated in organic compounds) can remain in the body for a longer period of time, potentially delivering additional radiation dose (US EPA 2024). As a low beta emitter, the potential dose from tritiated water is well below the US Nuclear Regulatory Commission's (US NRC) 0.001 Gray (Gy) annual dose limit to members of the public. In fact, the Commission calculated a maximum annual dose of less than 1×10^{-6} Gy to a member of the public from a significant tritiated water spill in Illinois (US NRC 2019).

Most of the tritium produced in nuclear power plants stems from



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the use of boron, which is a good neutron absorber, to help control the chain reactions. Toward that end, boron is added directly to the reactor coolant or used in the control rods to control the chain reaction. Much smaller amounts of tritium could also be produced from the splitting of ^{235}U in the reactor core (US NRC 2019).

Nuclear power plant licensees are required to control and monitor the release of radioactive liquids, such as tritium, to ensure that they remain below regulatory limits and do not pose a threat to public health and safety. In May 2006, US commercial nuclear power plants adopted the Nuclear Energy Institute (NEI) Groundwater Protection Initiative (GPI) to implement voluntary measures to minimize the potential for inadvertent releases of radioactive liquids to the environment and to enhance public trust and confidence in the industry. These measures have been captured in NEI-07-07 (Industry Groundwater Protection Initiative) and identify the actions necessary to implement the GPI in a timely and effective manner. At the same time, the US NRC formed a Liquid Radioactive Release Lessons Learned Taskforce to assess the inadvertent release of radioactive liquids into the environment at power reactor sites (NEI 2019).

Groundwater monitoring at New Jersey's nuclear power plant sites is also performed by the NJDEP as well as the licensee to ensure that the concentration of tritium in onsite monitoring wells does not exceed the New Jersey Groundwater Quality Standard and that there are no public health consequences and no environmental impacts beyond the site boundary of the generating stations.

The NJDEP requires remediation of tritium in groundwater when concentrations exceed New Jersey's Groundwater Quality Standard of 740 Becquerels per Liter (Bq L^{-1}). This Groundwater Quality Standard is the same as the US Environmental Protection Agency (US EPA) health-based Drinking Water Quality Standard. The US EPA chose 740 Bq L^{-1} because this is the average annual concentration that results in a consumer dose of 4.0×10^{-5} Gy y^{-1}.

DISCUSSION

Groundwater monitoring activities at the PSEG Nuclear, LLC (PSEG) Salem Unit 1 Nuclear Generating Station, located in Salem County, New Jersey, on the Delaware River (Fig. 1; NJDEP 2002), have been ongoing since the discovery of tritium contamination in groundwater in 2002. The source of the tritium was a release of contaminated water from the Salem Unit 1 Spent Fuel Pool that had migrated from the seismic gap between the plant's Fuel Handling Building and Auxiliary Building (Arcadis 2003). In 2003, PSEG undertook voluntary remediation of contaminated groundwater in the shallow aquifer. PSEG implemented the activities proposed in the Remedial Action Work Plan, which included hydraulically containing any further migration and reducing the tritium concentration in groundwater through extraction (Arcadis 2004). PSEG began monitoring the tritiated groundwater movement with a monitoring well network at the Salem Unit 1 site. Thirty shallow groundwater monitoring wells were installed to monitor the horizontal migration and to assess the effectiveness of remediation. Four deeper wells were installed to monitor the underlying Vincentown Formation.

Groundwater samples were initially collected on a weekly basis; however, as the number of monitoring wells increased and the analytical history of the individual monitoring wells was established, the sampling program was modified. The monitoring plan evolved to either biweekly, monthly, or quarterly

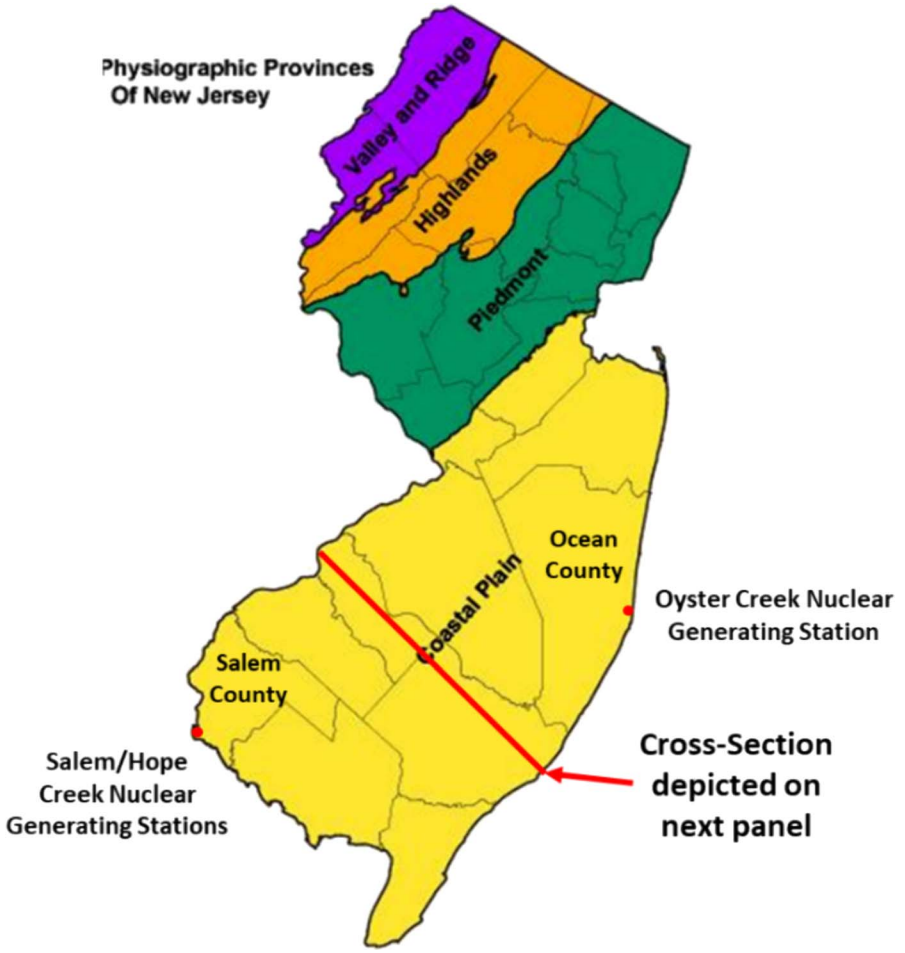

FIG. 1. Map of New Jersey's coastal plain. Source: (NJDEP 2002). New Jersey Geological Survey. https://dep.nj.gov/njgws/.

sampling based upon the analytical history of each well. Current sampling frequency is monthly, quarterly, and semi-annually, based on well-specific criteria for tritium concentrations from three consecutive samples. Monitoring wells are sampled using the low flow purging and sampling techniques described in the NJDEP "Field Sampling Procedures Manual (NJDEP August 2005)."

Groundwater samples were screened by the plant's Station Chemistry Department for radionuclide parameters prior to shipment to the licensee's laboratory, Teledyne Brown Engineering, in Knoxville, Tennessee. The licensee submits split samples from the groundwater monitoring wells to the NJDEP's radioanalytical contract laboratory, GEL Laboratories, LLC (GEL), located in Charleston, South Carolina. The Department's laboratory contractors are required to be certified by the NJDEP Office of Quality Assurance for specific radionuclide parameters, including cesium-134/137, gamma emitters, and tritium. Laboratories must be certified for these parameters by either the NJDEP's Environmental Lab Certification Program (ELCP) or be New Jersey accredited in the National Environmental Laboratory Accreditation Program (NELAP).

NJDEP's split samples were analyzed for tritium using liquid scintillation counting and US EPA Method 906.0: Tritium in Drinking Water (US EPA, EMSL 1980b). Following the installation of each monitoring well, an initial scan for gamma emitting radionuclides using gamma spectroscopy and US EPA Method 901.1: Gamma Emitting Radionuclides in Drinking Water was performed (US EPA, EMSL 1980a). No gamma emitters were ever detected in any of the groundwater monitoring wells. NJDEP's split sample results are made available to the public.

Results from wells in the Upper Shallow Aquifer

Prior to the initiation of remediation, tritium contamination exceeded New Jersey's Groundwater Quality Standard of 740 Bq L^{-1} in 14 of the shallow monitoring wells. As of the first quarter of 2019, only two shallow wells, located close to the source of the leak, exhibited tritium concentrations in excess of 740 Bq L^{-1}. The highest groundwater concentration detected in the pre-groundwater recovery was 5.55×10^5 Bq L^{-1} in Well AC in the immediate vicinity of the leak. The highest groundwater concentration in Well AC in February 2019 was 788 Bq L^{-1}. An estimated 1.2×10^{11} Bq L^{-1} of tritium has been removed from groundwater to date.

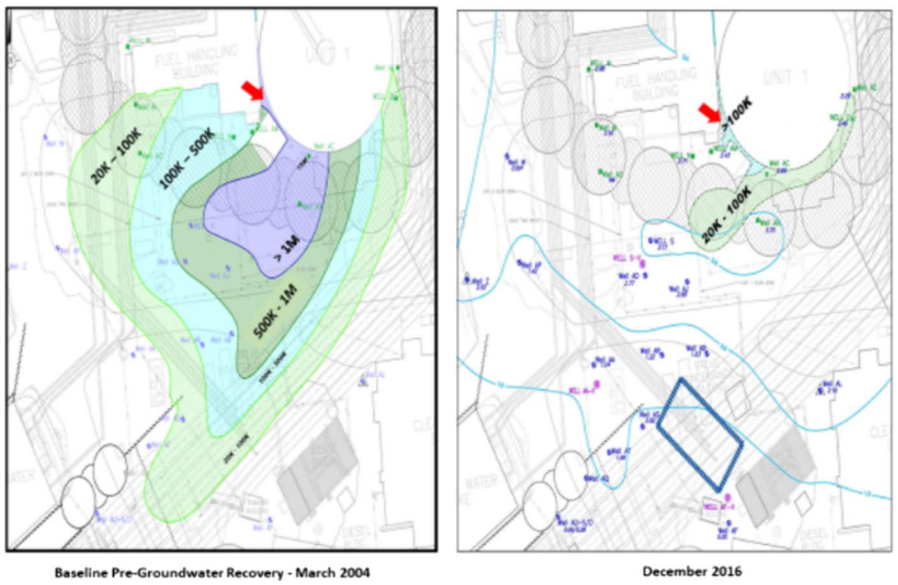

FIG. 2. Progress of remedial action at Salem Unit 1 Nuclear Generating Station. Source: PSEG Nuclear, LLC, 2017 Remedial Action Progress Report (Arcadis 2018).Tritium concentrations are in pCi L^{-1}.

Results from wells in the Vincentown Formation

Concentrations of tritium were only intermittently observed in ground water samples from the five (5) initially installed Vincentown wells. The maximum concentration was 143.19 Bq L^{-1} in 2004 (Well L). As a result of the low concentrations of tritium in these wells, the NJDEP became concerned that the Vincentown Formation wasn't being effectively monitored. Therefore, under the direction of the BNE in 2013, PSEG implemented an enhanced monitoring

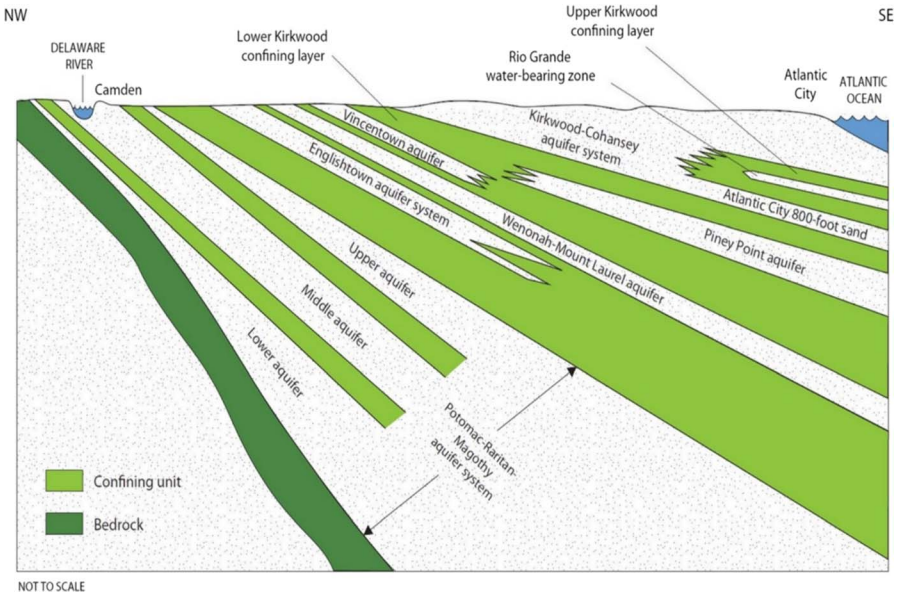

FIG. 3. Layered geology in New Jersey's coastal plain, Source: (NJ Pinelands Commision 2001). https://www.nj.gov/pinelands/science/complete/kc/. Figure derived from U.S. Geological Survey mapping and data.

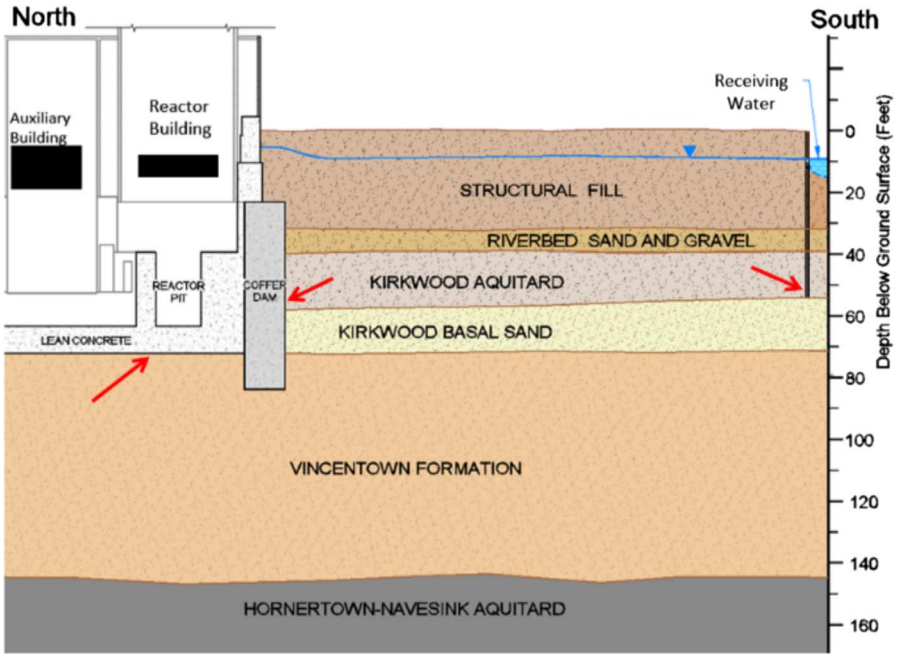

FIG. 4. Layered geology with noted penetrations. Source: PSEG Nuclear, LLC, Remedial Action Progress Report.

program in the deeper aquifer including the installation of several more monitoring wells to help better define the extent of tritium contamination in the Vincentown Formation. Groundwater is extracted from specific wells and discharged into the Delaware River via a permitted pathway where it is diluted with cooling water flow. Groundwater extraction was selected as the remedial strategy in 2005 and continues with the capacity to pump water from six wells.

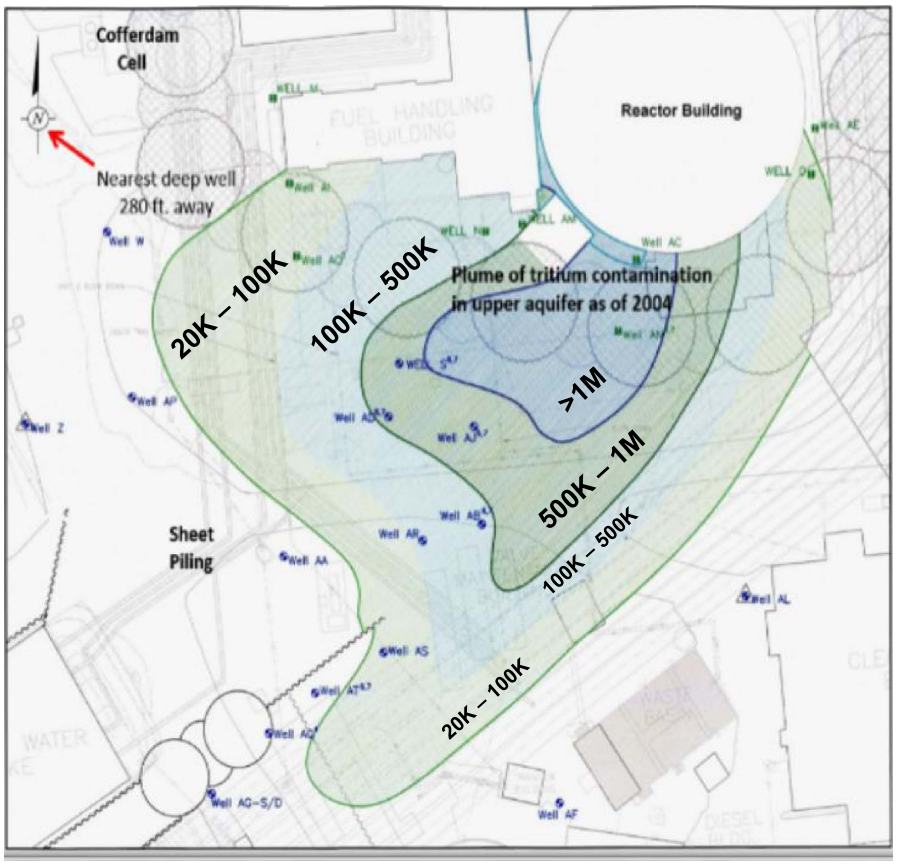

FIG. 5. Plume of tritium contamination in the upper aquifer at Salem Unit 1 Nuclear Generating Station. Source: PSEG Nuclear, LLC, Remedial Action Work Plan (Arcadis 2004). Tritium concentrations are in pCi L^{-1}.

Remediation at Salem Unit 1 Nuclear Generating Station has yielded significant reductions in groundwater tritium concentrations. Fig. 2 shows the groundwater tritium concentrations prior to the initiation of remediation and up through December 2016 (Arcadis 2018). The baseline pre-groundwater recovery concentration map is on the left side of the figure and the 2016 post-groundwater recovery concentration map is on the right. The highest concentration of tritium 5.55×10^5 Bq L^{-1} was detected in Well AC at the time of the discovery of a leak to the groundwater in 2003). This well was reading 1,343 Bq L^{-1} in December of 2016. The leak source is near the 6-inch seismic gap (arrow in Fig. 2). The pathway to on-site groundwater was from spent fuel pool leakage, which flowed through a construction joint into the seismic gap. New Jersey has four nuclear power plants located on the coastal plain (Fig. 1).

The layered geology of the New Jersey coastal plain is characterized by alternating layers of aquifers and confining units (Fig. 3; NJ Pinelands Commssion 2001). The diagram in Fig. 4 depicts the layered geology at the Salem Nuclear Generating Station. Note the penetrations through the confining layer as indicated by the arrows.

At the Salem Generating Station, the groundwater tritium plume from the spent fuel pool leak into the upper aquifer was characterized by 30 groundwater monitoring wells within 2 years. However, the licensee had no deep aquifer wells within the plume area (Fig. 5; Arcadis 2004) in spite of the fact that the building foundations, numerous 60-foot-diameter cofferdam cells, and sheet piling create multiple pathways

through the confining layer to the deeper aquifer.

The first well in the deeper aquifer, within the area of the contaminant plume, was not installed until 10 years after the discovery of the spent fuel pool leak. The mean tritium concentration in the lower aquifer (Well AA-V) between 2013 and 2016 was eight times higher than that of the upper aquifer (Well AA). The rate of downward flow of contaminated groundwater along structures penetrating the confining layer is likely to be much greater than the flow through the undisturbed portions of the formation. See Fig. 6 (Arcadis 2014).

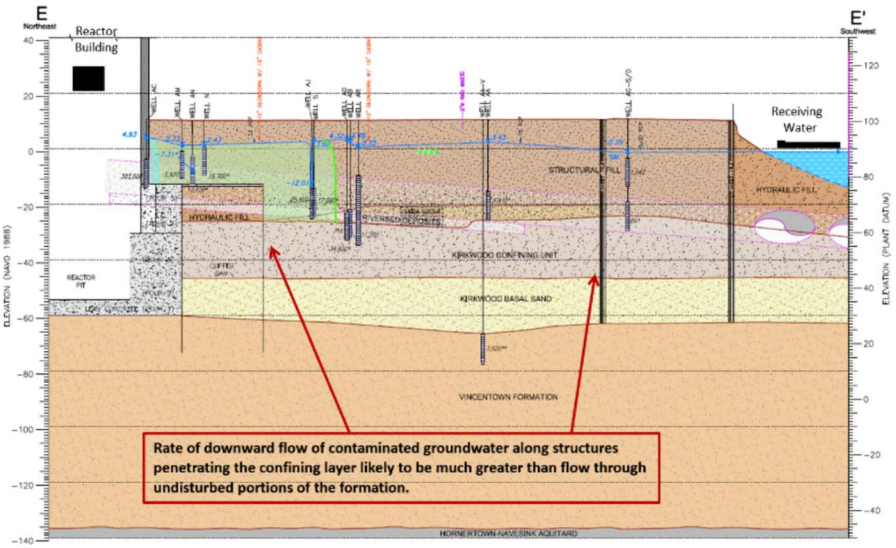

FIG. 6. Downward flow of tritium contamination along structures penetrating confining layer at the Salem Unit 1 Nuclear Generating Station. Source: PSEG Nuclear, LLC, Well AA-V Installation Report (Arcadis 2014).

CONCLUSION

The NJDEP continues to monitor the concentrations of tritium in groundwater associated with the spent fuel pool leak at Salem Unit 1 Nuclear Generating Station through analysis of split groundwater samples and review of PSEG Remedial Action Progress Reports and Quarterly Data submissions. The results of the monitoring program have demonstrated that sources of off-site groundwater, including drinking water sources, have not been impacted by the leak and that ongoing remedial activities have successfully reduced the level of tritium contamination in onsite groundwater.

An important lesson learned was that facility construction activities, such as building foundations, buried pipes and tunnels, cofferdams, and sheet piling, disturb the confining layers, and create pathways to deeper aquifers. These pathways must be considered during the development of the conceptual site model. See Fig. 6 and Fig. 7.

Proper plume characterization must include sampling in the formation to which the contaminant was released as well as concurrent sampling of underlying formations disturbed by facility construction.

While the intent of this paper was to convey that facility construction activities can disturb confining layers creating pathways to deeper aquifers, and remedial actions taken up through 2019, were discussed, it is important to mention the significant progress PSEG continues to make in voluntarily reducing tritium concentrations. Fig. 8 shows the plume of tritium contamination in the upper aquifer at Salem Unit 1 Nuclear Generating Station as of December 2021, reported in the 2022 Remedial Action Progress Report for Salem Generating Station (Arcadis 2023). The highest concentrations of tritium in groundwater have been detected mostly in shallow Well AC, which is screened within the area closest to the spent fuel pool release. Tritium concentrations

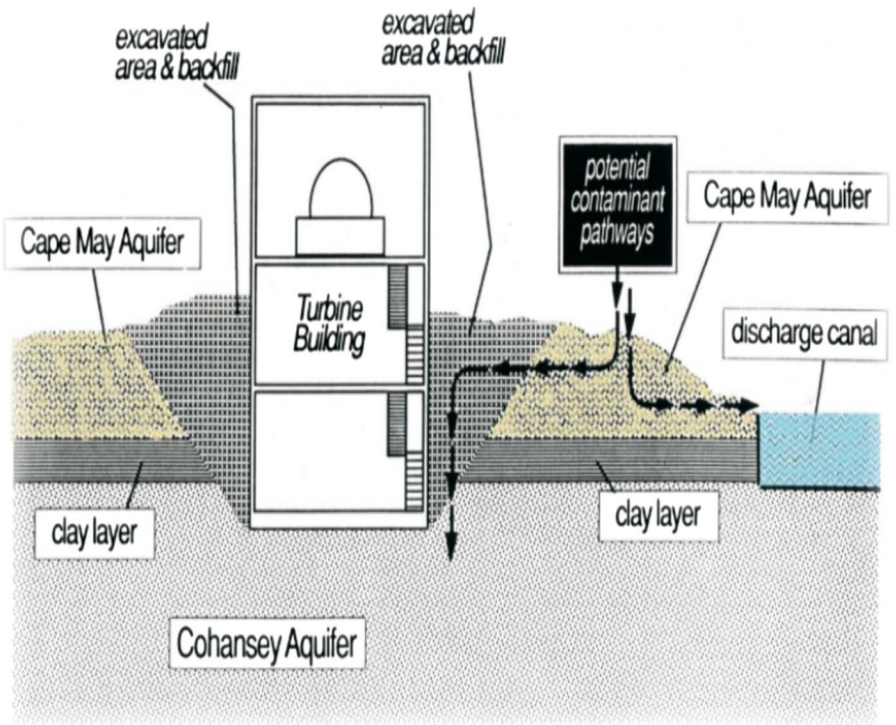

FIG. 7. Facility construction activities require proper plume characterization, Oyster Creek Nuclear Generating Station. Source: NJDEP BNE.

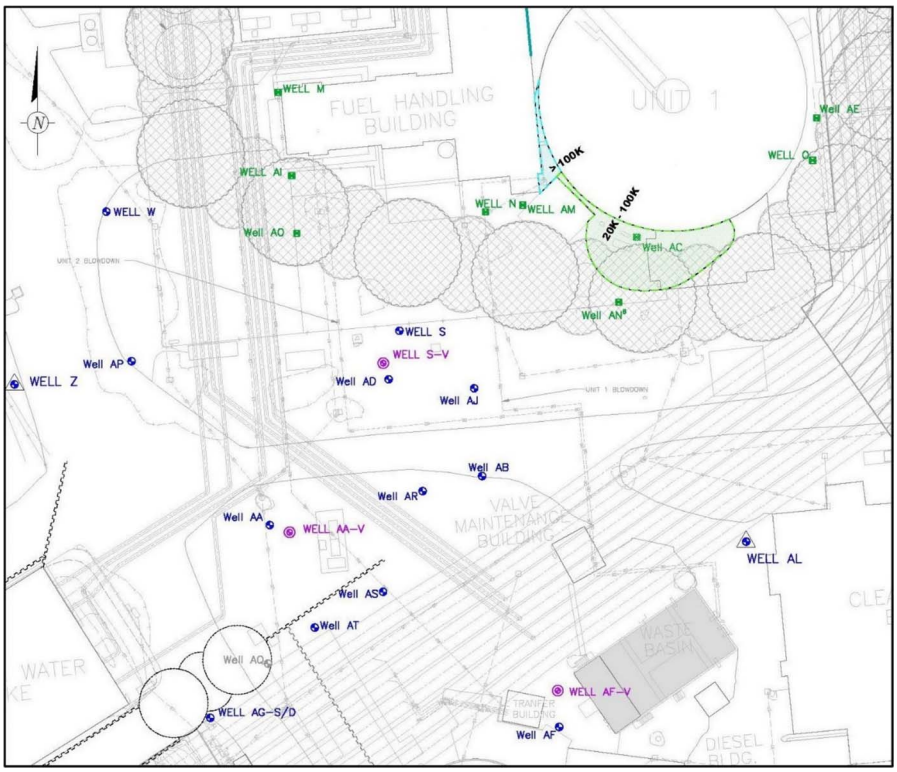

FIG. 8. Plume of tritium contamination in the upper aquifer at Salem Unit 1 Nuclear Generating Station as of 2021. Source: PSEG Nuclear, LLC, Remedial Action Progress Report, December 2022 (Arcadis 2022). Tritium concentrations are in pCi L^{-1}.

detected in Well AC have decreased approximately 99% since the well was installed in 2003. PSEG continues to provide annual Remedial Action Progress Reports and quarterly monitoring well data submissions to the NJDEP.

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