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Mr. Robert Evers
Enercon Services, Inc.
Indian Point Energy Center
450 Broadway
Buchanan, NY 10511-0308

Subject: Hydrogeologic Site Investigation Report
Indian Point Energy Center
Buchanan, New York

Dear Mr. Evers:

GZA GeoEnvironmental, Inc. (GZA) is pleased to provide the attached Hydrogeologic Site Investigation Report for the Indian Point Energy Center. The report provides a summary of the investigative methods, findings/conclusions and recommendations for work conducted from September 2005 through the end of September 2007.

If you have any questions, please contact either David or Matt.

GZA appreciates the opportunity to provide continued support to Enercon Services and Entergy.

Sincerely,

GZA GEOENVIRONMENTAL, INC.

David M. Winslow/MEA

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ACRONYMS

ADT	Aquifer Drilling and Testing
AGS	Advanced Geological Services
ALARA	As Low As Reasonably Achievable
AREOR	Annual Radiological Environmental Operating Report
ATV	Acoustical Televiewer
CSS	Containment Spray Sump
CSB	Chemical Systems Building
CSM	Conceptual Site Model
EPA	Environmental Protection Agency
EVS	Environmental Visualization Software
GA	Geophysical Applications, Inc.
GPR	Ground Penetrating Radar
GZA	GZA GeoEnvironmental, Inc.
IP	Indian Point
IP1-CSB	Indian Point Unit 1 Chemical Systems Building
IP1-FHB	Indian Point Unit 1 Fuel Handling Building
IP1-SFDS	Indian Point Unit 1 Sphere Foundation Drain Sump
IP1-SFPS	Indian Point Unit 1 Spent Fuel Pool
IP1-CB	Indian Point Unit 1 Containment Building
IP2-FSB	Indian Point Unit 2 Fuel Storage Building
IP2-PAB	Indian Point Unit 2 Primary Auxiliary Building
IP2-SFP	Indian Point Unit 2 Spent Fuel PoolS
IP2-TB	Indian Point Unit 2 Turbine Generator Building
IP2-TY	Indian Point Unit 2 Transformer Yard
IP2-VC	Indian Point Unit 2 Vapor Containment
K	Hydraulic Conductivity
NGVD 29	National Geodetic Vertical Datum of 1929
NYSDEC	New York State Department of Environmental Conservation
MGM	Million Gallons per Minute
MNA	Monitored Natural Attenuation
MW	Monitoring Well
NEI	Nuclear Energy Institute
NCD	North Curtain Drain
NRC	Nuclear Regulatory Commission
OCA	Owner Controlled Area
OTV	Optical Televiewer
RWST	Reactor Water Storage Tank
RQD	Rock Quality Designation
SFDS	Sphere Foundation Drain Sump
SFP	Spent Fuel Pool
SOP	Standard Operating Procedure
SSC	Structures, Systems and Components
TGB	Turbine Generator Building
TY	Transformer Yard
USGS	United States Geological Survey
VC	Vapor Containment

EXECUTIVE SUMMARY

This report presents the results of a two-year comprehensive hydrogeologic site investigation of the Indian Point Energy Center (Site) conducted by GZA GeoEnvironmental, Inc. (GZA). The study was initiated in response to an apparent release of Tritium to the subsurface, initially discovered in August of 2005 during Unit 2 construction activities associated with the Independent Spent Fuel Storage Installation Project. These investigations were subsequently expanded to include areas of the Site where credible potential sources of leakage might exist, and encompassed all three reactor units. Ultimately, these investigations traced the contamination back to two separate structures, the Unit 2 and Unit 1 Spent Fuel Pools (SFPs). The two commingled plumes, resulting from these SFPs releases, have been fully characterized and their extent, activity and impact determined. The two primary radionuclide contaminants of interest were found to be Tritium and Strontium. Other contaminants, Cesium, Cobalt, and Nickel, have been found in a subset of the groundwater samples, but always in conjunction with Tritium or Strontium. Therefore, while the focus of the investigation was on Tritium and Strontium, it inherently addresses the full extent of groundwater radionuclide contamination. The investigations have further shown that the contaminated groundwater can not migrate off-property to the North, East or South. The plumes ultimately discharge to the Hudson River to the West.

Throughout the two years of the investigation, the groundwater mass flux and radiological release to the Hudson River have been assessed. These assessments, along with the resulting Conceptual Site Model, have been used by Entergy to assess dose impact. At no time have analyses of existing Site conditions yielded any indication of potential adverse environmental or health risk. In fact, radiological assessments have consistently shown that the releases to the environment are a small percentage of regulatory limits.

SOURCES OF CONTAMINATION

As stated above, the investigations found that the groundwater contamination is the result of releases from the Unit 2 and the Unit 1 SFPs. Our studies found no evidence of any release from Unit 3.

The predominant radionuclide found in the plume from the Unit 2 SFP pool is Tritium. The releases were due to: 1) historic damage in 1990 to the SFP liner, with subsequent discovery and repair in 1992; and 2) a weld imperfection in the stainless steel Transfer Canal liner identified by Entergy in September 2007, and repaired in December 2007. To the extent possible, the Unit 2 pool liner has been fully tested and repairs have been completed. The identified leakage has therefore been eliminated and/or controlled by Entergy. Specifically, Entergy has: 1) confirmed that the damage to the liner associated with the 1992 release was repaired by the prior owner and is no longer leaking; 2) installed a containment system (collection box) at the site of the leakage discovered in 2005, which precludes further release to the groundwater; and 3) after an exhaustive liner inspection, identified a weld imperfection in the Transfer Canal liner that was then prevented from leaking by draining the canal. The weld was then subsequently repaired by Entergy in mid-December 2007. Therefore, all identified Unit 2 SFP leaks have been addressed. Water likely remains between the Unit 2 SFP stainless steel liner and the concrete walls, and thus additional active leaks can not be completely ruled out. However, if they exist at all, the data indicate they must be small and of little impact to the groundwater.

The Unit 1 plume is characterized by Strontium from legacy leakage of the Unit 1 fuel pools. At present, the Unit 1 pools have been drained with the exception of the Unit 1 West Fuel Pool which still contains spent fuel. This West Pool leaks water under the fuel building and is responsible for the Unit 1 Strontium groundwater plume discovered in 2006. Prior to that time, the previous owner had identified leakage from the West Fuel Pool in the 1990's and was managing the leakage by collecting it from a re-configured footing drain that surrounded the fuel building. However, based on the groundwater investigation, it has been determined that the pool leakage management program was not successful in collecting all of the leakage. As a result, uncollected contaminants released from the Unit 1 Spent Fuel Pools, past and present, have been observed during the groundwater investigation effort at various locations near the site of Unit 1. In response to the finding that the leak collection system was not functioning as believed, Entergy promptly initiated a program to reduce the concentration of radionuclides in the Unit 1 West Pool's water, beginning in April 2006, via enhanced demineralization water treatment. The planned fuel removal and pool draining will completely eliminate this release source by year end 2008.

EXTENT OF CONTAMINATION

The groundwater contamination is, and will remain, limited to the Indian Point Energy Center property, because the migration of Site contaminants is controlled by groundwater flow, which, in turn, is governed by the post-construction hydrogeologic setting. Plant construction required reduction in bedrock surface elevations and installation of foundation drains. These man-made features have lowered the groundwater elevations beneath the facility, redirecting groundwater to flow to the West towards the Hudson River; and not to the North, East or South. Because of the nature and age of the releases, groundwater contaminant migration rates, and interdictions by Entergy to eliminate/control releases, the groundwater contaminant plumes have reached their maximum spatial extent and should now decrease over time.

LONG TERM MONITORING

Long term groundwater monitoring is ongoing; a network of multi-level groundwater monitoring installations has been established at the facility. These "wells" are located downgradient of, and in close proximity to, both existing and potential release locations. Groundwater testing is performed quarterly on the majority of these wells, with the rest remaining on standby to provide added detail, if required. The resulting information is provided on a yearly basis to the Nuclear Regulatory Commission

(NRC). The information is used to assess changes in groundwater relative to dose impact assessment and to detect future releases, should they occur.

In addition to the groundwater samples from the network of monitoring wells, Entergy obtained various off-Site samples of environmental media including off-Site wells, reservoirs and the Hudson River. In addition, Entergy participated in a fish sampling program with the NRC and New York State Department of Environmental Conservation (NYSDEC). None of the samples analyzed, including the samples split with regulatory agencies, detected any radioactivity in excess of environmental background levels.

GZA believes that the recommended remediation technology discussed below will cause the concentrations of radionuclides in the groundwater plumes to decrease over time. The continued monitoring of groundwater is expected to demonstrate that trend and support the conclusion that the identified leaks have been terminated. However, GZA expects that contaminant concentrations will fluctuate over time due to natural variations in groundwater recharge and that a potential future short term increase in concentrations does not, in and of itself, indicate a new leak. It is further emphasized that the groundwater releases to the river are only a small percentage of the regulatory limits, which are of no threat to public health.

PROPOSED REMEDIATION

GZA has recommended the following corrective measures to Entergy, which they are implementing:

1. Repair the identified Unit 2 Transfer Canal liner weld imperfection (completed December 2007).
2. Continue source term reduction in the Unit 1 West Pool via the installed demineralization system (ongoing until completion of No. 3 below).
3. Remove the remaining Unit 1 fuel and drain the West Pool (in-process).
4. Implement long term groundwater monitoring (in-process).

The proposed remediation technology is source elimination/control (Nos. 1 and 3 above) with subsequent Monitored Natural Attenuation, or MNA. MNA is a recognized and proven remedial approach that allows natural processes to reduce contaminant concentrations. The associated monitoring is intended to verify that reductions are occurring in an anticipated manner. The Indian Point Energy Center Site is well suited for this approach because: 1) interdictions to eliminate or reduce releases have been made; 2) the nature and extent of contamination is known; 3) the contaminant plumes have reached their maximum extent; and 4) the single receptor of the contamination, the Hudson River, is monitored, with radiological assessments consistently demonstrating that the releases to the environment are a small percentage of regulatory limits, and no threat to public health or safety.

1.0 INTRODUCTION

This report presents the results of hydrogeological studies performed by GZA GeoEnvironmental, Inc. (GZA) at the Indian Point Energy Center (IPEC) in Buchanan, New York (Site). See **Figure 1.1**[1] for a Locus Plan. The report was prepared by GZA under the terms of an agreement with Enercon Services, Inc. for Entergy Nuclear Northeast, and describes services completed between September 2005 (the beginning of our services) and September 2007.

Our investigations were conducted in a cooperative and open manner. Entergy provided full and open access and there were regular and frequent meetings with representatives of the United States Nuclear Regulatory Commission (NRC), the United States Geological Survey (USGS), and the New York State Department of Environmental Conservation (NYSDEC). Further, we presented our preliminary findings at a number of external stakeholder and public meetings.

From the onset of the investigations, GZA routinely computed the groundwater mass flux[2] and associated radiological release to the Hudson River. Using these data, the potential impacts of releases to the river were assessed by Entergy and compared to existing regulatory thresholds. At no time did these analyses yield any indication of potential adverse environmental or health risk as assessed by Entergy as well as the principal regulatory authorities. In fact, radiological assessments have consistently shown that the releases to the environment are a small percentage of regulatory limits, and no threat to public health or safety. In this regard, it is also important to note that the groundwater is not used as a source of drinking water on or near the Site.

This report documents two years of comprehensive hydrogeological investigations. The text of the report describes Site conditions, GZA's investigations, and findings, and presents conclusions and recommendations. Supporting information is provided in tables, on figures and in appendices. To understand how we formed our opinions, it is important to review the report in its entirety, including **Appendix A** Limitations.

1.1 PURPOSE

The overall purpose of our services was to identify the nature and extent of radiological groundwater contamination that originates at IPEC, and assess the hydrogeological implications of that contamination. More specifically, our objectives were to:

- Identify the nature and extent of radiological groundwater contamination;
- Establish the sources of the radiological groundwater contamination;

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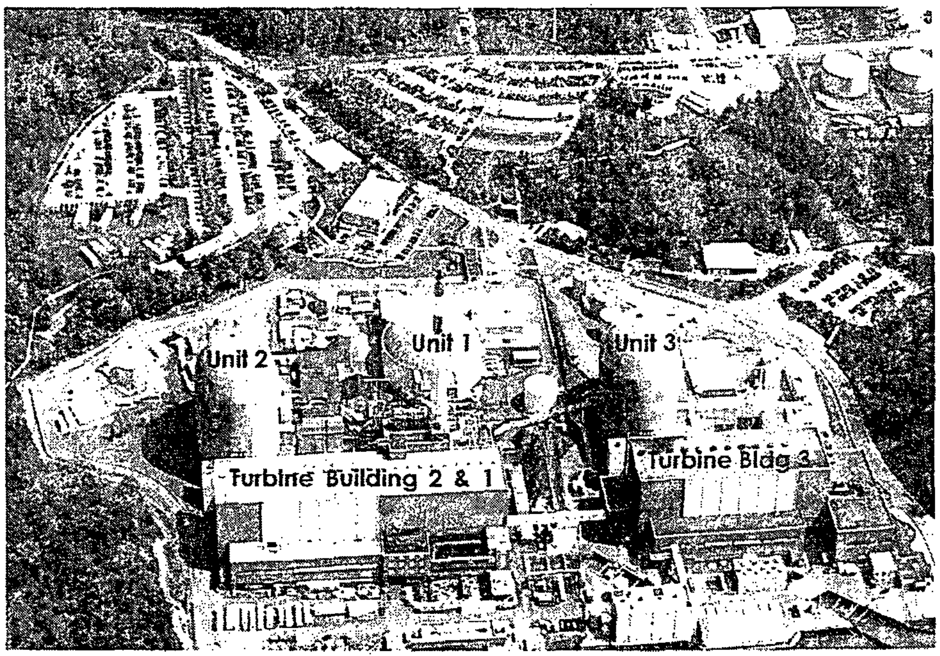
[1] Figures referenced by specific number are contained as full size drawings in Volume 3 of this report. Additional smaller scale figures, photographs, etc. are embedded within the text for immediate reference.
[2] Flux (or mass flux) is defined as the amount of groundwater that flows through a unit subsurface area per unit time.

- Evaluate the mechanisms controlling the groundwater transport of radiological contamination;
- Estimate both the mass of groundwater transporting contaminants, and the radiological activity associated with these contaminant pathways;
- Develop a groundwater monitoring network that addresses IPEC's short term and long term needs, and is consistent with the Nuclear Energy Institute's (NEI's) Groundwater Protection Initiative; and
- Recommend, as required, appropriate remedial measures.

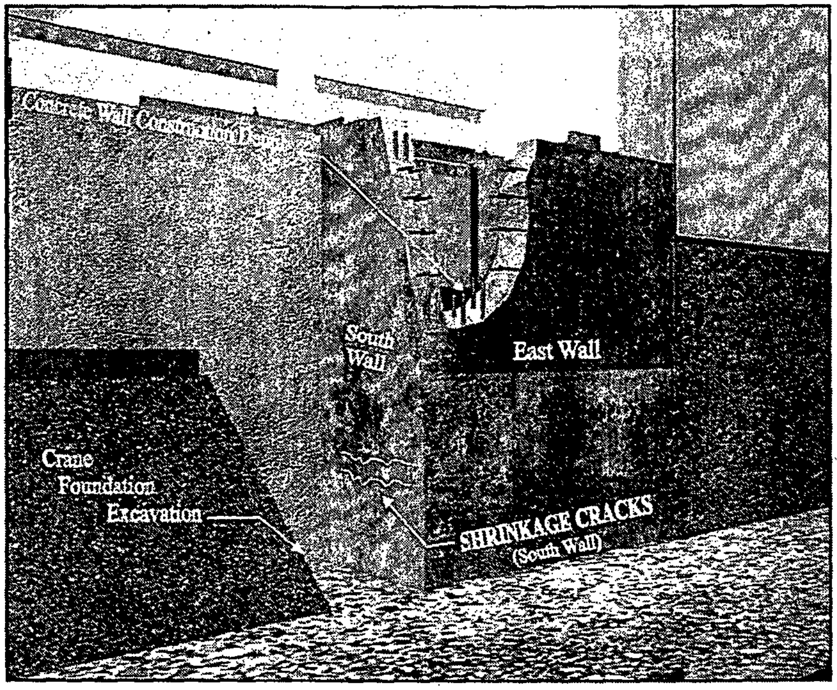
1.2 BACKGROUND

In August 2005, Entergy was excavating in the Unit 2 Fuel Storage Building (IP2-FSB) Loading Bay, adjacent to the South wall of the Spent Fuel Pool (IP2-SFP), in preparation for installation of gantry crane foundations required for the Independent Spent Fuel Storage Installation Project (see **Figure 1.2** and the following illustration).



IPEC LOOKING EAST FROM ABOVE THE HUDSON RIVER

While removing existing backfill material from along the South wall of the SFP, two shrinkage cracks in the concrete pool wall (about 1/64" wide) were observed (refer to **Section 8.1** for additional information). The concrete wall in the area of these cracks appeared damp.



UNIT 2 SFP SHRINKAGE CRACKS IDENTIFIED IN SEPTEMBER 2005

Initially, a temporary, plastic membrane collection device was installed to facilitate water retention and sampling as there was no visibly free-flowing liquid. Analyses of the collected moisture indicated that it had the radiological and chemical characteristics of IP2-SFP water. The primary radioactive constituent was Tritium. This finding initiated work to terminate the known release from these shrinkage cracks. Permanent containment of the release, and prevention of any further migration into the subsurface, was accomplished by installing a waterproof physical containment ("collection box") over the two shrinkage cracks prior to backfilling the gantry crane foundations and SFP wall. This containment was then piped to a permanent collection point such that any future leakage from the crack could be monitored[3]. In addition, Entergy also began extensive investigations of the stainless steel liner in the Unit 2 Fuel Pool itself, as well as the integral Transfer Canal. Subsurface investigations were also started to evaluate if the groundwater had become contaminated from the release.

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[3] Subsequent monitoring has indicated that the leakage from the crack, which had only been typically as high as 1.5 L/day (peak of about 2 L/day) from its discovery through the fall of 2005, has since fallen off dramatically. (L=liters).

As part of these early investigations, Entergy sampled groundwater on September 29, 2005 from a nearby existing downgradient monitoring well, MW-111. This monitoring well is located between the IP2-SFP and the downgradient Hudson River to the West (see **Figure 1.3** for well location). The analysis results, reported on October 5, 2005, indicated an elevated Tritium concentration. The elevated Tritium in MW-111 was consistent with a release from the shrinkage cracks that had migrated into the on-Site groundwater. Entergy therefore began an extensive investigation to understand the extent of the Unit 2 groundwater contamination and potential impacts to the environment.

Although the early subsurface investigations were focused primarily on potential sources of contamination, the project team also reviewed: regional hydrogeological information, plant design/construction details, and available Site-specific groundwater monitoring results. This early work led to three conclusions:

- The recently identified shrinkage cracks had resulted in releases of Tritium to the groundwater;
- It was unlikely that contaminated groundwater was migrating off-property to the North, East or South; and
- Tritium-contaminated groundwater likely had, and would continue to, migrate to the Hudson River to the West.

In response to these three early conclusions, Entergy tasked GZA with developing a network of groundwater monitoring wells. The primary objectives for this network were to facilitate comprehensive investigation of the IP2-SFP Tritium release location, as well as evaluate the potential for releases at other locations across the Site. Additional objectives included:

- Monitoring of the southern boundary of the Site (previously identified by others as downgradient);
- Monitoring attenuation of the contaminant plume(s) identified on-Site;
- Early detection of leaks in areas of ongoing active operations, should they occur in the future; and
- Monitoring of the groundwater adjacent to the Hudson River to provide the required groundwater data for Entergy's radiological impact evaluations.

The groundwater monitoring network ultimately developed by GZA, and supported by Entergy, was comprised of shallow and deep installations at 59 monitoring locations. These installations were completed in both soil overburden and bedrock. The installations generally include multi-level instrumentation which allows acquisition of depth-discrete groundwater samples and automatic recording of depth-specific groundwater elevations via electronic pressure transducers. The wells were drilled in a phased manner, with resulting data being used to modify and guide the work of subsequent investigations. This iterative progression is in accordance with the Observational Method[4] approach (see **Section 2.0**).

During the course of the expanded investigations in 2006, Strontium-90 was detected in, and downgradient of, the western portion of the Unit 2 Transformer Yard (IP2-TY). While the transformer yard is located immediately downgradient of the Unit 2 Spent Fuel Pool (IP2-SFP), the source of this Strontium in the groundwater could not reasonably be associated with a release from the IP2-SFP. This conclusion was particularly appropriate when evaluated in light of the sampling data from the upgradient transformer yard wells and ultimately from wells directly adjacent to the SFP itself. The ongoing subsurface investigation program was therefore further expanded to encompass not only the IP2-SFP source area, but also other potential sources across the entire Site, including Units 1 and 3. These subsequent phases of investigation ultimately established the retired Unit 1 plant as the source of the Strontium contamination identified[5] in the groundwater. More specifically, the Unit 1 fuel storage pool complex, where historic legacy pool leakage was known to exist, was confirmed as the Strontium source. This fuel pool complex is collectively termed the Unit 1 Spent Fuel Pools (IP1-SFPs). Following detection of radionuclides in the groundwater associated with IP1-SFPs, Entergy accelerated efforts to reduce activity in the IP1-SFPs, along with acceleration of the already ongoing planning for the subsequent fuel rod removal and complete pool drainage.

As indicated above, later phases of the investigations encompassed the entire Site, including all three Units (IP1, IP2 and IP3). These investigations found no evidence of releases to the groundwater from the IPEC Unit 3 plant complex. In this regard, it is important to note that the design and construction of the IP3-SFP incorporates a secondary leak detection telltale drain system, in addition to the primary stainless steel liner. The earlier Unit 1 and Unit 2 SFPs were not designed with this feature.

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[4] a. *Use of the Observational Method in the Investigation and Monitoring of a Spent Fuel Pool Release*, Barvenik, et. al., NEI Groundwater Workshop, Oct. 2007.

b. *Use of the Observational Method in the Remedial Investigation and Cleanup of Contaminated Land*, Dean, A.R. and M.J. Barvenik, The Seventh Geotechnique Symposium - Geotechnical Aspects of Contaminated Land, sponsored by the Institution of Civil Engineers, London, Volume XLII, Number 1, March 1992.

c. Advantages and Limitations of the Observational Method in Applied Soil Mechanics, Peck, R.B., Geotechnique 1969, No. 2, 171-187.

[5] In addition to Strontium, other radionuclides (Nickel, Cobalt and Cesium) were also sporadically detected in groundwater. These other radionuclides were continuously assessed within the context of the overall hydrologic model. Based upon their occurrence, Strontium, in combination with Tritium, provides full delineation of radiological groundwater plumes at the IPEC Site.

2.0 SCOPE OF SERVICES

This section outlines the scope of our two-plus year-long investigation. Consistent with well established hydrogeologic practices, GZA followed the Observational Method. That is, GZA developed a Conceptual Site Model (see **Section 3.0**) that described our understanding of groundwater flow and contaminant transport at IPEC, and performed investigations to test the validity of our model. In response to test data, we revised the model and/or performed additional testing to clarify findings. This iterative, step-wise phased approach allows for better focused testing, and a more comprehensive review of data. It also reduces the chances of missing critical information, and generally completes studies in less time. GZA executed the scope in three phases.

2.1 PHASE I

Phase I investigations commenced in September 2005. Consistent with the concerns raised by the observed IP2-SFP crack leakage, the Phase I investigation program focused on: 1) Identifying the groundwater flow paths which would intercept potential releases from IP2-SFP; and 2) Evaluating groundwater contaminant fate and transport mechanisms in this area of the facility. This work included:

- Identification, retrieval and evaluation of historic geologic, hydrogeologic and geotechnical reports to form the basis of our initial Conceptual Site Model (CSM);
- Development of an initial CSM;
- Identification, retrieval and evaluation of historic facility Site plans and construction details pursuant to the impact of man-made features on groundwater flow directions and Tritium migration, with subsequent refinement of the CSM;
- Installation of nine groundwater monitoring wells, a number of which contained multiple sampling levels, in the area of the Tritium release;
- Installation of four stilling wells[6], three within the Discharge Canal and one in the Hudson River, to allow groundwater elevations to be compared to these surface water elevations (to evaluate if the Hudson River is the ultimate discharge point for any potential IP2-SFP release);
- Performance of elevation and location surveys to establish reference points for groundwater elevation measurement;
- Installation of electronic pressure transducers in newly drilled boreholes and previously existing wells to continuously monitor groundwater elevation fluctuations, as influenced by climatic/seasonal variability, tidal influences and the drilling of nearby boreholes (to assess interconnections between boreholes at different locations);
- Geophysical borehole testing to provide further bedrock fracture identification, location and groundwater flow information;

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[6] Stilling wells are typically constructed of slotted pipe or well screen. They are placed in surface water bodies to house pressure transducers for water level measurement. Their purpose is to dampen-out high frequency pressure fluctuations in the water body, typically due to flow-induced turbulence, such that more representative readings can be obtained. Stilling wells are not included as monitoring wells with reference to numbers of monitoring wells installed.

- Packer testing of specific bedrock boreholes to provide initial depth-specific groundwater samples, measurement of depth-specific groundwater elevations and flow capacity of the fracture zones;
- Completion of the boreholes as screened overburden wells, open bedrock wells, or multi-level monitoring wells as appropriate for the subsurface conditions encountered;
- Testing of open bedrock and screened boreholes to measure formation groundwater flow capacity;
- Ground Penetrating Radar (GPR) analysis of the key locations to evaluate top of bedrock elevations relative to preferential groundwater flow through soil backfill;
- Sampling of groundwater from the monitoring wells and analyzing the samples for Tritium and gamma emitters; and
- Computation of the groundwater flux and radiological activity to the Hudson River for use by Entergy in their dose computations.

2.2 PHASE II

Phase II investigations commenced in January 2006. The focus of this work was to: 1) Confirm initial findings; 2) Better estimate the quantity of contaminated groundwater at the facility that discharges to the Hudson River; and 3) Establish a network of wells suitable for identifying potential leaks at all three units across the Site and for long term monitoring of groundwater. This phase of work included:

- Re-evaluation of our CSM to guide the selection of borehole locations and establish testing requirements;
- Identification of accessible areas from which to drill boreholes to measure groundwater elevations and the contaminant concentrations;
- Drilling of 23 additional boreholes through soil and bedrock to depths of up to 200 feet, including coring to provide bedrock core samples for inspection (to locate fractures in the bedrock which likely conduct groundwater flow);
- Performance of elevation and location surveys to establish reference points for groundwater elevation measurement;
- Installation of electronic pressure transducers in newly drilled boreholes to continuously monitor groundwater elevation fluctuations, as influenced by climatic/seasonal variability, tidal influences and the drilling of nearby boreholes (to assess interconnections between boreholes at different locations);
- Geophysical borehole testing to provide further bedrock fracture identification, location and groundwater flow information;
- Packer testing of specific bedrock boreholes to provide depth-specific groundwater samples, measurement of depth-specific groundwater elevations and flow capacity of the fracture zones;
- Completion of the boreholes as screened overburden wells, open bedrock wells, or multi-level monitoring wells as appropriate for the subsurface conditions encountered;
- Conducting tests on open bedrock and screened boreholes to measure formation groundwater flow capacity;
- Ground Penetrating Radar (GPR) analysis of the key locations to evaluate top of bedrock elevations relative to preferential groundwater flow through soil backfill;

- Sampling of groundwater from the monitoring wells and analyzing the samples for Tritium and additional radionuclides of interest (including Strontium, gamma emitters, Nickel-63 and transuranics); and
- Re-computing the groundwater flux and radiological activity to the Hudson River (based on the more current data and refined CSM) for use by Entergy in their dose computations.

2.3 PHASE III

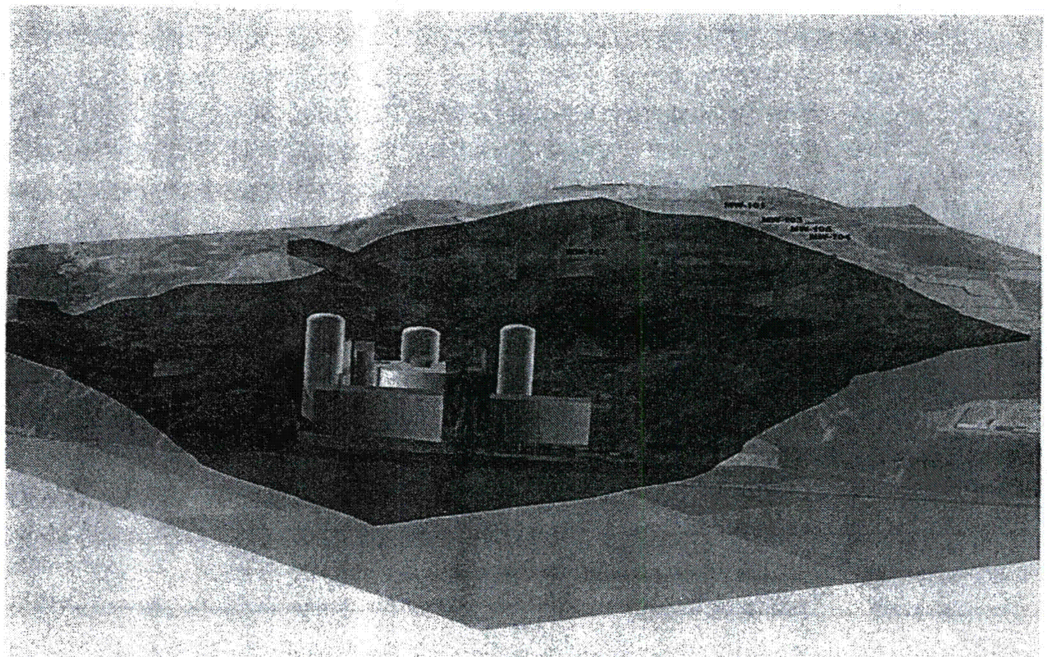
Phase III investigations commenced in June 2006. The focus of the Phase III work was to:
1) Better delineate the extent of Strontium detected during Phase II investigations; and
2) Improve characterization of bedrock aquifer properties to allow evaluation of remedial alternatives. This phase of work included:

- Re-evaluation of our CSM to guide the selection of borehole locations and establish testing requirements;
- Installation of additional wells (MW-53 through MW-67 and U1-CSS) to further delineate the horizontal extent of groundwater contamination (this work was begun in Phase II);
- Installation of deep wells (MW-54, -60, -61, -62, -63, -66, and -67) to establish the vertical extent of contamination;
- Conducting hydraulic tests on boreholes and completed wells to assess the transmissivity of bedrock fracture zones and overburden;
- Installation of electronic pressure transducers in newly drilled boreholes and existing wells to continuously monitor groundwater elevation fluctuations due to climatic/seasonal variability, tidal influences and the drilling of nearby boreholes (to assess interconnections between boreholes at different locations);
- Geophysical borehole testing to provide further bedrock fracture identification, location and groundwater flow information;
- Packer testing of specific bedrock boreholes to provide depth-specific groundwater samples, measurement of depth-specific groundwater elevations and flow capacity of the fracture zones;
- Completion of the boreholes as screened overburden wells, open bedrock wells, or multi-level monitoring wells as appropriate for the subsurface conditions encountered;
- Conducting a 72-hour Pumping Test to assess hydraulic properties of the bedrock as well as to assess the feasibility of managing Tritium-contaminated groundwater through hydraulic containment;
- Performance of a tracer test to better assess contaminant migration and transport mechanisms, particularly in the unsaturated zone;
- Sampling of groundwater from the monitoring wells and analyzing the samples for radionuclides; and
- Re-computing the groundwater flux and radiological activity to the Hudson River (based on the more current data and refined CSM) for use by Entergy in their dose computations.

3.0 CONCEPTUAL HYDROGEOLOGIC MODEL

This section, together with associated figures, constitutes our Conceptual Site Model (CSM). The key components of the model consisted of: the hydrogeologic setting; general groundwater flow patterns; identified contaminant sources; contaminants of potential concern; and identified receptors. GZA used the CSM to guide our investigations, identify and fill data gaps, assess the reasonableness of findings, and develop parameters controlling contaminant transport. It was an iterative process and, as studies progressed, we modified the CSM to better fit observed conditions. With completion of the investigations and further refinement of the CSM, our CSM was consistent with both the Site-specific project data and published data for the area.

The CSM incorporates our understanding of Site construction practices as they influence contaminant migration. Critical in this regard is that, according to construction plans, lean concrete was used as backfill material for foundation walls in a number of locations, primarily associated with Unit 1 structures. We also note that in some areas where construction plans show soil backfill, we found that lean concrete was actually used. This is likely due to the relatively low cost of concrete during the 1950's and the uniqueness of the construction for these first nuclear power plants. At the subsequently constructed Units 2 and 3, it appears soil or blast rock was the material most commonly used as backfill against foundation walls.



SCHEMATIC REPRESENTATION OF GROUNDWATER FLOW INTO THE SITE FROM THE NORTH, SOUTH, AND EAST

3.1 HYDROGEOLOGIC SETTING

The Site watershed is limited in areal extent. GZA assumed that the top of the watershed defines a no-flow boundary in the aquifer. The distance from the upgradient no-flow boundary located at the top of the watershed, to the river, is on the order of 2,200 feet (see **Figure 3.1**). This length limits the volume of precipitation available for aquifer recharge. Recharge is further limited by the density of structures and areal extent of paving, which induces direct run-off. An average annual recharge rate of 5.5 inches per year was initially selected[7] as representative for the Site area, which is the USGS estimated average in Westchester County where IPEC is located.

3.2 GENERAL GROUNDWATER FLOW PATTERNS

Groundwater flow takes place in three dimensions. In general, flow at the top of the watershed is largely downward and flow near the river's edge is largely upward. In the mid-section of the watershed, flows are predominantly horizontal. Based on the location of the Site in the watershed and information indicating that the top of the bedrock is more fractured, GZA initially estimated, and later confirmed that the bottom of the local groundwater flow to be at or above elevation -200 feet (National Geodetic Vertical Datum of 1929[8], NGVD 29)[9]. Note that temporal and spatial variations in areal recharge rates, rock heterogeneities, and tidal influences cause local variations from these general flow patterns. In fact, Site groundwater flow patterns in some areas are dominated by shallow anthropogenic Site features. These features include pumping from building foundation drains, foundation walls, subsurface utilities, and flows in the intake structures and Discharge Canal.

Based upon the regional topography, Site topography (see **Figure 3.2**), anthropogenic influences, and the geostructural setting, even at the initial stages of the investigations GZA expected that groundwater would flow into IPEC from the North, East and South, and then discharge to the Hudson River, with portions of the flow being intercepted by the cooling water intake and Discharge Canal (see **Figure 3.3**). However, based on our review of reports available at the start of the investigations, it was unclear what the role that anisotropic bedrock structure played in groundwater migration. That is, there was information suggesting groundwater flows would have a primarily southern component (see **Section 6.4** for a description of the regional area and Site-specific geologic setting).

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[7] As discussed in **Section 6.0**, the initial average areal recharge rate of 5.5 inches/year was subsequently increased somewhat as we refined our CSM.

[8] The National Geodetic Vertical Datum of 1929 (NGVD 29) is the renamed Sea Level Datum of 1929. The datum was renamed because it is a hybrid model, and *not a pure model of mean sea level*, the geoid, or any other equipotential surface. NGVD 29, which is based on "an averaging" of multiple points in the US and Canada, is the vertical "sea level" control datum established for vertical control surveying in the United States of America by the General Adjustment of 1929. The datum is used to measure elevation or altitude above, and depression or depth below, "mean sea level" (MSL). It is noted that there is no single MSL, because it varies from place to place and over time.

[9] During a mid-phase of the work, we concluded that the bottom of the local groundwater flow may be deeper, more likely between elevations -200 to -350 feet NGVD 29. This conjecture was based on the observed vertical distribution of heads, bedrock fracture patterns, and the observed contaminant concentrations at the time. We therefore increased our drilling depth to 350 feet (multi-level monitoring well installation MW-67) to investigate this issue. Subsequently, the most recent data better fit with a 200-foot-deep flow model.

Based on our studies, including a full-scale Pumping Test and tidal response testing, we have shown that in the area of groundwater contamination, and on the scale of the contaminant plumes, the direction and quantity of groundwater flow can be estimated using an equivalent porous media model. We state this recognizing that an individual bedrock zone may represent flow in a single or limited number of fractures which over a relatively short distance is not representative of average conditions. In terms of our equivalent porous media model, this condition represents an aquifer heterogeneity. However, over sufficient volumes of bedrock (which is the case for the work at IPEC), the bedrock groundwater flux can be estimated based on an equivalent porous media model using Darcy's Law[10].

3.3 IDENTIFIED CONTAMINANT SOURCES

GZA, in conjunction with facility personnel, conducted a review of available construction drawings, aerial photographs, prior reports, and documented releases, and interviewed Entergy personnel to identify potential groundwater contaminant sources.

That review, in conjunction with the observed distribution of contaminants, identified IP2-SFP and IP1-SFPs, along with legacy piping associated with Unit 1, as sources of the radiological groundwater contamination. The locations of these structures are shown on **Figure 3.4.** No release was identified in the Unit 3 area. This finding is consistent with, and reflects, changes in construction practices over time[11]. Refer to **Section 8.0** for additional information pursuant to source area description.

3.4 CONTAMINANTS OF INTEREST

Throughout this report, Tritium and Strontium are discussed as the principal radiological constituents associated with the groundwater contamination investigation performed at IPEC. Both radionuclides served as the most representative contaminant tracer tools from the perspective of frequency of observed occurrence, as well as contaminant transport[12] across the Site. Other radionuclides (primarily Cs-137, Ni-63, Co-60) were more sporadically identified and isolated to specific locations within the Site. These radionuclides are encompassed by the Unit 2 (Tritium) and Unit 1 (Strontium) plumes. We also note these other radionuclides carry a smaller potential radiological impact as compared to Strontium. These contaminants were also continuously assessed within the context of the overall site hydrological model as well as the plume information gleaned from the Unit 1 and Unit 2 plume data. All detected radionuclides have been

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[10] *Interpretation of Hydraulic Tests and Implications Towards Representative Elementary Volume for Bedrock Systems*, Thomas Ballerstero, October 2003, AGU San Francisco.

[11] The absence of Unit 3 sources is attributed to the design upgrades incorporated in the more recently constructed IP3-SFP.

[12] A combination of Tritium and Strontium allow full characterization of radiological groundwater plume nature and extent at the IPEC Site given their divergent behavior in the subsurface. Tritium is completely conserved in the groundwater with no partitioning to natural or anthropogenic subsurface materials. It, therefore, moves with and as fast as the groundwater, and thus serves as an indicator of the leading edge of a recent release. Strontium provides strong partitioning characteristics and long half-life. It is, therefore, an indicator of older, historic releases.

accounted for by Entergy in their dose assessment analyses (radiological impact evaluations). Accounting for these data was performed via USNRC Annual Reporting documents that have been made public (year-end 2005 and 2006) and will continue to be reported on (Refer to RG1.21 report). Additional discussion of the identified sources of contaminants and the properties affecting contaminant migration are provided in **Sections 8.0** and **9.0.**

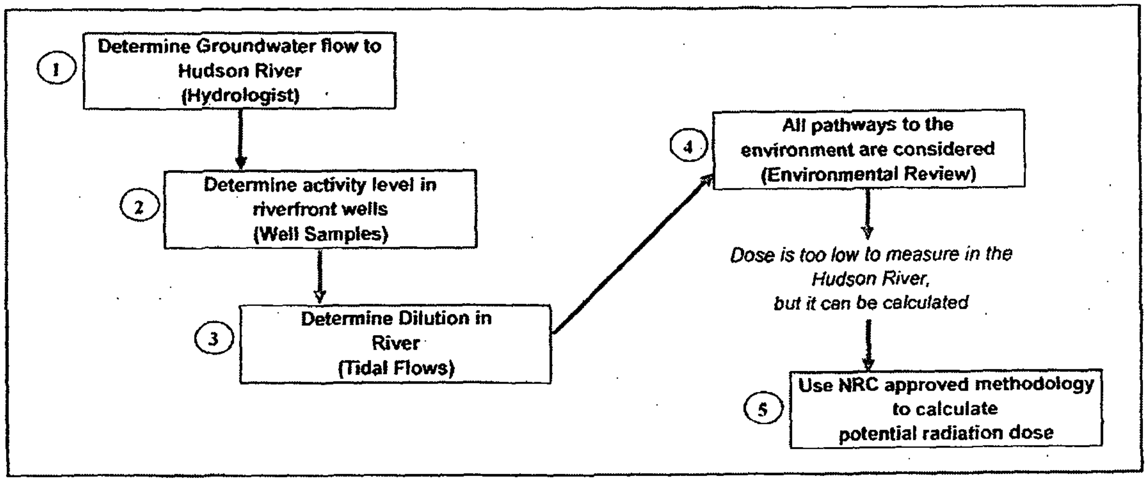
3.5 IDENTIFIED RECEPTORS

The NRC has set forth guidance for calculations of radiation dose to the public, and IPEC follows this guidance for radioactive effluents, including those from groundwater. IPEC is required to perform an environmental pathway analysis to determine the possible ways in which radioactivity released to the Hudson River can cause radiation dose. Receptors for radioactive releases to the environment are considered to be actual or hypothetical individuals exposed to radioactive materials either directly or indirectly.

Title 10 of the Code of Federal Regulations, Part 50 (10CFR50) Appendix I states: "*Account shall be taken of the cumulative effect of all sources and pathways within the plant contributing to the particular type of effluent being considered.*" 10CFR50 Appendix I provides numerical guidelines on liquid releases of radioactivity, such that releases "*will not result in an estimated annual dose or dose commitment from liquid effluents for any individual in an unrestricted area from all pathways of exposure in excess of 3 millirems to the total body or 10 millirems to any organ.*"

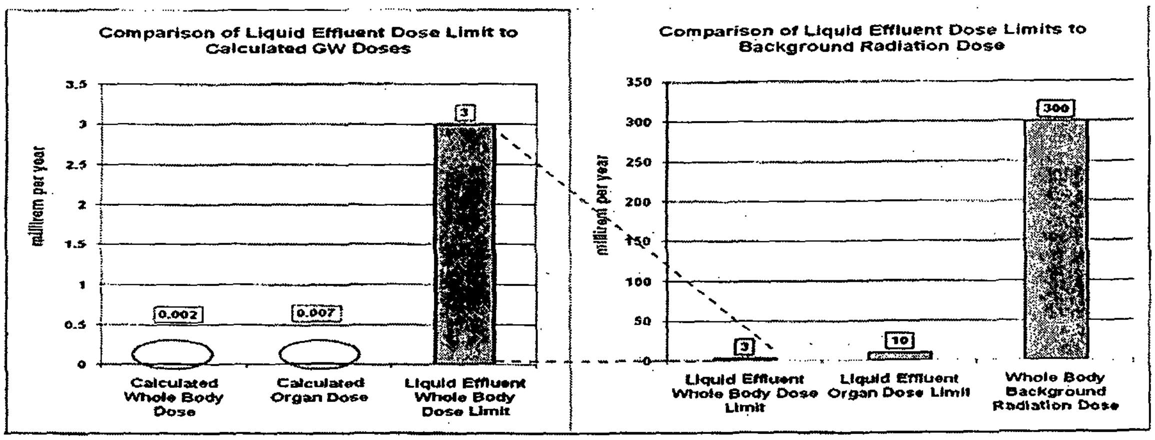
IPEC has reviewed the potential pathways that result in dose to the public and are viable for the Site. Potential pathways considered included drinking water consumption, aquatic foods, exposure to shoreline sediments, swimming, boating, and irrigation. As discussed below, drinking water is not a viable pathway for releases to the Hudson River. Regulatory Guide 1.109, "Calculation of Annual Doses to Man from Routine Releases of Reactor Effluents for the Purpose of Evaluating Compliance with 10 CFR 50, Appendix I" provides guidance and acceptable methodologies for calculating radiation dose from environmental releases. The NRC guidance uses the maximum exposed individual approach, where doses are calculated to hypothetical individuals in each of four age groups (infant, child, teen, and adult). Maximum individuals are characterized as "maximum" with regard to food consumption and occupancy. Regulatory Guide 1.109 describes a pathway as "significant" if a conservative evaluation yields an additional dose increment of at least 10 percent of the total from all pathways. Based on the above description, the only significant pathway for liquid releases is for consumption of aquatic foods; i.e., Hudson River fish and invertebrates.

The specific methodology used to calculate doses from liquid radioactive effluents is based on NRC guidance and is contained in the Indian Point Offsite Dose Calculation Manual (ODCM). The volume of groundwater traversing the site and discharging into the Hudson River, as estimated by GZA using the data as presented in this groundwater report, is used in conjunction with measured concentrations of radionuclides in groundwater to estimate the total amount of radionuclides to the Hudson River, and their potential dose impact. In 2005 and 2006, groundwater releases resulted in a small fraction of the offsite dose limits established by the NRC for each site. This dose is calculated from measured radionuclides in groundwater, using the methodology in the ODCM. A simplified description of the methodology is shown in the figure below.



SIMPLIFIED GROUNDWATER DOSE CALCULATION METHODOLOGY

Radiation doses are reported annually by IPEC in an NRC-required Annual Radioactive Effluent Report. An overview of the results is shown in the figure below.



COMPARISON OF BACKGROUND, DOSE LIMITS, AND CALCULATED GROUNDWATER DOSE – 2006

For the purposes of this study, the migration of contaminated groundwater is the pathway of interest. The contaminants of interest are not volatile; therefore, they remain in the subsurface bedrock, soil and groundwater until discharge to the river.

There is no current or reasonable anticipated use of groundwater at the IPEC. According to the NYSDEC[13], there are no active potable water wells or other production wells on the

[13] Early in the investigative process, the NYSDEC requested that the New York State Department of Health assess the presence of drinking water supply wells in the vicinity of the Site. The NYSDEC informed Entergy and GZA that no drinking water supply wells were located on the East side of the Hudson River in the vicinity of the Site in June 2006.

East side (Plant side) of the Hudson River in proximity to the IPEC[14]. Drinking water in the area (Town of Buchanan and City of Peekskill) is supplied by the communities and is sourced from surface water reservoirs located in Westchester County and the Catskills region of New York. The nearest of these reservoirs (Camp Field Reservoir) is located 3.3 miles North-Northeast of the Site and its surface water elevation is hundreds of feet above the IPEC, in a cross-gradient direction and several watersheds away. In addition, groundwater flow directions on the Site are to the West towards the Hudson River. Therefore, it is not possible for the contaminated groundwater at IPEC to ever impact these drinking water sources.

Groundwater beneath the IPEC flows to the Hudson River and therefore flows through portions of the river bank and river bottom. The river bank at the Site consists of sections of vertical bulkheads and some rip-rap outside of the contaminated flow zone. The size of the Hudson River and the hydraulic properties of the underlying bedrock preclude natural or pumping-induced migration of contaminated groundwater to the West side of the river. Therefore, conditions at the IPEC pose no threat to potable water supplies.

In summary, the only pathway of significance for groundwater is through consumption of fish and invertebrates in the Hudson River, and the calculated doses are less than 1/100 of the federal limits. As described above, potable water is not a viable pathway and no dose calculations are necessary in that regard.

GZA utilized Environmental Data Resources, Inc. to conduct a search for public water supply wells within 1 mile of the Site. According to records maintained by the USEPA, there were no water supply wells located within the search radii.

[14] According to the Rockland County Department of Health, there are municipal drinking water supply wells operated in Rockland County. GZA formally requested, through a Freedom of Information Law Application (F01-07-004), information regarding the elevation of groundwater in these wells to assess if there was any potential for IPEC to impact these wells. The information was not made available to GZA for security reasons. The closest active drinking water well in Rockland County is over 4.5 miles Southwest of the Site on the West side of the Hudson River.

4.0 FIELD INVESTIGATIONS

This section provides a description of our field activities. The studies were conducted in three phases between October 2005 and September 2007. Field activities were performed, in accordance with general industry practice and regulatory guidelines, to develop and validate our CSM (see **Section 3.0**).

The field exploration program was developed by GZA in cooperation with Enercon and Entergy. A team of GZA engineers, geologists and scientists was present to observe and document drilling efforts, classify soil and rock samples, direct field testing (packer tests, etc.) and collect other hydrogeologic data. Borehole development, well installation and packer testing were performed by GZA and the drilling contractor, Aquifer Drilling and Testing (ADT), New Hyde Park, New York. The exploration program also included the use of geophysical exploration techniques to help identify underground utilities, evaluate the location of the bedrock surface, and evaluate the nature of bedrock fractures in select boreholes. Advanced Geological Services (AGS) and Geophysical Applications, Inc. (GA), both under GZA's oversight, conducted this work.

The following provides a broad overview of our investigations. Refer to subsequent subsections for more information.

Geological Reconnaissance

- Review of Relevant Geological Literature and Previous Reports
- Site Reconnaissance to Observe Outcrops of Bedrock
- Geostructural Logging of the Rock Wall within the IP2-FSB Crane Foundation Excavation

Test Drilling - Planning, Execution, Post-Drill Activity

- Review of Existing Utility Plans
- Surface Geophysical Utility Surveys (to further locate utilities)
- Vacuum Excavation of 39 boreholes (for safety; to reduce risk of encountering underground utilities or structures)
- Test Boring Advancement (bedrock borings, overburden borings)
- Borehole Development (to remove rock cuttings and drill water; preparation for hydraulic testing in boreholes)
- Borehole Geophysical Surveys (to evaluate fractures along the borehole wall)

Monitoring Well Installations

- Bedrock Wells
- Open Rock Wells
- Waterloo Systems
- Nested Wells
- Overburden Wells
- Wellhead Completion

- Wellhead Elevation Surveying

Hydraulic Testing to Evaluate Hydraulic Conductivity of Bedrock

- Specific Capacity Testing
- Rising Head Hydraulic Conductivity Testing (pneumatic and hydraulic slug tests)
- Bedrock Packer Hydraulic Conductivity Testing
- A Pumping Test (a 72 hour Pump Test to evaluate the hydraulic properties of the bedrock)

Water Sampling

- On-Site Sampling of Groundwater, Surface Water and Facility Water
- Off-Site Sampling of Groundwater and Surface Water

Groundwater Elevation Monitoring and Pressure Transducer Data

- Installation of In-Situ and Geokon Transducers
- Data Retrieval

Organic Dye Tracer Testing

- Injection Well Construction
- Tracer Introduction
- Sampling Methods

Geophysical Testing – Identification of Preferential Groundwater Flow Paths

- Ground Penetrating Radar Surveys at Unit 2, Unit 3 and the Owner Controlled Area (OCA) Access Road
- Seismic Refraction, GPR and Electromagnetic Surveys between the Protected Area and southern Warehouse

As-built locations of the explorations are shown on **Figure 1.3**. **Table 4.1** provides a summary of well locations and installation details. The following sections describe the key aspects of the completed work. Explorations logs, test records and additional information are presented in the Appendices.

4.1 GEOLOGIC RECONNAISSANCE

To develop a preliminary understanding of the subsurface conditions expected to occur beneath the Site, GZA reviewed USGS publications relating to the local and regional geology as well as available Site-specific geologic reports. GZA further conducted a reconnaissance of the Site to identify the type of bedrock exposed, relative fracture density and locations of expected overburden. Specifically included was the logging of the rock wall in the construction excavation at Unit 2 (refer to **Section 6.0** for additional detail on Site Geology). This information was used to help design the subsurface investigation methods.

4.2 TEST DRILLING

Forty-seven borings were completed by GZA as part of this program, forty-two of these borings were converted to monitoring installations, one was converted to a recovery well and one was converted to a tracer injection point[15]. Boring logs for the bedrock borings and the additional overburden borings are provided in **Appendix B**. Boring locations and elevations are provided in **Table 4.1**. Final sampling elevations are also provided in **Table 4.1**. Test Boring/Monitoring Installation locations are shown on **Figure 1.3**. In viewing the figure, note that test boring designations are the same as the monitoring installation[16] designations (see **Section 4.3.4**). In addition, a tracer injection point was installed along the side of the casing of MW-30 (see **Section 7.0** for details).

Prior to advancement of the borings, a utility identification and clearance program was implemented to reduce the risk of encountering underground utilities, and to maintain the safety of on-Site personnel during drilling activities. GZA personnel, AGS personnel and Site personnel first performed a reconnaissance of the proposed boring locations. Site personnel then utilized Site plans to assess the potential presence of subsurface utilities in the area of the proposed boring locations. Following this initial screening, AGS personnel performed a surface geophysical survey of the area around the proposed boring locations using GPR and radiofrequency utility locating equipment. The results of the survey were marked on the ground surface using spray paint. Entergy personnel performed a final reconnaissance prior to approving the locations.

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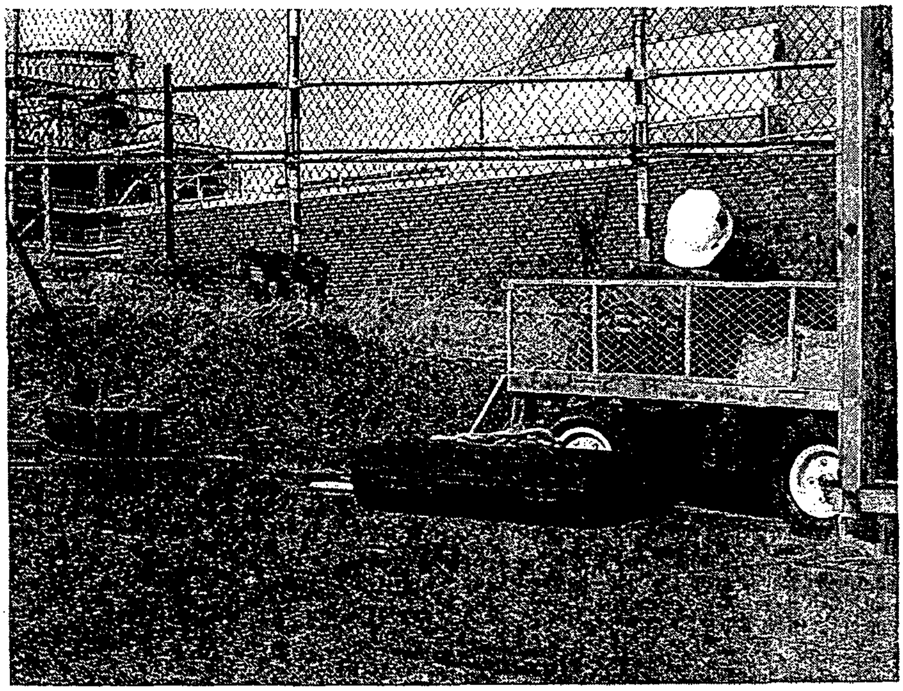
[15] Borings are defined as test sites that were excavated with hand held or mechanical drilling devices. Monitoring installations are defined as boreholes (or wellbores) that were completed to allow groundwater monitoring and generally include multiple monitoring levels over the depth of the boring (either "nested well" casings within one borehole or Waterloo multi-level completions). In several instances, a monitoring installation location designation, such as MW-49, may have two discrete borings, in which case it is counted as two installations, but represented on the figures as a single location for clarity. Attempted borings which met refusal and had to be re-drilled are not included in the boring count.

[16] *Monitoring installations* are commonly referred to as *Monitoring wells*, which in this usage, may include multiple, individual well casings. This generic usage is also used herein.

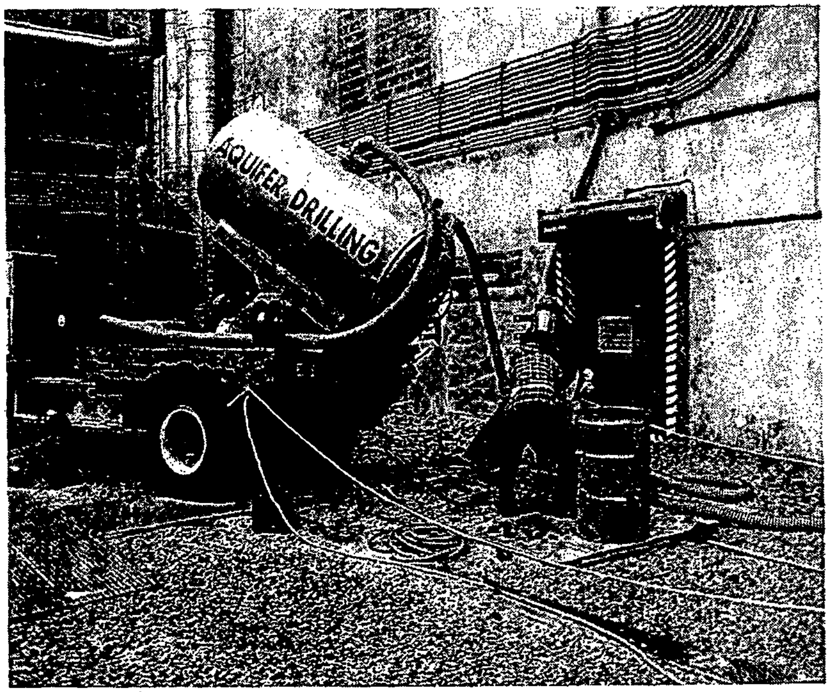


SURFACE GEOPHYSICAL SURVEY

At thirty nine of the boring locations, overburden was vacuum-excavated until bedrock was encountered, or to the practical limits of the vacuum excavation technique. To further reduce the risk associated with the drilling program, during advancement of the borings to bedrock, a downhole magnetometer was utilized every two feet to assess the presence of metallic objects potentially related to subsurface utilities.

The test borings were performed by ADT with a combination of three drill rigs: a track-mounted CME LC55 rotary drill rig, a truck-mounted CME 75 rotary drill rig, and an electric track-mounted Davie DK 515 rotary drill rig. The original program consisted of advancing borings into bedrock to desired terminal depths using wire line HQ direct rotary coring techniques. This resulted in a nominal 3.85-inch diameter borehole. Where overburden was present, either a four-inch or six-inch casing was installed into the rock and grouted in place.

At certain locations where overburden occurred beyond the bottom of the vacuum-excavated test pits, soil samples were collected at 5-foot intervals, from the bottom of the vacuum-excavated test pit, using a 2-inch outside diameter (OD) split-spoon sampler driven by a 140-pound hammer falling 30 inches, to characterize soils. These samples were visually classified using the Burmister Classification System. At all locations, either vacuum-excavated test pits or hand-excavated test pits were performed to clear utilities prior to advancing boreholes. Grab samples were collected during the advancement of the test pits to visually characterize the overburden soils.



VACUUM EXCAVATION

During the drilling program, rigorous field protocols were implemented to limit the risk of cross-contamination. All down-hole drilling tools, testing equipment, and well materials were steam cleaned or pressure washed prior to use on the Site, subsequent to the completion of a boring, and prior to leaving the Site. Water used during drilling, testing and well installations was drawn from the Buchanan, New York public water supply from on-Site connections. Waste water, waste soil, and decontamination wash water were placed in 55-gallon drums and transferred to Site personnel for proper disposal.

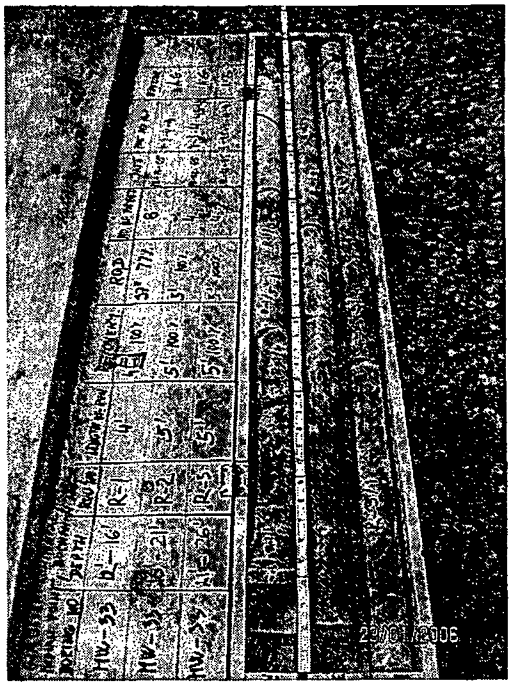
4.2.1 Bedrock Borings

Thirty-eight of the borings were drilled in bedrock, including U1-CSS which was installed horizontally through the East wall of the Unit 1 Containment Spray Sump using hand coring techniques. The borings were completed using rotary techniques with water as the drilling fluid and either permanent 4-inch or temporary 6-inch casing to keep the borehole open through overburden soils. Once rock was encountered, it was cored using HQ-size double-tube core barrels with diamond studded bits in general accordance with ASTM D2113 [6]. Core runs were generally 5 feet in length, with a nominal 3 inch diameter. Shorter or incomplete runs were made when the drilling team believed the core barrel to be blocked.

The rock samples were classified and logged by GZA field personnel, and the descriptions and rock quality designations were reviewed and checked by a Senior GZA Geologist. Rock classification was based on the International Society of Rock Mechanics (ISRM) System with adaptation to suit the identified rock and structure.

The rock core was logged as soon as practical after it was extracted from the core barrel. The following information was generally noted for each core run:

- Depth of core run
- Percent core recovery
- Rock Quality Designation (RQD)
- Rock type, including color, texture, degree of weathering and hardness
- Character of discontinuities, joint spacing, orientation, roughness and alteration
- Nature of joint infilling materials, where encountered
- Presence of apparently water-filled fractures



BEDROCK CORE OBTAINED FROM DRILLING USED FOR EVALUATION OF FRACTURES

During rock coring activities, potable water was used as a drilling fluid to cool and lubricate the core barrel and remove cuttings from the borehole. The drilling fluid was circulated down the borehole around the core that had been cut, flowed between the core and core barrel, and exited through the bit. The drilling fluid then circulated up the annular space and was discharged at the land surface to a mud tub. The volume of water lost during drilling was recorded and later, during development, an attempt was made to remove the amount lost to the formation.

In addition, drilling parameters, such as the type of drilling equipment, core barrel and casing size, drilling rate, and groundwater condition were recorded. Cumulatively, this information provided insights relative to rock conditions, and the potential for the transport of groundwater migration in bedrock fractures.

Bedrock borings ranged in depth from 30 feet below ground surface at MW-33, -34 and -35 to 350 feet below ground surface at MW-67. As described below in **Section 4.4**, the majority of the rock borings were completed as monitoring well locations. One exception was MW-61, which was abandoned when a length of HQ casing separated in the borehole due to drilling difficulties related to a 70-foot length of clay-filled fault gouge, and could not be retrieved. The boring was subsequently grouted and a second boring, designated MW-66, was advanced approximately 10 feet East of the MW-61 location.

As discussed earlier, one boring, U1-CSS, was installed using a hand-held coring machine through the East wall of the IP1-CSS. This borehole was advanced horizontally approximately 70 inches into the bedrock to the East of the Superheater Building.

4.2.2 Overburden Borings

In areas where groundwater was encountered in the overburden deposits, overburden (soil) borings were drilled to further evaluate water quality in the shallow aquifer. Five borings, designated MW-49, -52, -62, -63, and -66 were advanced immediately adjacent to the bedrock boring of the same name. In addition, three overburden borings, designated MW-38 and MW-64, were advanced at stand alone locations. MW-38 was advanced to assess groundwater quality and migration pathways along the Discharge Canal. MW-64 was advanced to determine the backfill material and construction properties of the Discharge Canal as it runs beneath the Superheater Building, and was terminated at a depth of 3 feet when concrete was encountered beneath the slab of the building. Additionally, a tracer injection well (T1-U1-1) was installed within overburden above the North Curtain Drain (NCD) along the North wall of the IP1-FHB.

Seven of the borings were advanced using water rotary techniques and temporary six-inch casing. MW-64 was advanced using a concrete core until lean concrete was encountered under the building slab. Seven of the borings were completed as single monitoring wells.

ADVANCEMENT OF BORINGS ALONG RIVERFRONT

4.2.3 Borehole Development

After drilling was completed and prior to conducting hydraulic tests within a borehole, borehole development was conducted to remove rock cuttings from the borings, which could otherwise restrict water flow into the fractures and alter packer testing results, as well as to remove drilling water lost to the formation during drilling. The boreholes were developed either by pumping and surging with a 3.7-inch surge block and a Grundfos Redi-Flo 2 submersible pump, or by pumping with a submersible pump along the length of the borehole. Sufficient water was pumped out of the borehole to account for water lost during drilling and until well water was visually free of turbidity.

4.2.4 Borehole Geophysical Analysis

Upon completion of borehole development, a suite of geophysical surveys was conducted in select boreholes (borehole geophysics was biased towards the deeper boreholes) by GA of Holliston, Massachusetts to obtain information on the presence of water bearing fractures in the rock. This work took place between November 2005 and July 2007, and involved twenty-three borings MW-30, -31, -32, -33, -34, -39, -40, -51, -52, -53, -54, -55, -56, -57, -58, -59, -60, -62, -63, -65, -66, -67 and RW-1.

GA performed fluid resistivity, temperature and conductivity logging; heat pulse flow meter logging; and optical and acoustical televiewer logging (OTV/ATV). A Mount Sopris model 4MXA or 4MXB logging winch equipped with a Mount Sopris model MGX-11 electronics console recorded conventional logs at each well. All conventional log data was recorded at 0.1-foot depth increments.

Fluid temperature and fluid resistivity logs were recorded during the first downward logging run at each borehole using a Mount Sopris caliper probe with a fluid temperature/fluid resistivity subassembly. These fluid logs were obtained using a downward logging speed of approximately 4 to 5 feet per minute. Caliper data were subsequently recorded while pulling the same probe upward at approximately 10 feet per minute.

ATV data were obtained using an Advanced Logic Technologies (ALT) model AB140 acoustical televiewer probe with a Mount Sopris winch and an ALT model Abox electronics console. ATV data were recorded at 0.01-foot depth intervals with 288 pixels for a 360-degree scan around the borehole wall. Logging speeds were approximately 4 feet per minute with this probe.

OTV data were recorded using an ALT model OB140 probe, also with a Mount Sopris winch and the ALT electronics console. OTV data were stored at depth increments of 0.007 feet, with 288 pixels for each 360-degree scan around the borehole wall. OTV logging speeds were also approximately 4 feet per minute.

A pair of centralizer assemblies positioned the ATV and OTV probes near the middle of each borehole. Each centralizer included four stainless steel bow springs, clamped to the probe housings with brass compression fittings, at positions recommended by the probe manufacturer to minimize the risk of interference with the probes' three internal component magnetometers.

Flowmeter data were recorded with a Mount Sopris model HPF-2293 heat-pulse flowmeter probe at specific depths selected from field graphs of the caliper, fluid temperature and fluid resistivity logs. Flowmeter data were initially recorded under ambient conditions. The same test depths were subsequently repeated while pumping at 0.4 to 0.75 gallons per minute (gpm) with a Grundfos, Fultz or Whale pump. The pump was positioned a few feet below the observed static water level in each well. In some cases, the pump was operated so as to maintain the water level some number of feet below the static level (if the well produced little water and the water level was constantly dropping while pumping).

A detailed description of the geophysical logging results for each borehole is included in **Appendix C.**

4.3 WELL INSTALLATIONS

Bedrock and overburden monitoring installations were constructed in boreholes to allow for future recording of groundwater levels and the collection of groundwater quality samples. Further, we installed nested piezometers in single boreholes to screen multiple levels of bedrock and overburden within a single borehole and alleviate the need for multiple borings in areas not easily accessed. For specific well installation details, refer to the well construction logs provided in **Appendix D**. In addition, eighteen monitoring wells were previously installed at the Site prior to this investigation and included: MW-101, MW-103, MW-104, MW-105, MW-107, MW-108, MW-109, MW-110, MW-111, MW-112, U3-1, U3-2, U3-3, U3-4S, U3-4D, U3-T1, U3-T2 and I-2.

4.3.1 Bedrock Wells

Following borehole advancement and testing, GZA evaluated the rock cores, geophysical logs, and other hydrologic and radionuclide test data to assess fracture spacing and potential yield. Using these data, GZA selected intervals within the boreholes to be completed as permanently screened monitoring wells. The selected well screen intervals were intended to span hydraulically active zones within the bedrock.

4.3.1.1 Open Rock Wells

Four bedrock borings, designated MW-33, -34, -35 and -46, were left as open borehole monitoring points. MW-46 is located in the Unit 3 Transformer Yard (IP3-TY), and MW-33, -34 and -35 are located in the Unit 2 Transformer Yard (IP2-TY) where the water table spans the hydraulically active shallow bedrock. The wetted lengths of the borehole were appropriate for one sampling zone at these locations.

Recovery well RW-1, located in the IP2-FSB truck bay, is also an open borehole. The borehole was installed and a Pumping Test conducted (described in **Section 4.4.4**) to test the feasibility of using hydraulic containment in the vicinity of Unit 2, should it be found appropriate. This location was used as the pumping well during the Pumping

Test. During the interim between completion of the Pumping Test and completion of a hydraulic containment system, a series of temporary packers were installed in the borehole to prevent or limit non-ambient, downward migration of radionuclides through the borehole. RW-1 was also used as a monitoring point during the tracer test.

MW-66 is an open borehole to 200 feet below grade. A Flute liner system was installed in the borehole in September 2007 to limit the vertical migration of contaminants until such time as either a multi-level monitoring well is completed or the boring is abandoned.

U1-CSS is an open borehole advanced horizontally into the bedrock behind the East wall of the Superheater Building. A watertight flange was mounted to the concrete wall of the IP1-CSS and steel piping was extended vertically upward through the floor of the Superheater Building. The well was completed as a standpipe with shut-off valves and overflow bypass in case of any artesian effect.

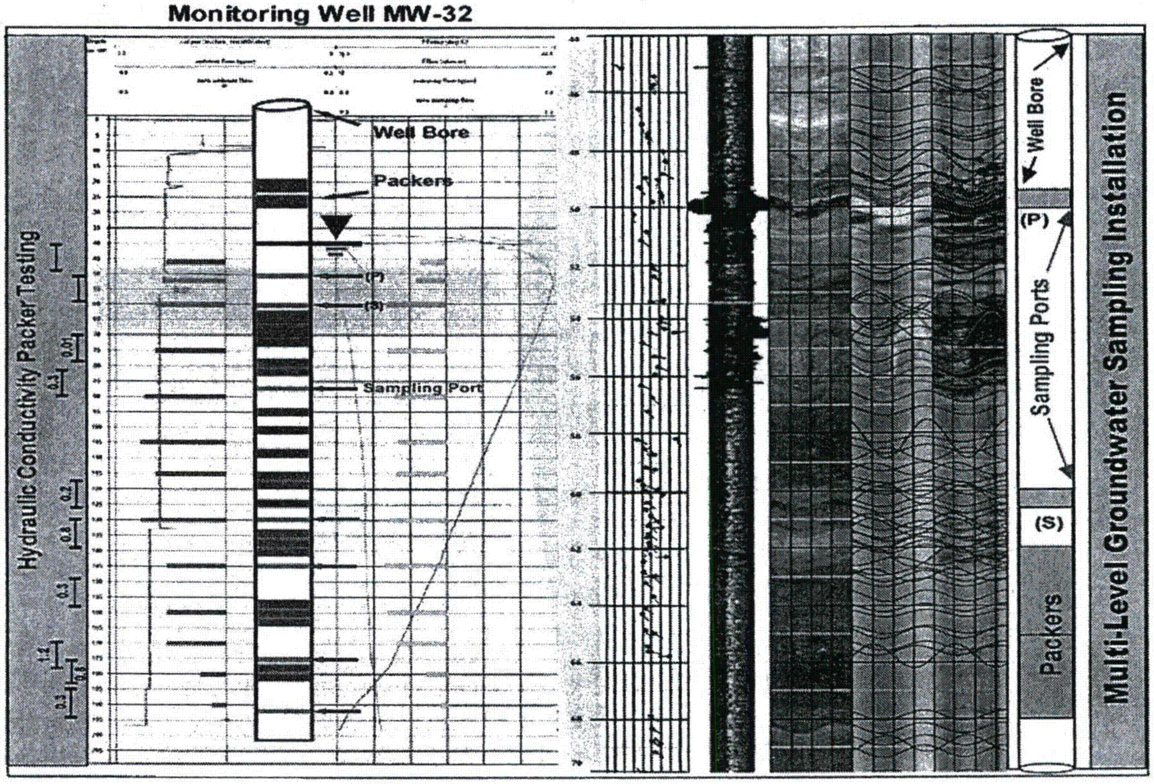
4.3.1.2 Waterloo Multi-Level Completion Wells

Twelve borehole locations, designated MW-30, -31, -32, -39, -40, -51, -52, -54, -60, -62, -63, and -67, were completed with Waterloo multi-level sampling systems. The Waterloo system uses modular components which form a sealed casing string of various casing lengths, packers, ports, a base plug and a surface manifold. This configuration allows accurate placement of ports at precise monitoring zones. Stainless steel sampling pumps are connected to the stem of each port and individually connect that monitoring zone to the surface. The Waterloo systems are constructed of 2-inch-diameter Schedule 80 PVC risers with 3-foot-long packers that inflate to fill a 4-inch borehole.

Multiple levels of monitoring ports were installed in each borehole. In several cases, redundant ports were also installed (typically, within approximately two feet of each other). In the borehole, the associated sampling zones are isolated from each other by a series of packers. The monitoring ports are constructed from stainless steel. Each monitoring port has two openings: one for sampling and one for monitoring piezometric pressures. A sampling pump and pressure transducer are dedicated to each monitoring port. Each sampling pump is individually connected to the surface manifold by 0.25-inch nylon tubing. In general, monitoring ports were placed within sampling zones adjacent to the fractures that were observed to be the most hydraulically active. Sampling zone lengths were varied with the objective of making them less than ten feet in length, but longer where either: 1) more low transmissivity fractures were required to allow enough flow for reasonable sampling times, and/or 2) two conductive fractures needed to be captured within a single sampling zone given that the total number of monitoring ports was limited to seven per borehole. Packers were placed at locations where the data (geophysical logging, packer testing, rock core photographs, etc.) indicated that the bedrock was the least fractured. In areas where packer placement could not avoid all fractures, zones with nearly horizontal fractures were favored. The overall objective of packer placement was to achieve a vertical borehole conductivity equal to or less than that of the original bedrock removed from the borehole.

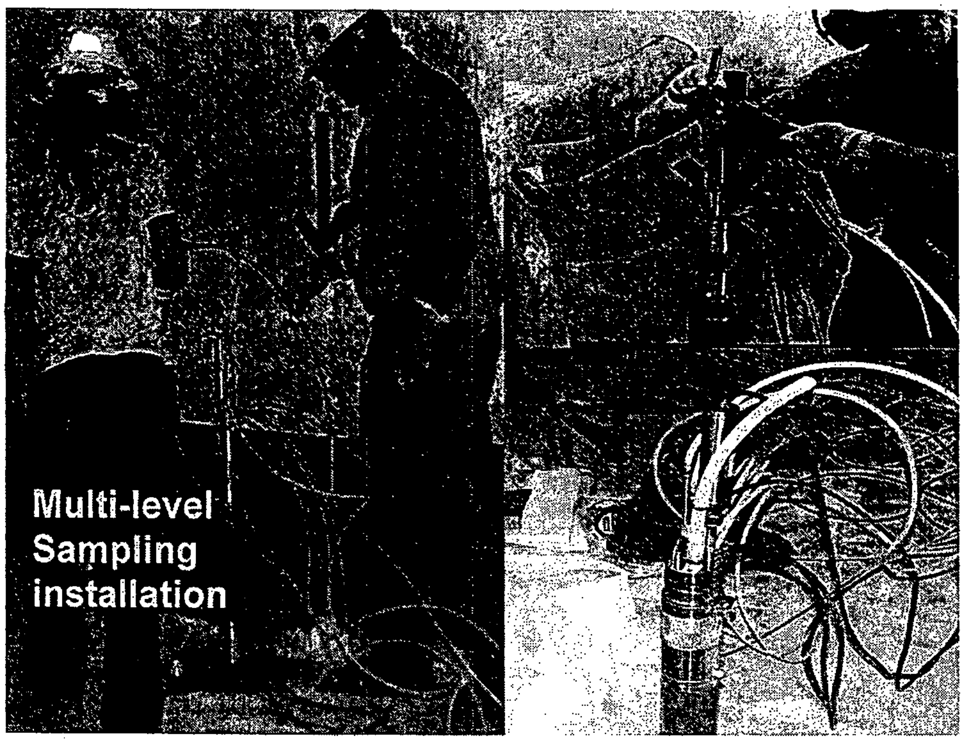
A schematic of the data and analysis process used to design the multi-level installations is included below.

Monitoring Well MW-32



EXAMPLE OF DATA AND ANALYSES USED TO DESIGN MULTILEVEL INSTALLATION

The manifold completes the system at the surface. It organizes, identifies, and coordinates the sample tubing, air drive line tubing, and/or transducer cables from each monitoring zone (see photo below of tubing and cabling during system assembly and installation). The manifold allows connection to each transducer in turn, and a simple, one-step connection for operation of pumps. Dedicated pumps allow individual zones to be purged separately; the manifold also allows for the purging of many zones simultaneously from one borehole to reduce sampling times.



SAMPLING PORTS, TUBING AND CABLING FOR MULTI- LEVEL SYSTEM ASSEMBLY AND INSTALLATION

4.3.1.3 Nested Wells

Nested monitoring wells were installed in 18 locations, designated MW-36, -37, -41, -42, -43, -44, -45, -47, -48, -49, -50, -53, -55, -56, -57, -58, -59, and -65. In general, the nested wells consisted of the installation of one or more one-inch diameter Schedule 80 PVC wells screened at varying intervals in bedrock and a two-inch Schedule 80 PVC well in the shallow West sampling zone of the boring, either in the bedrock or overburden.

In general, well screens consisting of 0.02-inch slotted PVC pipe were installed at lengths between 2 and 10 feet. Once the screened intervals were selected, the PVC well point was lowered into the boring to the desired depth. Appropriately sized filter pack material was placed from one foot below the screened interval to a minimum of one foot above the screened interval. The depth of the filter pack was measured on several occasions during installation to assess the affects of bridging and verify that the filter pack material was placed at the required depths. The intervals between well screens were sealed using bentonite pellets.

4.3.2 Overburden Wells

Three wells, MW-38, -49-26, -52-12 were completed as either two-inch diameter or four-inch diameter groundwater monitoring wells. The wells were constructed of Schedule 40 PVC screen and solid riser to ground surface. A 0.02-inch slot size was selected for the well screens based on existing knowledge of the Site soil conditions. From field observations, the shallow groundwater table was expected to be influenced by daily tidal fluctuations of approximately 2.7 feet. Consequently, well screens were installed such that the top of the screens were above mean high-tide water levels and of sufficient length to accommodate groundwater sampling needs. The annular space around the screen and riser was backfilled with #2 filter sand to approximately 2 feet above the top of the screen. The remaining annular space was backfilled with bentonite and grout.

In order to sample two intervals in deep fill and overburden deposits observed near the Hudson River (in borings at MW-62, -63, and -66), GZA installed two one-inch Schedule 40 PVC wells, or one one-inch and one two-inch well, at these three locations. One of the well screens spanned the tidally influenced shallow water table, and one at the top of rock in a more gravel-rich layer beneath silty, historic, river bottom sediments.

In addition, GZA installed one tracer injection well situated in the overburden above the Unit 1 North Curtain Drain. This well is constructed of two-inch Schedule 40 PVC. The screened interval was backfilled with #2 filter sand to approximately 2 feet above the screen. The remaining annular space was backfilled with bentonite grout. A second tracer injection point was completed adjacent to MW-30's casing.

4.3.3 Wellhead Completion

To protect the monitoring installations against damage and the elements, most installations were finished at the ground surface with an 8-inch or 12-inch flush mount protective casing with a concrete pad. To accommodate the multi-purge, sampling manifold of the Waterloo Systems well installations, the wellheads were completed with a 2 foot by 2 foot by 2 foot well vault. The well vaults were concreted in-place by Entergy subcontractors after the completion of the rock borings. The well vaults are equipped with hinged diamond plate steel lids that are rated for truck wheel loads.

4.3.4 Well Nomenclature

GZA designated names to newly installed monitoring installations[17], typically with the prefix "MW-". Nomenclature of single-interval installations, such as MW-33, were designated a number typically indicative of the order in which locations were selected prior to drilling. Nomenclature of installations containing Waterloo systems or nested piezometers, such as MW-30-69, were designated a number followed by a monitoring depth interval. In Waterloo installations, the depth interval suffix is indicative of the depth to the sampling port from the top of the well casing. In nested piezometers, the monitoring depth interval suffix is indicative of the depth to the bottom of the piezometer from the top of the well riser. These depths are rounded to the nearest foot.

Throughout the course of the investigation, alterations were made to well casings and adjacent ground surfaces due to equipment installation, hydraulic conductivity testing,

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[17] *Monitoring installations* are commonly referred to as *Monitoring wells*, which in this usage, may include multiple, individual well casings. This generic usage is also used herein.

well vault installation, and Site construction activities. In May 2007, GZA reassigned the names of multilevel installations to maintain the above described nomenclature basis as an easily verifiable tool in the field. Changes in installation nomenclature are provided in **Table 4.2**. It should be noted that the provided groundwater and tracer test analytical data, piezometric data, well construction and development logs, transducer installation logs, sampling logs, hydraulic conductivity testing logs, and survey reports dated prior to May 2007 reference the original designated installation nomenclature.

4.3.5 Wellhead Elevation Surveying

As-built surveys of the newly installed monitoring installations were performed in December 2005, March 2006, April 2006, November 2006, January 2007, and May 2007 by Badey and Watson, Inc. **Figure 1.3** reflects the surveyed locations. The survey results are summarized in **Appendix E** and in **Table 4.1**. Note that **Appendix E** survey reports dated prior to May 2007 reference original installation nomenclature. **Table 4.3** includes changes in casing and ground surface elevations and dates of alterations and resurveys throughout the course of the investigation. Elevations are reported with respect to the National Geodetic Vertical Datum of 1929 (NGVD 29)[18], which is also the datum used by the plant.

4.4 HYDRAULIC TESTING

Four types of in situ tests were performed on existing and newly installed monitoring wells to characterize hydrogeologic properties of the bedrock and overburden, and facilitate the selection of well screen and piezometric sampling intervals. These included short duration specific capacity tests, rising head hydraulic conductivity tests, bedrock packer hydraulic conductivity tests, and the Pumping Test. The following sections describe the equipment and procedures used during this testing program.

4.4.1 Short Duration Specific Capacity Tests

A total of eight specific capacity tests and eight extraction tests were performed to assess hydraulic conductivity (K). See **Table 4.4** for a summary of hydraulic conductivity data.

The testing was conducted by pumping water from the well at a constant rate in order to achieve "measurable drawdown" within the well that would stabilize after a relatively short period of time. "Measurable drawdown" was considered between 1.5 and 10 feet for the purposes of this study. Once drawdown apparently stabilized, pumping was allowed to continue at a constant rate for at least thirty additional minutes before pumping ceased.

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[18] The National Geodetic Vertical Datum of 1929 (NGVD 29) is the renamed Sea Level Datum of 1929. The datum was renamed because it is a hybrid model, and *not a pure model of mean sea level*, the geoid, or any other equipotential surface. NGVD29, which is based on "an averaging" of multiple points in the US and Canada, is the vertical "sea level" control datum established for vertical control surveying in the United States of America by the General Adjustment of 1929. The datum is used to measure elevation or altitude above, and depression or depth below, "mean sea level" (MSL). It is noted that there is no single MSL, because it varies from place to place and over time.

If measurable drawdown within the well could not be achieved, and the maximum capacity of the pump was reached, pumping was allowed to continue at a constant rate for approximately thirty minutes, and the pump was turned off. If the characteristics of the monitoring well and immediately surrounding hydrogeology did not allow for a more suitable method of hydraulic testing, the well was characterized as having a K value "greater than" the value estimated at the maximum pumping rate.

If stabilized drawdown within the well could not be achieved, and the water level in the well continued to decline after attempts to minimize pumping rate to the minimum pumping capability of the pump, the pump was turned off. If alternative methods of testing could not be appropriately implemented due to well characteristics, water levels during the recovery period of this test were analyzed and interpreted for K values.

A Grundfos II Readi-Flo submersible pump or peristaltic pump was used for specific capacity testing, and drawdown was measured using an electronic water level meter and/or pressure transducers. Flow rates were either measured using an in-line flow meter, or estimated by measuring the time required to fill a calibrated container. Transducer-logged water level measurements were typically recorded at thirty second or one minute intervals, while manual water level measurements were typically logged every one to five minutes. The entire pumping duration for each test was typically between thirty and ninety minutes.

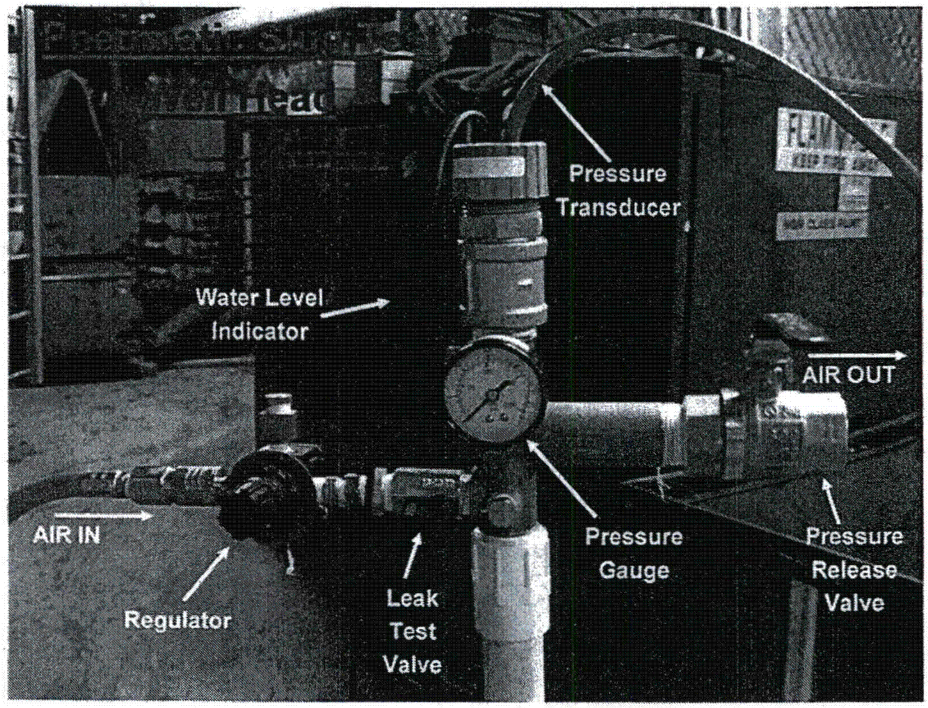
GZA performed specific capacity tests between January 2006 and April 2007. Measurements were also recorded during borehole development. The logs are included in **Appendix F**.

4.4.2 Rising Head Hydraulic Conductivity Tests

A total of forty-three rising head hydraulic conductivity tests were performed at eighteen monitoring wells at the Site. Rising head K tests (slug tests) were performed in MW-36-41, -36-53, -37-57, -41-64, and -42-51 via traditional slug testing. Pneumatic slug tests were performed in monitoring wells MW-53-120, -55-24, -55-24, -55-35, -55-54, -56-85, -57-20, -57-45, -58-65, -59-31, -59-45, -59-68, and -65-80. Hydraulic conductivity (and transmissivity) estimates were then calculated from those results. The calculations for the hydraulic conductivity estimates are provided in **Appendix G**.

At each of the traditional slug tested monitoring wells, the resting (static) water level was measured along with the depth and diameter of the well. A pressure transducer was installed within the screened portion of the tested well to record water level measurements at 10 second intervals. Pressure transducers in immediately adjacent wells also recorded water level measurements at 10 second to one minute intervals. During the first part of the slug test a rod (slug) of approximately 7 feet long was quickly inserted into the tested well below the water table in order to nearly instantaneously displace a volume of water equivalent to the volume of the slug. The raised head of the water column was then dissipated back down to its initial static level. When equilibration at static water level was reached a rising head test was conducted. The slug was quickly withdrawn from the monitoring well, resulting in a nearly instantaneous decline in the water level within the tested well. The lowered head of the water column recovered to its initial static water level.

At each of the pneumatic slug tested wells, static water level was recorded, as well as the depth and diameter of the well. Pressure transducers were installed within the screened portion of the tested well and in adjacent wells to record water level measurements at 1 to 3 second intervals. A pneumatic slug test well head was attached and sealed to the top of the tested well (see enclosed photo below). The well head was then pressurized using compressed air in order to lower the water column to a predetermined depth that was measured using pressure transducers. The water column was not permitted to decline below the top of the well screen. When pressure transducer readings stabilized and the water level in the well was below the water level indicated, the air pressure was instantaneously released through a valve on the pneumatic slug test well head, and the water column was allowed to recover to its initial static water level.

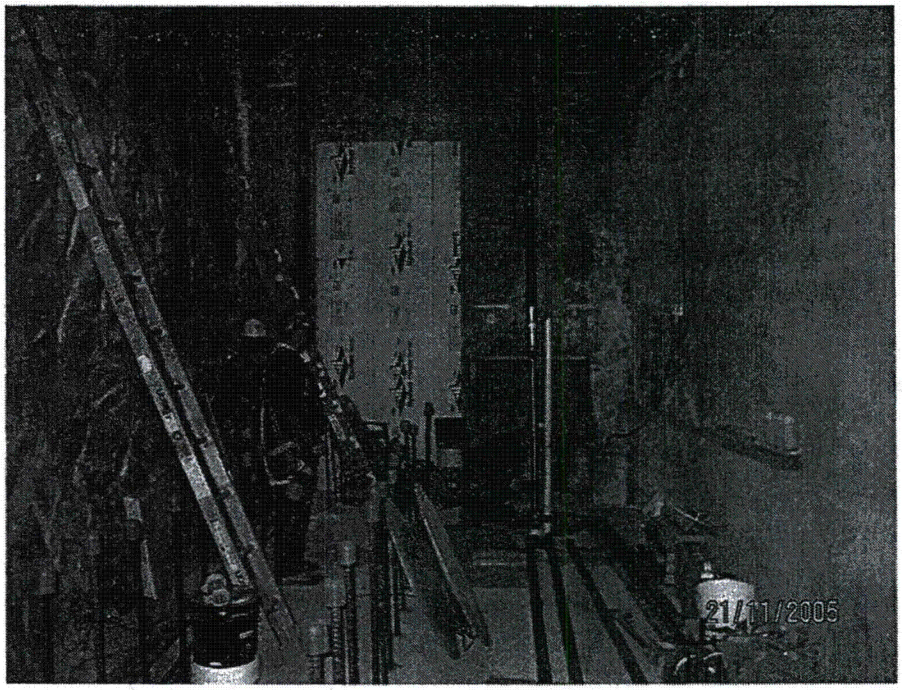


PNUEMATIC SLUG TEST WELL HEAD INSTRUMENTATION

Slug test logs are provided in **Appendix H**. Estimated K values are provided in **Table 4.4**. **Figure 4.1** represents a diagram of the pneumatic slug test well head.

4.4.3 Bedrock Packer Extraction Hydraulic Conductivity Testing

Under the direction of GZA personnel, ADT conducted 186 packer hydraulic conductivity tests between November 2005 and August 2007 in boreholes MW-30, -31, -32, -39, -40, -51, -52, -54, -60, -62, -63, -66 and -67.



PACKER TESTING OF MW-30 WITHIN IP2-SFP EXCAVATION

Bedrock packer hydraulic conductivity testing (packer testing) was performed to estimate the equivalent hydraulic conductivity of the bedrock in the vicinity of the borehole locations. The use of packers permitted the localization of a specific depth interval within a bedrock borehole for sampling and hydraulic conductivity testing. The primary hydraulic conductivity of unfractured marble is insignificant. Bedrock groundwater flow, therefore, is controlled by fractures in the rock formation. However, not all rock fractures are hydraulically active. Accordingly, packer tests were used to assess which rock zones have the ability to transmit measurable quantities of groundwater, and to estimate the equivalent hydraulic conductivities of those fractures.

During packer testing, water samples were collected for Tritium analysis for each tested interval in all boreholes except MW-40. Water samples were also collected for Strontium analysis for every other tested interval in boreholes MW-54, -60, -62, -63, -66, and -67.

Prior to the initiation of packer testing at the Site, the packer assembly was pressure tested. Also, prior to the start of packer testing at each borehole, all downhole equipment was disassembled and steam cleaned. The submersible pump was removed from the packer assembly and decontaminated using a fresh water and Alconox solution. A quality assurance/quality control (QA/QC) sample was collected from this pump after the decontamination process was completed. After reassembly of the packer equipment, packers and air lines were tested for leaks.

Packer tests were performed using an assembly composed of two inflatable bladders, or "packers", with a length of perforated pipe making up the 10-foot test zone between the two packers. A Grundfos Rediflo II submersible pump was placed within this 10-foot-long test zone. Pressure transducers were positioned above, within and below the test zone.

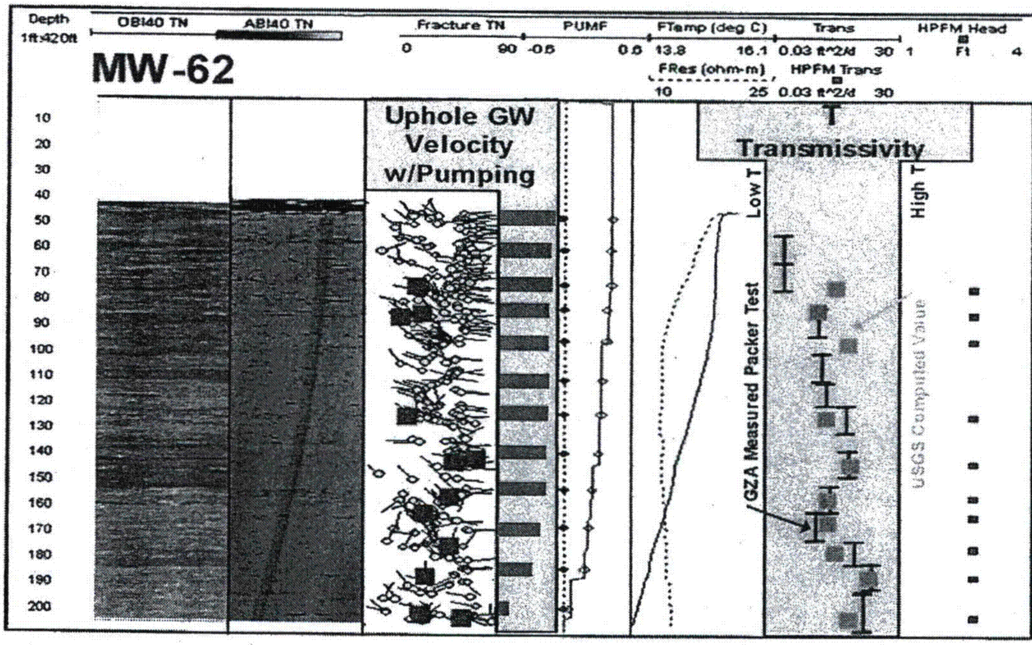
Using a drill rig hoist, the packer assembly was lowered on two-inch-diameter Schedule 80 pipe to the appropriate test depths within each tested borehole. See **Figure 4.2** for a schematic of the packer test assemblage.

Water levels above, within, and below the tested zone were recorded at ten second intervals using pressure transducers. Packers were inflated with 160-195 psi of nitrogen, and water levels were allowed to equilibrate. Once pressures had equilibrated, the pump was turned on and the tested zone was slow purged for at least ten minutes at a rate of 2 to 10 gallons per hour (gph). During this initial purge, a sample was collected for Tritium analysis in boreholes MW-30, MW-31, MW-32, MW-39, MW-51 and MW-52. Immediately following this initial purging period, the pumping rate was increased to a rate of 0.5 to 4 gallons per minute (gpm) in order to achieve drawdown of approximately 10 to 30 feet within the tested zone.

During drawdown, pressure transducer data was observed and compared to assess the potential for cross-zone communication, either through fractures interconnecting around the packer or incomplete seals by the packers. If significant drawdown could not be achieved, a short term sustained yield test was conducted. Once significant drawdown was achieved, or sustained yield was maintained for at least 30 minutes, a sample was collected for Tritium analysis. The pump was turned off, and the water level within the test zone was allowed to recover for either 30 minutes or until 80 percent recovery was achieved. For test zones in which sufficient recovery had been achieved, a final sample was collected for Tritium analysis. This sample was collected from all packer test zones except in borehole MW-40. In some test zones, as noted above, an additional sample was collected for Strontium analysis. After samples were retrieved, the packers were deflated and pressure transducer data was collected.

Packer test intervals and test pressures were measured in the field and recorded by GZA personnel along with all pertinent testing data. Hydraulic conductivity calculations and methodologies are presented in **Appendix G**. Packer test result summary sheets are presented in **Appendix I**. **Table 4.4** summarizes hydraulic conductivity data collected during packer testing.

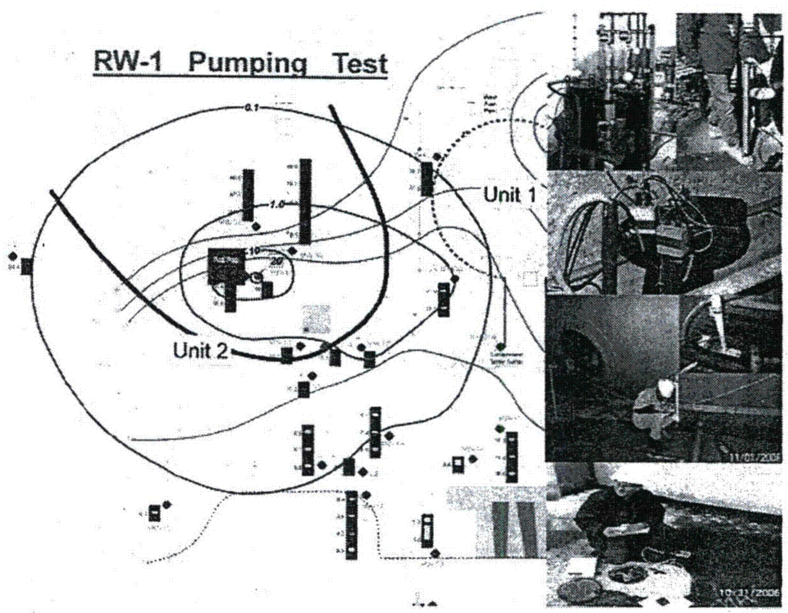
In addition to the analyses referenced above, depth-specific borehole transmissivity values were also computed by the USGS using the heat pulse flow meter data collected during the geophysical logging. These data generally confirmed the packer testing values computed as discussed above (see figure below for an example comparison). In some cases however, these two methods did not correlate well, as reflective of the limitations inherent with each method. For example, the heat pulse flow meter analyses yielded lower transmissivity values where the packer testing transducer data indicated leakage around the packers. In other cases, the heat pulse flow meter analyses proved to be too insensitive to measure lower transmissivity values.



COMPARISON OF PACKER TESTING TO HEAT PULSE FLOW METER ANALYSIS OF TRANSMISSIVITY

4.4.4 Pumping Test

GZA conducted a step drawdown, constant rate drawdown, and aquifer recovery test in recovery well RW-1 near the IP2-SFP as shown on **Figure 1.3**. Collectively, these tests are referred to as the "Pumping Test." The Pumping Test was performed in general accordance with our Standard Operating Procedure (SOP) dated October 11, 2006 and submitted as part of the "Pumping Test Report" dated and submitted to Entergy on December 8, 2006. A schematic of the Pumping Test data, testing and pumping equipment, and data monitoring is provided below.



EQUIPMENT, MONITORING AND DATA FROM PUMPING TEST OF RW-1

Prior to the Pumping Test, GZA installed select instrumentation including flow meters, precision gauges, and valving at the well head to control flow and to collect samples, and transducers in wells and drains to measure water level response to pumping.

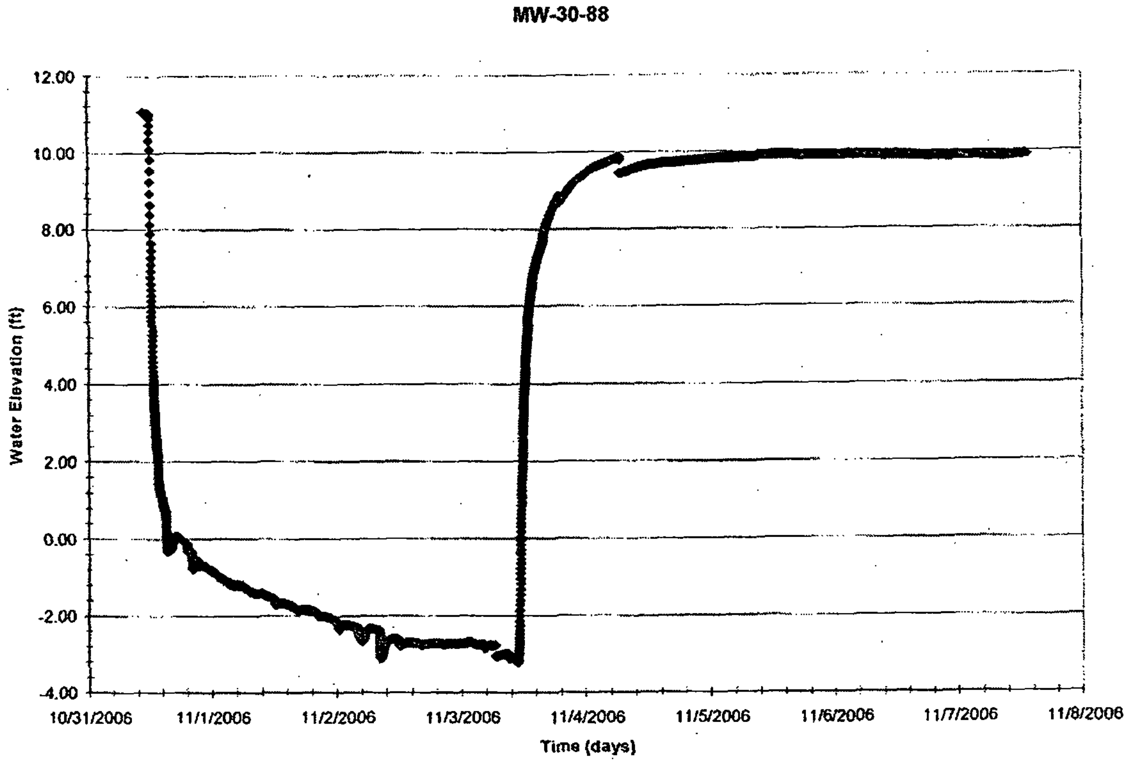
GZA conducted the Pumping Test by extracting groundwater from RW-1 at the following average flow rates:

Test Name	Begin Date	End Date	Pumping Rate at RW-1
Step Drawdown	10/25/2006	10/25/2006	2 gpm for 88 minutes 4 gpm for 77 minutes 5 gpm for 63 minutes 7 gpm for 28 minutes
Constant Rate Drawdown	10/31/2006	11/3/2006	4 gpm for 71 hours
Recovery	11/3/2006	11/6/2006	No pumping

PUMPING TEST SUMMARY TABLE

During the Pumping Test, we monitored and recorded the following:

- Water level elevations with 75 pressure transducers at 44 groundwater monitoring wells at the Site. Water levels in the 15 primary monitoring wells (i.e., I-2, MW-30, -31, -32, -33, -34, -35, -36, -37, -42, -47, -51, -52, -53, and -111) were monitored once per minute. The remaining 29 wells (MW-38, -39, -41, -43, -44, -45, -46, -48, -49, -50, -54, -55, -56, -57, -58, -59, -60, -62, -63, -65, -108, -109, U3-2, U3-3, U3-C1, U3-T1, U3-T2, U3-4D, and U3-4S) were monitored hourly.
- Water quality parameters; we also collected groundwater samples for Tritium and Strontium analysis during the step drawdown and constant rate drawdown test at RW-1.
- Flow rates at the IP1-NCD and IP1-SFDS, and the IP2-Curtain Drain; generally at the frequency and using the methods stated in the SOP.
- Precipitation via data available from the on-Site meteorological tower or via information available at www.wunderground.com for the surrounding area.



EXAMPLE OF TIME VS DRAWDOWN CURVE FOR MW-30

The Pumping Test activities are further detailed in our December 8, 2006 report. The results of the Pumping Test are described in **Section 6.0**.

4.5 WATER SAMPLING

Sampling of on-Site groundwater and surface water sources and off-Site groundwater and surface water sources was conducted during the period of this study. The locations and methods of sampling are described in the following sections. The results of the sampling are discussed in **Section 10.0**.

4.5.1 On-Site Groundwater Sampling

On-Site groundwater sampling commenced in August 2005, upon observation of the moist shrinkage cracks in the IP2-SFP wall. Through May 2007, sampling was conducted primarily by Entergy personnel. During this period, GZA personnel collected groundwater samples only during packer testing and when conducting low flow groundwater sampling at monitoring wells MW-30 and MW-42. After May 2007, GZA personnel conducted all groundwater sampling. Over 700 groundwater samples were collected during the study.

GZA and Entergy personnel collected groundwater samples using traditional purge techniques, modified purge techniques, or low flow sampling techniques. Groundwater samples were collected from specific intervals in monitoring wells MW-30 and the 2-inch diameter well-screened interval of MW-42 using low flow purging and sampling methods described in the USEPA's Low Flow Purging and Sampling Guidance document. These sampling techniques are described in the following sections.

4.5.1.1 Purging

At the early stages of the project, Entergy personnel sampled open borehole wells and nested piezometers by purging the traditional 3 to 5 times the volume of water standing in the well casing[19]. This was accomplished with either a dedicated submersible pump, a peristaltic pump with dedicated tubing, or a Waterra foot-valve pump with dedicated tubing. As the investigation proceeded, GZA became concerned that the standardly-required purge volume could force unrepresentative displacement of contaminants in the low conductivity bedrock through sampling-induced drawdown in the wells. We therefore reduced the purge volume, for wells not low flow-sampled, to 1.5 well volumes for the remainder of the investigation. This modification to the sampling procedures was discussed with the regulators. By May 2007, low flow sampling procedures had been adopted and implemented for all wells.

4.5.1.2 Low Flow Sampling

The low flow sampling method allows collection of groundwater samples representative of ambient flow conditions at discrete sampling zones, while limiting the accumulation of wastewater, mobilization of contaminants, and turbidity of samples by reducing pumping rate and drawdown. GZA collected low flow groundwater samples using peristaltic pumps, Grundfos Readiflo II submersible pumps, and several models of submersible pumps manufactured by Proactiv. Low flow samples were also collected at discrete sampling intervals of deeper boreholes using Solinst Multilevel Waterloo sampling systems. The use of Waterloo systems for low flow sample collection is summarized in the following section. With the exception of wells MW-30 and MW-42, GZA began low flow sampling in May 2007. GZA collected samples from MW-30 and MW-42 using low flow techniques starting in January 2006.

GZA collected low flow samples by slowly pumping from a predetermined well depth while monitoring water quality parameters, including pH, specific conductance, temperature, turbidity, dissolved oxygen, and oxygen reduction potential (ORP). Water quality parameters were monitored using a Horiba U22 water quality meter with an in-line flow-through cell. Pumping rates were typically between 100 and 400 ml per minute, and drawdown within the well was typically limited to between 0.1 and 1.0 foot.

GZA recorded water quality parameters, water level, and flow rate every five to ten minutes during a pre-sampling purge which lasted generally between one half hour and three hours. Samples were collected upon stabilization of water quality parameters listed above. Low flow sampling logs are provided in **Appendix J**. Note that sampling logs dated prior to May 2007 reference original well nomenclature.

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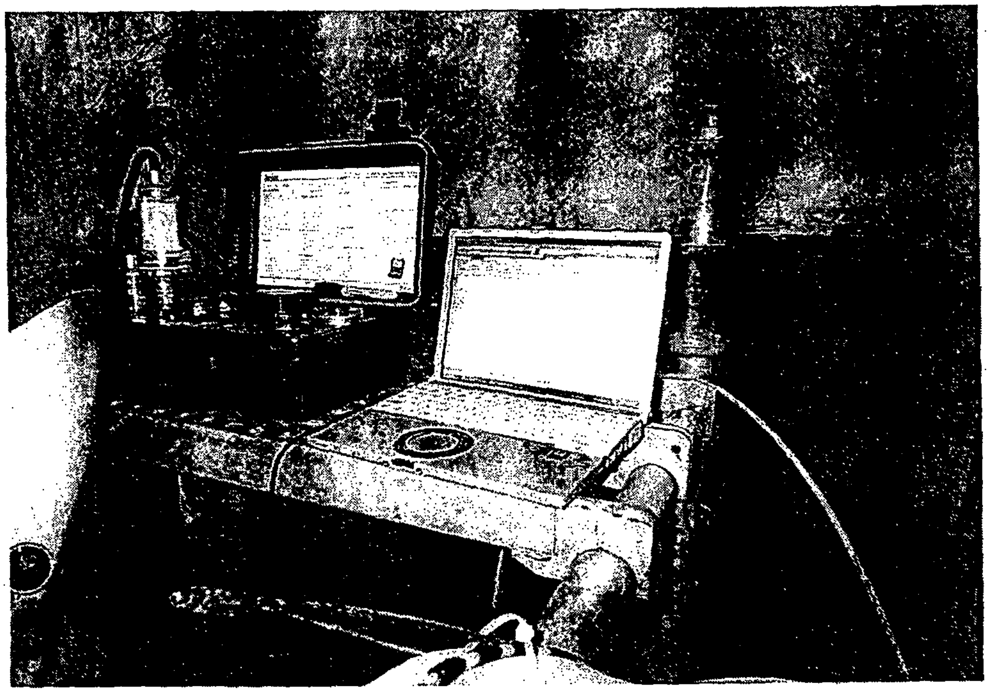
[19] Water quality parameters during well purging were not measured by Entergy personnel as part of their groundwater sampling rounds.

4.5.1.3 Waterloo Low Flow Sampling

Low flow sampling was also conducted in Waterloo installations at MW-30, -31, -32, -39, -40, -51, -52, -54, -60, -62, -63, and -67. Samples were taken from discrete intervals unless the interval was depressurized, in which case 1.5 well volumes were purged prior to sampling.



LOW FLOW SAMPLING OF MW-30

4.5.1.4 Discrete Interval Packer Sampling

During packer testing prior to installation of Waterloo systems, GZA collected groundwater samples representative of several distinct elevations within each borehole. GZA collected water samples for Tritium analysis for each tested interval in all boreholes except MW-40. Water samples were also collected for Strontium analysis in boreholes MW-54, -60, -62, -63, and -66. Sampling procedures were described in **Section 4.4.3.**

4.5.2 On-Site Surface Water Sampling

On January 19, 2007, GZA collected samples from the Discharge Canal and Hudson River to evaluate major cation geochemistry. This sampling was designed to help us assess potential sources of water found within monitoring wells MW-38 and -48. Samples were collected with dedicated high density polyethylene bailers. In addition, Entergy routinely collects composite water samples from the Discharge Canal to evaluate the discharge of radionuclides to the Hudson River. These samples are collected using peristaltic pumps at locations indicated in the Annual Radiological Environmental Operating Report (AREOR).

4.5.3 Off-Site Groundwater Sampling

At the beginning stages of the investigation, prior to a thorough understanding of the hydrogeology of the Site, several off-Site groundwater wells were sampled by Entergy personnel to assess the potential for off-Site contamination. These data are presented in the AREOR and the sampling is conducted under the Radiological Environmental Monitoring Program (REMP). During the course of this study, the normal sampling frequencies were increased to either monthly or quarterly to assess regional background concentrations of contaminants of interest. These sampling points included: four USGS monitoring wells, three LaFarge property wells, and the Fifth Street well in Buchanan. **Figure 4.3** shows the locations of the USGS Wells. **Figure 1.3** portrays the location of the LaFarge wells. Please refer to the AREOR for the location of the Fifth Street well.

USGS Wells - On December 5 and 6, 2006, GZA personnel, accompanied by a New York State Department of Environmental Conservation (NYSDEC) representative, collected groundwater samples from four USGS groundwater monitoring wells to assess background concentrations for Tritium, Strontium and Cesium in the region. The wells were located in Harriman State Park, Rockland County, (RO543); Carmel, New York, Putnam County (P1217); Fort Montgomery, New York, Orange County (local municipal water monitoring well); and Doodletown, New York, Rockland County (RO18). All four monitoring wells were completed in bedrock. The NYSDEC provided GZA with borehole geophysical data. All four wells exhibited upward vertical gradients. GZA selected sample locations based upon the flowmeter data so as to sample the groundwater at a depth just below where it was presumed to be exiting the borehole. The groundwater samples were transported to Entergy under chain of custody procedures. Entergy personnel then shipped the samples to Areva Laboratories in Westboro, Massachusetts for analysis of Tritium, Strontium and Cesium.

LaFarge Wells - GZA personnel supervised the collection of groundwater samples from the Lafarge property immediately South of the Site from groundwater monitoring wells MW-1 through MW-3. Samples were collected by LaFarge's environmental consultant, Groundwater and Environmental Services, Inc., under the oversight of Entergy personnel, GZA and NYSDEC representatives on September 19, 2006. Groundwater samples were collected using a bladder pump following low flow procedures described below. The depths of the wells are shown on **Table 4.1**.

Fifth Street Well - Entergy personnel, accompanied by NRC and NYSDEC personnel, collected samples from the Fifth Street well in Buchanan, New York on November 30, 2005. This well is a former private drinking water well no longer in use.

4.5.4 Off-Site Surface Water Sampling

During the course of this study, off-Site surface water was sampled at the following locations: the Camp Field Reservoir and the New Croton Reservoir, Algonquin Creek, Trap Rock Quarry, the LaFarge property (Gypsum Plant) outfall, and the Hudson River (see **Figure 4.4** for the locations of the Reservoirs). The sampling frequency discussed in the AREOR was increased during the investigation. Detailed sample locations are discussed in the AREOR.

4.6 PIEZOMETRIC LEVELS AND PRESSURE TRANSDUCER DATA

GZA measured piezometric levels at 67 locations at the Site over time (between October 2005 and September 2007) using a system of electronic pressure transducers. These measurements were converted to groundwater elevations (NGVD 29) by referencing the depth of the transducer below the water table at a given time to the elevation of the top of the monitoring well riser. GZA used the resulting data to estimate hydraulic properties of the soil and bedrock, and assess the effects of precipitation, tidal influences, seasonality, and pumping on groundwater flow patterns.

This section describes the methods we used to collect and manage this data. Discussions on the use of the data are presented in **Sections 6.0** and **10.0**.

4.6.1 Transducer Types and Data Retrieval

GZA used two types of transducers, depending on the well type and application. In open wells, GZA installed MiniTroll and LevelTroll transducers, which are vented pneumatic transducers with internal dataloggers. These transducers are manufactured by In-Situ® Inc. In wells equipped with Waterloo systems, GZA installed non-vented vibrating wire transducers manufactured by Geokon® Inc. Each of these transducers was connected to a Geokon datalogger box located within the well vault.

GZA selected and installed pressure transducers within the appropriate operating pressure range required for each well or well interval. **Table 4.5** provides the accuracy of the transducers as reported by In-Situ and Geokon. This table also provides the type of transducer used in each well or well interval.

GZA collected data from In-Situ transducers typically every one to three months, or as needed. We exported data collected from each transducer from data files recognizable only by Win-Situ software into Microsoft® Excel® spreadsheets. Generally, no external data manipulation was required for these data reports. On occasion, adjustments to data were required to correct for daylight savings time, or to correct for measured disturbance of the transducer position within the well.

GZA collected water level data from each Geokon datalogger typically every two weeks to two months, or as needed. After collection, we exported the raw data into Excel spreadsheets and converted reported water levels to water elevations. Because the Geokon transducers are not vented, we adjusted total pressures to account for barometric pressure changes. Into each data report, GZA incorporated: 1) the barometer reading recorded during wellhead zeroing of the respective transducer; and 2) the barometric pressures recorded at or near the Site at the time the total pressures were recorded. Barometric pressures for this project were recorded on an on-going basis on Site using a Geokon transducer exposed to atmosphere. At different times, the barometric pressure transducer was installed several feet above the maximum water table in MW-31, MW-65, and MW-56. For verification, GZA also used barometric pressure data collected by West Point Military Academy, less than ten miles from the Site.

4.6.2 Data Availability and Preservation

A compact disk containing piezometric data collected between October 2005 and September 2007 is provided in **Appendix K**. The data is organized by well number in Excel spreadsheets. Note that piezometric data dated prior to May 2007 reference original well nomenclature.

Graphs of water levels between October 2005 and February 2007 are presented in **Appendix L**. Transducer installation logs are provided in **Appendix M**. As indicated by the legend on the first sheet of this Appendix, colors on these graphs illustrate changes in groundwater temperature. Each graph presents water levels from wells that are grouped together based on proximity to each other and association with selected Site features. Well locations are shown in **Figure 1.3**.

4.7 TRACER TESTING

To further test the Conceptual Site Model and assess groundwater flow paths from the source areas, GZA conducted an organic tracer test consisting of the injection of Fluorescein (a common dye used in anti-freeze) at a tracer introduction point located close to a potential source of Tritium at IP2-FSB. The injection well was installed approximately four feet South of the expansion crack observed in the South wall of the IP2-SFP, adjacent to monitoring well MW-30. The injection well was designed to allow the injection of tracer onto the top of bedrock located at elevation 52 feet. This elevation corresponds to the bottom of the IP2-SFP. Tracer was then gravity fed into the injection well and flushed with water. After injection, routine sampling and monitoring for the presence of tracer in Site wells commenced and continued for 27 weeks[20].

The tracer introduction was made on February 8, 2007. Tap water was introduced into the injection well adjacent to MW-30 beginning at 10:30 hours. By 10:41 hours, 30 gallons of water had been introduced into the injection well to wet the surfaces of the material down gradient from the injection well. The water introduction was then suspended while ten pounds of Fluorescein dye mixture containing approximately 75% dye and 25% diluent, all of which had previously been dissolved in ten gallons of water, was introduced into the injection well. The dye mixture was introduced between 10:42 and 10:50 hours. Tap water introduction was resumed at 10:51 hours and continued until 11:40 hours. A total of 210 gallons of water was used: 30 gallons to wet the surfaces, 10 gallons to dissolve the tracer, and 170 gallons to flush the tracer out of the dry well into the surrounding bedrock fracture system. Water introduction was made at a mean rate of three gallons per minute.

Sampling and monitoring continued through mid-August 2007, which constituted the completion of the test. The well locations monitored during the organic tracer test and the sampling results are presented in **Appendix N**.

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[20] In addition to the routine sampling, specific wells were sampled for a longer period of time as part of short term variability testing (see **Section 9.0**).

The following sections describe the key elements of the test. The results of the tracer test are discussed in **Section 7.0.**

4.7.1 Injection Well Construction

Following excavation of soil and rock along the southern wall of the IP2-SFP for the construction of a new foundation for a heavier crane, the top of rock was exposed along the South wall of the IP2-SFP at elevation 52 feet. Prior to pouring a mud-mat, construction of the crane foundation and backfilling of the excavation, GZA installed one groundwater monitoring well (MW-30) and one dye injection well. The dye injection well was constructed of one-inch Schedule 40 PVC pipe which terminated at elevation 52 feet. In order to provide a reservoir for the dye to accumulate in prior to seeping into bedrock fractures, a one-foot-thick layer of ¾-inch crushed stone was placed on the top of rock over an area approximately 6 feet by 6 feet square. A mud-mat was poured over the crushed stone layer and across the entire floor of the excavation. The excavation was then backfilled. This injection well design allowed for the dye to be injected on the top of rock and infiltrate into the bedrock in a similar manner as water leaking from the South wall of the IP2-SFP.

4.7.2 Background Sampling

Prior to injection of dye, GZA collected background samples to assess the potential of Fluorescein to be present in the subsurface. Almost all sample locations (which included manholes, surface water bodies, nested wells, Waterloo wells) were sampled for approximately one week periods two to five times prior to dye introduction. This set of data helped in the selection of dye type and quantity, and assured that background levels of Fluorescein were not an obstacle to conducting the groundwater tracing investigation.

4.7.3 Sampling Stations

Sampling stations were selected by GZA for their relevance to the project. Some stations were established as control stations. Control stations were established to detect any fluorescent compounds not introduced as part of this investigation which might enter the study area. Most sampling stations were established to detect dyes introduced during this investigation.

Sampling stations included manholes into the Site drainage system, open waters such as the Discharge Canal and the Hudson River, clusters of nested wells, open borehole wells, and wells with Waterloo packer systems installed. Primary reliance for the detection of dye was placed on activated carbon samplers except at Waterloo locations. One carbon sampler was placed in each well and two were placed in open water locations and in manholes. Open water locations may have strong currents that could damage or wash away a sampler. Placing two samplers at these locations helped ensure that data would be collected for any given time interval and provided duplicate samples for quality assurance. At Waterloo wells, water was the only sampling medium.

Carbon samplers are continuous, accumulative samplers that virtually assure that dye migrating with groundwater is not missed at sampling locations. These samplers, however, provide information on the concentration of dye at a specific time. Because water is an instantaneous sample instead of a continuous sample the Waterloo wells were sampled more frequently.

The sampling schedule was designed to help ensure that the time the tracer arrived was recorded, and that it would be unlikely that a transient event would fail to be detected at any sampling location. The latter point only applies to the Waterloo sampling locations, since carbon packets collect samples continuously. Grab samples of water only represent the conditions at the instant the water is collected.

High frequency (or high intensity) sampling stations were selected based primarily on three criteria:

- The boundaries of the Unit 1 plume. Most wells that are located within the plume were sampled frequently.
- The premise that non-detections of dye could be as important as detections. Therefore, a "halo" of wells expected to have no detectable dye were sampled surrounding the Unit 1 plume so that the boundaries of the tracer plume would be well defined.
- That there was the possibility of poor correspondence between the tracer plume and the Unit 1 plume at some locations, and that the network might have to be adjusted to maintain the halo of non-detection sampling locations. This resulted in frequent review of the sampling network, and sampling stations were moved from the low intensity to high intensity sampling schedule as tracer was detected near the margins of the high intensity sampling network.

4.7.4 Analysis Schedule

Samples were typically shipped from the Site on the sample collection day or the next day to accommodate next day delivery. Primary samples (both carbon and water) were analyzed within five working days after receipt. Water samples analyzed because of tracer detections in the associated carbon samplers were analyzed within five working days following the carbon analyses. Results were communicated to both Ozark Underground Laboratory (OUL) and GZA project management for review of the detections and consideration of whether or not the sampling network should be modified.

4.8 ADDITIONAL GEOPHYSICAL TESTING TO EVALUATE FLOW PATHS

In addition to the downhole geophysical testing described in **Section 4.2.4**, a series of geophysical surveys was conducted to assess the depth to bedrock in certain areas of the Site and to identify the potential presence of preferential groundwater flow paths along utility trenches cut into bedrock. The major findings of the surveys are graphically shown on **Figure 1.3.**

Under the oversight of GZA, AGS conducted surface geophysical surveys to assess depth to bedrock within the IP2-TY, along the North side of IP2-Turbine Generator Building (TB), within the IP3-TY and along the OCA access road on the southern side of the Protected Area. AGS used ground penetrating radar (GPR) and electromagnetic (EM) survey equipment to complete the surveys. The survey reports are attached in **Appendix O.** The results of the surveys indicate that bedrock is fairly shallow beneath the areas investigated, except for the areas along the Hudson River where the depth to bedrock increases.

Specifically, the following work was completed:

- A GPR survey was conducted to assess depth to bedrock and potential utility trenches cut into bedrock in the IP3-TY.
- A GPR survey was conducted to assess the potential for contaminants to enter groundwater through leaking stormwater pipes (E-Series) and flow with groundwater towards the Hudson River within utility trenches cut into rock along the OCA access road on the South side of the Protected Area, and to identify depth to bedrock and any utility trenches cut into rock along this roadway.
- In order to assess the presence of subsurface utility trenches to provide preferential pathways for contaminated groundwater to flow to the North, thus accounting for the impacts to groundwater observed in monitoring well MW-48 and MW-38, AGS performed a geophysical survey consisting of a seismic refraction survey, GPR survey, and an EM survey to provide information on bedrock topography on the southern side of the Site between the Protected Area and the southern warehouse.
- In addition, several utilities were identified using EM survey techniques. However, no information regarding the nature of the backfill along the utilities could be discerned from the geophysical information.

The findings of the geophysical survey work are discussed in **Section 6.0**.

5.0 LABORATORY TESTING

Entergy and GZA arranged for, and managed, the analyses of groundwater samples. Between October 2005 and the end of September 2007, over 700 samples were analyzed for radiological contaminants, and, as part of the tracer test, nearly 4,400 samples were analyzed for Fluorescein. In addition, a limited number of samples were analyzed for selected water quality parameters. This section describes the respective testing programs as well as some of the Quality Assurance/Quality Control (QA/QC) procedures used to assess the validity of the data.

5.1 RADIOLOGICAL

Entergy and GZA personnel both collected groundwater samples for radiological analysis from existing and newly installed wells between October 2005 and September 2007. Groundwater samples were sent by Entergy personnel via chain of custody to outside laboratories for analysis of select parameters including Tritium, Strontium, gamma emitters (including Cesium, and Cobalt), and Nickel[21]. Samples were analyzed at the following laboratories: IPEC, Teledyne Brown Engineering, Inc., located at 2508 Quality Lane, Knoxville, Tennessee; Areva NP, Inc. located at 29 Research Drive, Westboro, Massachusetts; James A Fitzpatrick, NPP Environmental Laboratory, located at 268 Lake Road, Lycoming, New York; and General Engineering Laboratories located at 2040 Savage Road, Charleston, South Carolina. The results of the groundwater analyses are summarized in **Table 5.1**. Note that the sample nomenclature for groundwater analytical data collected after May 2007 are provided in the figures, however, location nomenclature prior to May 2007 may differ[22] due to subsequent casing reference point upgrades.

5.1.1 Hydrogeologic Site Investigation Analytical Data

Groundwater samples were typically analyzed for the following: Tritium by EPA Method 906; Strontium by EPA Method 905; and gamma emitters (including Cesium and Cobalt). In addition, transuranics and Nickel (as well as other "hard to detect" radionuclides) were also analyzed in specific instances, as appropriate.

Quality control criteria utilized during this investigation included the following as appropriate: laboratory blanks; field duplicates; laboratory duplicates; laboratory control samples; matrix spikes and matrix spike duplicates; initial and continuing calibrations; instrument tuning; internal standards; and regulatory split samples.

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[21] Tritium and Strontium were the primary radionuclides focused on during the current work pursuant to source identification, groundwater flow analysis and contaminant plume delineation. Radionuclides other than Tritium and Strontium also exist to a limited extent and are fully addressed within the context of the Unit 2 Tritium and Unit 1 Strontium discussions.

[22] See **Section 4.3.4.** Note, however: 1) High priority and fast track sampling preceded casing elevation surveys and vault installation in several cases, 2) low flow sampling within a well screen resulted in collection of samples at depths differing from the well nomenclature, and 3) reinstallation of Waterloo multilevel wells to upgrade packer assemblies. In addition, sample intervals are designated by depth from top of casing.

An overall evaluation of the data indicates that the sample handling, shipment and analytical procedures have been complied with, and the analytical results should be useable. However, during one time period (August and September 2006), Strontium analytical results from Teledyne Brown Engineering, Inc. were as much as an order of magnitude different than split samples analyzed by the NRC and the NYSDOH. (Following verification of this information, the laboratory was dropped from the investigation program.) Therefore, that sample set was not utilized as part of the investigation.

Data Collection and Tracking

The data collection and data tracking phase included the following:

- Preparing all sample bottle labels and chain-of-custody forms;
- Documenting all required data in field log books and field logs;
- Performing data entry of the sampling information into Entergy's database system; and
- Quality assurance/quality control reviews of all data entry.

Laboratory Analysis

The laboratory analysis phase included the following:

- Regular communication between the laboratory and the project laboratory data manager;
- Reviewing the laboratory's sample receipt acknowledgement form;
- Documenting the project's progress in Entergy's database system; and
- Laboratory preparation of the Electronic Data Deliverable (EDD).

Data Loading

The data loading phase included the following:

- Loading all EDDs into the database;
- Resolving any data loading issues;
- Creating a post-load report for content review; and
- Notifying the project team when EDDs were available.

Data Visualization and Analysis

The data visualization and analysis phase included the initial data review by the project team and the production of data queries and draft reports to interpret the data. This phase was accomplished through the use of query tools and preformatted reports in the database.

5.2 ORGANIC TRACER

Sampling for the tracer was based on both activated carbon samplers and on grab water samples. All analyses were conducted using a Shimadzu RF5301 fluorescence spectrophotometer operated under a synchronous scan protocol. Details of the analytical approach are presented in the Ozark Underground Laboratory (OUL) procedures and criteria document **(Appendix P)**.

5.3 WATER QUALITY PARAMETERS

Groundwater samples were collected from monitoring wells MW-38, MW-48-23, and MW-48-38 and also from the Discharge Canal and Hudson River. The groundwater was collected as a grab sample using low flow sampling techniques. The surface water samples from the top of the water column were collected using bailers. The samples were collected at high and low tides. Groundwater samples were also collected at mid tide[23]. The samples were sent under chain-of-custody procedures to Life Science Laboratories, Inc., Brittonfield Parkway, Suite 200, East Syracuse, NY 13057. The samples were analyzed for Bicarbonate Alkalinity (as $CaCO_3$) under EPA Method M2320; Iron, Magnesium, Sodium, and Calcium under EPA Method 6010; and Sulfate and Chloride under EPA Method E300.

[23] Sample nomenclature was as follows: Monitoring Location Name-Depth Interval (if applicable). Tide Interval (H=High, M=Mid, L=Low) and replicate number (if applicable).

6.0 HYDROGEOLOGIC SETTING

This section describes the hydrogeologic setting at IPEC. Our description is based on a literature search and the findings of our field investigation program. The hydrogeology is described in reference to the two components of an unconfined aquifer found at IPEC; overburden and bedrock. Both the overburden (in select areas) and bedrock are groundwater-bearing zones which are monitored at the Site. Refer to **Section 4.0** for a summary of the groundwater monitoring system.

6.1 REGIONAL SETTING

The surface topography in the region of the Site slopes downward relatively steeply towards the Hudson River and is characterized by ground surface elevations ranging between approximately 10 and approximately 140 feet above the National Geodetic Vertical Datum of 1929 (NGVD 29). Refer to **Figures 1.3** and **3.2** for Site and regional topographical maps.

The Hudson River is a tidally influenced estuary in the vicinity of the Site, generally experiencing two high tides and two low tides daily. Near high tide, the river experiences a flood current running North. Near low tide, the river experiences an ebb current flowing South. Surface water elevations of the Hudson River as measured at Peekskill, NY, approximately two miles North of the Site, from October 20, 2005 through May 8, 2006 have ranged from -1.31 feet to 3.26 feet NGVD 29. On-Site measurements indicate that the Hudson River elevations vary between -1.1 feet to 3.8 feet NGVD 29.

Other surface water features include the cooling water Discharge Canal with a mean surface water elevation of approximately 1.7 feet above the Hudson River. The Discharge Canal is shown on **Figure 1.3**. The Discharge Canal conveys up to 1.76 million gallons per minute (MGM) from Units 2 and 3, discharging to the Hudson River. As shown on cross-sections A-A' and B-B' on **Figure 1.3**, the walls of the canal are constructed of low structural concrete. However, the current condition and thickness of the canal bottom is variable and appears to range from a 0.5-foot-thick mud slab in the IP2 area (based on construction drawings) to a bedrock bottom in the IP1 area.

Stormwater at developed portions of the region and Site is directed towards and collected in catch basins and discharged to surface water bodies. Stormwater discharges from the Site are routed to the cooling water Discharge Canal[24], the Hudson River, or the groundwater regime through leaks from the storm system.

6.2 GROUNDWATER RECHARGE

Groundwater recharge at and near the Site is limited to precipitation. That is, there is no significant artificial recharge or irrigation in the area. Precipitation in the vicinity of the

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[24] There are stormwater outfalls that discharge directly to the Hudson River.

Site is approximately 36 inches per year[25]. Recognizing that a portion of precipitation is lost to evaporation, transpiration, and run-off, direct recharge to an aquifer was estimated. Large scale modeling performed by the USGS for Westchester County, NY[26], suggests that groundwater recharge to glacial till-covered bedrock hills, typical of the conditions near Indian Point, ranges from 3.6 to 7.5 inches per year with an average of 5.5 inches per year. Our experience in a similar hydrogeologic setting[27] found higher natural recharge rates, averaging approximately 10 inches per year. Considering all available information, we believe recharge at the Site is between 1/10 and 1/3 of precipitation. Based on our evaluation, we estimate recharge on and up-gradient of the Site is approximately 10 inches/year[28]. Note that for the purposes of this study (as opposed to water supply evaluations), it is conservative to use high estimates for recharge.

6.3 GROUNDWATER DISCHARGE

Groundwater flows from areas of higher heads to areas of lower heads along the path of least resistance. At the Site, discharge from the groundwater occurs into the Discharge Canal, the Hudson River, and to system underdrains. As evidenced by Site groundwater contours, groundwater discharge is not uniform along the river or to the Discharge Canal. That is, the aquifer in areas of the Site with higher transmissivities (lower resistance to flow) will discharge more water than other areas. Similarly, the water table fluctuates seasonally (due to long term changes in average recharge rates) and locally during rainfall events and periods of snow melt. Consequently, groundwater discharge is not constant in time. Additionally, changes in the river elevation cause additional short term variations in discharge rates.

The Hudson River is the regional sink in the area. As such, groundwater from the upland areas to either side of the river valley flow towards and discharge to the river under ambient conditions, see **Figure 6.10**. Groundwater from IPEC does not flow under the river to the other side (e.g., to Rockland County) under ambient conditions. Further, because of the hydraulic properties of the bedrock, as well as the size of the Hudson River in this area, there is no reason to believe that pumping or injection (non-ambient conditions) could induce such flows.

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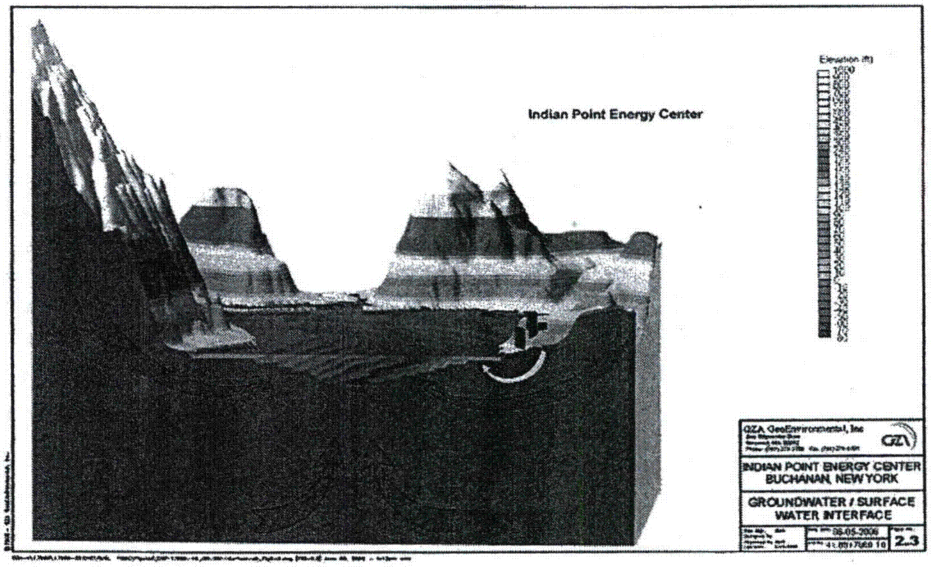
[25] This precipitation value is a 10 year average of data available from the on-Site meteorological station.

[26] USGS. Water Use, Ground-Water Recharge and Availability, and Quality of Water in the Greenwich Area, Fairfield County, Connecticut and Westchester County, New York, 2000-2002.

[27] Calibrated Groundwater Model, Central Landfill Super Fund Site, Johnston Rhode Island, June 2006

[28] Areal Recharge varies temporarily and spatially. The average of 10 inches per year is an estimated watershed-wide, long term average. The development at the Site induces additional runoff. We believe that this potential decrease in areal recharge is offset by recharge from exfiltration of leaky stormwater systems. As discussed in **Section 6.7**, this appears to be the case.



GROUNDWATER FLOW BELOW AND INTO HUDSON RIVER

Foundation drains at three structures (see **Section 6.7**) intercept groundwater (see **Figure 1.3**). This water is conveyed, via gravity flow and/or pumping, to the Discharge Canal, creating local depression in the water table and a flattening of hydraulic gradients downgradient of the structure. With these conditions noted, over a period of months the rate of groundwater discharge to the river at IPEC is continuous and fairly constant. Discussions on the rate of discharge are provided in **Section 6.7**.

6.4 GEOLOGY

This section describes the geology of the Site and region. It is based upon a literature search and the results of our investigations. **Figure 6.2** portrays the regional bedrock geology. The narrative is organized to convey the role of geologic and tectonic processes in creating the mechanisms by which groundwater flows through the Site[29]. Findings support our Conceptual Site Model (CSM) and indicate that the bedrock at the Site is characterized by sufficiently interconnected small bedrock fractures to allow the hydrogeologic system to function and be modeled as a non-homogeneous, anisotropic, porous media.

6.4.1 Overburden Geology

The Lower Hudson Valley has been subjected to repeated glacial advance and retreat, creating a typical glacial morphology of main and tributary valleys and bedrock ledges. The glaciers have controlled the deposition of unconsolidated deposits in the region, although these are absent locally due to erosion and excavation. Glacial till lies directly on the bedrock surface and is generally less than 10 feet thick, although it is locally thicker against steep North-facing bedrock slopes. The till is typically unstratified and

[29] The Inwood Marble, which predominates at the Site, is a crystalline metamorphic rock type. As such, it has a very low primary porosity (i.e., water does not flow through the intact rock itself, but is confined to the fractures in the rock.

poorly sorted. Locally, it consists of a silty, fine- to medium-grained, brown, sandy matrix containing fine gravel to boulder-size bedrock fragments. Fluvial and lacustrine glacial deposits occur in valley bottoms and valley walls. The glacio-fluvial deposits are typically medium to coarse sand and gravel with minor silt. The lacustrine deposits are finely laminated and varved clays fining upwards to fine- to medium-grained sand, and the fluvial/deltaic sediments are mixtures of coarser sands and gravels and finer sands to clays. Recent deposits are essentially flood plain and marsh deposits along the Hudson River, its tributaries, and small enclosed drainage basins.

Overburden geology at the Site is limited to a layer ranging from ground surface to between 3.5 and 59 feet below ground surface (bgs), with thicknesses generally increasing towards the Hudson River. Overburden materials are dominated by anthropogenic fill (borings MW-41, -49, -52, as well as the upper 20 feet of -39, -48, -61, -62, -63, -66 and 67). Soil-based fill materials at the Site consist primarily of silty clay, sand and gravel mixtures (i.e., regraded/transported on-site glacial till) or gravel/cobble/boulder-size blast rock. In areas adjacent to structures excavated into bedrock, the fill occurs as concrete, compacted granular soils, and blast rock fill. Native materials occur as open areas of glacial till overlying bedrock, or silty clays, organic silt and clay, and sandy material overlain by granular fill. A 20- to 50-foot-thick sequence of river sediments (organic silts) is found along the Hudson River above bedrock in borings MW-38, -48, -61, -62, -63, -66 and 67 The approximate location of natural materials is shown on **Figure 6.3**.

6.4.2 Bedrock Geology

The geology of the Site has been investigated and reported by Dames & Moore (1975) prior to this program. **Figures 6.2** and **6.4** show the bedrock geology of the region and the Site, respectively. The current investigations have added substantial detail to this assessment which shows that the bedrock beneath the Site is considerably fractured and contains sufficient interconnectivity to support groundwater flow, at the scale of the Site, as flow through a non-homogeneous, anisotropic, porous media.

The Site is located in a complex of Cambro-Ordovician rocks represented by the Manhattan Formation and Inwood Marble Formation in angular unconformity. The Site lies predominantly upon the Inwood Marble Formation as an angular unconformity with the Manhattan Formation. The oldest rock is the Inwood Formation, which was derived from deposition of carbonate materials in a shallow inland sea during the Cambrian through the early Ordovician period. The Manhattan Formation is interpreted to post-date the Middle Ordovician regional unconformity with the Inwood Marble and represents sediments derived from continental or volcanic island materials in deeper waters.

During the Ordovician period, an island arc system consisting of a series of volcanic islands appeared off the coast of what is currently North America as a subduction zone developed in response to oceanic crust colliding with continental crust. The presence of the volcanic island arc system resulted in interlayering of volcanic material with the sedimentary rocks of the Inwood Marble and Manhattan Formations. As continued subduction occurred and continental land mass began to collide with continental North America during the Taconic and Acadian Orogenies, the rocks of the Inwood Marble

Formation and the Manhattan Formation underwent substantial metamorphism and deformation.

The Inwood Marble is a relatively pure carbonate rock of dolomitic and/or calcic mineralogy with silica rich zones. The rock tends to be coarsely sacherroidal with remnant foliation and intercalated mica schist. The color and crystalline texture vary from place to place due to the various levels of metamorphism; the color is typically white to blue grey. The metamorphic grade is locally elevated due to minor intrusions. The common minerals are calcite, dolomite, muscovite, quartz, pyrite and microcline. The Manhattan Formation is represented on the Site by two distinct members. The lower member is an assemblage of schist, schistose gneiss and amphibolites intercalated with marble, white quartzite and fine-grained metapelite. The marble bearing lower member of the Manhattan Formation likely represents transition from a shallow carbonate sea to deeper water sedimentation and maybe the equivalent to the Balmville Limestone which occurs in Dutchess County[30]. The middle member is garnet rich mica schist. The upper member consists of biotite-muscovite mica schist with quartz-feldspar laminae.

The original sediments have undergone repeated intense phases of burial, metamorphism, uplift, folding and faulting due to: three phases of continental collision (the Taconic, Acadian, and Alleghanian); continental rifting as the present Atlantic Ocean began to form in the Mesozoic; erosion/uplift; and recent glacial rebound. All of these processes have resulted in the presence of fractures that affect the hydraulic properties of the material. The main deformational events are represented by multiple superimposed textures and structures including faults, healed breccias, crenulations, foliation slips, micro-faults, and continuous/truncated joints/fractures. The first phase of fold deformation (F_1) was essentially ductile and produced isoclinal folds contemporaneous with the most intense metamorphism. It was at this time that the dominant foliation likely developed along original bedding planes. The cooling period following this phase marks the onset of regional brittle faulting and development of fractures along the bedding planes. The second phase of folding (F_2) is characterized by flexural slip, indicative of brittle conditions, producing distinct fault and fracture orientations: a conjugate system normal to the foliation; West-Northwest and North-South conjugate strike-slip faults; Northwest faults and fractures parallel to the direction of extension; and thrust and extension fractures parallel to the foliation.

The Cortlandt Complex (a large igneous intrusion located East of the Site) was intruded during the F_2 phase. The post-Cortlandt dislocations were associated with a third phase of folding (F_3) causing a mutual rotation of the structural elements producing a complex of conjugate features with a wide range of orientations as described by Dames & Moore and found during our study. On the Site, the regional features are represented by North-Northeast and North-Northwest trending faults in cross-cutting relationships, representing a conjugate system with a North-South regional compression direction. The final tectonic event was associated with a shear system oriented North-East, reactivating movement along Northeast-trending faults and minor North-Northeast to North-Northwest-trending faults. In addition to these major events, there has been minor

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[30] In Vermont, this unit is equivalent to the Whipple Marble.

normal movement on North-South and Northwest-trending faults associated with continental rifting during the Mesozoic Era.

Finally, post-deformational uplift and glacial rebound have resulted in a series of fractures related to expansion, after the rock mass/ice load was removed during erosion and glacial retreat. These manifest themselves as semi-sinuous or undulating horizontal relief fractures.

6.4.3 Groundwater in Bedrock

In metamorphic bedrock such as the marble present at the Site, groundwater occurs and migrates in open spaces such as fractures. These void spaces are termed secondary porosity. The primary porosity consists of void spaces within the rock matrix itself. The Inwood Marble has a very low primary porosity which does not contribute to the flow or storage of significant volumes of water. Therefore, the presence of fractures and faults ultimately determines the hydraulic conductivity of the bedrock mass. The fracture aperture spacing and the degree of fracture interconnectivity are dominant variables in how groundwater flows through the fractured bedrock environment. Groundwater flows from areas of higher hydraulic head to areas of lower hydraulic head along fractures providing the least resistance. If the structure of the rock is dominated by fractures and foliations of a single orientation, then groundwater flow will be along this orientation towards areas of lower hydraulic head. Also, if fractures are separated by large distances and not interconnected, groundwater will flow in a relatively limited number of fractures and flow will be governed by the orientation of local structures within the rock. This may result in groundwater flow occurring along paths that may not be reflected in topography. However, if there are abundant sets of fractures of differing orientations relatively close together and interconnected, groundwater flow will typically mimic topography.

GZA found no evidences of solution features (i.e., cavities, voids). Such features (if present) can control the direction of groundwater flow. Carbonate rocks have relatively high solubility under certain ambient surface conditions. This can result in solution cavities and caves known as karst systems. In these situations, groundwater can flow predominantly along open cavities and result in preferential pathways. Our assessment of over 3,200 linear feet of rock core and 2,950 linear feet of borehole geophysical logs found no evidence of any large scale solution features. Minor, discontinuous vugs (small unfilled cavities) and voids were observed primarily along partially healed fractures with euhedral calcite crystals growing into fractures. This evidence suggests that prior to denudation, resulting in exposure of the rocks to the current elevations; hydrothermal fluids were percolating through open fractures. Mineralization occurred along the fracture planes resulting in a significant number of healed fractures observed in the rock. In some cases, the fractures were partially healed, resulting in the occurrence of vugs in some of the more brecciated zones. The presence of calcite deposition in fractures supports our observations that solution features are not prevalent at the Site. That is, open fractures are due to tectonic forces, that carbonate is precipitating within the fractures, and no large solution cavity process is occurring.

Since earlier conceptual models for the Site hypothesized that groundwater flow would be to the South-Southeast along the original F1 foliation and fracture sets, we performed a detailed structural analysis of the bedrock to assess whether groundwater flow would be dominated by discrete fracture flow or would behave more in accordance with flow through porous media. This analysis had implications relative to on-Site contaminant migration and the potential for off-Site migration via dominant fracture sets.

6.4.4 Regional Scale Geostructure

GZA assessed regional fracture patterns presented in the Dames & Moore (1975) report as a photo lineament analysis (**Figure 6.5**). On the regional scale of the lineament analysis, there are three sets of intersecting fracture orientations. The major strike orientations within a 15 mile radius of the Site indicated a Northeast, North, and East-West trend. A review of the major tributaries to the Hudson River indicates the drainage pattern is predominantly aligned with similar orientations and generally structurally controlled.

6.4.5 Site Scale Geostructure

On a Site scale, GZA projected the fracture plane orientations calculated from the borehole geophysical data onto one elevation (elevation 10 feet) to create a Site lineament analysis (**Figure 6.6**). Assessment of the more permeable fractures on this projection showed that fractures were oriented consistent with the regional assessment (Northeast, North and East-West), and that fracture orientations intersect one another. In addition, our Site scale lineament analysis showed a number of Northwest orientated fractures located between Unit 1 and Unit 2 in the area where the Unit 1 and Unit 2 plumes commingle. Evaluation of the preconstruction bedrock topography also indicated that this was a low point in the bedrock surface. Low points in marble bedrock surfaces are usually associated with areas of higher fracture density or faulting as these would be areas more prone to weathering, erosion and glacial gouging. This presents further evidence for a zone of higher transmissivity.

Based upon the regional and Site scale lineament analyses, it was apparent that the multiple fracture orientations result in intersections of fracture planes. However, more detailed analysis was required. Therefore, GZA assessed the individual rock cores and fracture orientations calculated from the borehole geophysical analysis.

6.4.6 Borehole Scale Geostructure

Twenty-three of the forty-seven boreholes were evaluated using acoustical televiewer (ATV) and optical televiewer (OTV) borehole logging techniques by Geophysical Applications, Inc. The ATV data establishes naturally occurring joint/fracture dip angles and planer dip directions for planer features intersecting a borehole.

The apparent joint/fracture orientations and depths were input into a stereographic framework using DIPS software developed by RocScience, Inc. of Toronto, Canada, after correction from magnetic North to true North. The stereographic projections are a southern hemispheric view and are equal-angle based. The program presents the joint/fracture dip and dip direction in a tabular format with customizing options, and allows joint/fracture set selection to establish groups of domains and families of geostructural data.

The 4,623 data points from the 23 boreholes were input into the DIPS program. The polar projections for all the boreholes are presented as **Figure 6.7**. In our opinion, these data show three dominant, apparent, conjugate sets of fractures striking to the Northeast-Southwest, East-West, and North-South. The majority of the dip angles range consistently between 30 and 70 degrees for each major orientation. In addition, there are many horizontal and vertical fractures. The orientations of the fractures, the conjugate sets of fractures, and the presence of vertical and horizontal fractures all support a high degree of interconnectivity.

The database also contains columns showing the depth of the individual joint/fractures and apparent vertical continuous spacing[31]. In each borehole, three average values of apparent vertical joint set spacing for depths between 0-30 feet, 30-100 feet, and depths greater than 100 feet were calculated and summarized in the following table. No significant differences in joint spacing with depth were found.

AVERAGE APPARENT JOINT SPACING, FT							
	Depth Below top of the rock				**Depth Below top of the rock**		
Borehole	**0~30ft**	**30ft~100ft**	**>100ft**	**Borehole**	**0~30ft**	**30ft~100ft**	**>100ft**
MW-30	0.53	0.64	--	MW-55	0.48	0.47	--
MW-31	1.46	0.63	--	MW-56	--	0.32	--
MW-32	--	0.36	0.39	MW-57	0.55	0.30	--
MW-34	0.72	--	--	MW-58	0.32	0.66	--
MW-35	0.80	--	--	MW-59	0.35	0.41	--
MW-39	--	0.66	0.67	MW-60	1.38	0.83	0.59
MW-40	0.37	1.11	1.69	MW-62	--	0.49	0.64
MW-51	0.37	0.88	0.84	MW-63	--	0.35	0.44
MW-52	0.45	0.58	0.89	MW-65	--	1.26	--
MW-53	--	0.71	--	MW-66	--	0.75	0.59
MW-54	0.47	0.58	0.39	MW-67	0.47	0.59	0.54
				RW-1	--	2.22	1.71

AVERAGE APPARENT JOINT SPACING

Joint spacing is a significant parameter in assessing flow in a fractured rock and assessing the validity of using an equivalent porous media flow model. The spacing of joints was determined by direct measurement from rock core samples or from ATV data in 22 boreholes, and is presented in a database (**Appendix Q**). These data indicate an apparent joint/fracture spacing between 0.3 and 2.2 feet, with an average of 0.7 feet.

Based upon the assessment described above, the data suggest that the bedrock aquifer can be visualized as a series of polygonal blocks separated by interconnected fractures. This geometry is graphically portrayed by a series of seven apparent fracture

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[31] Apparent vertical spacing is the distance between joint/fractures along the vertical line of the borehole.

profiles designated A-A' through G-G' presented on **Figure 6.9**; profile locations are presented in **Figure 6.8**. The profiles show the orientation and potential connectivity of the geostructure if the ATV borehole measured planes extended for 1,000 feet (500 feet on either side of the borehole). The joint/fracture lines represent the trace of the plane projected onto a vertical profile. Additional illustrations of the fracture orientations in three dimensions are presented in **Section 6.4.8.**

6.4.7 Geologic Faults

The groundwater flow pattern and thus contaminant transport can be further influenced by the presence of faults. These faults can either act as barriers or conduits to flow depending on the presence of clay-rich fault gouge. Rock core samples revealed significant clay fault gouge zones that generally ranged between 0.2 and 0.7 vertical feet thick at borehole locations MW-31, -50, -54, -60, and -61. These zones were encountered at depths ranging between 39 and 200 feet below existing grades. The dip angles were measured by the ATV methods and ranged between 49 and 82 degrees at locations MW-31, MW-54, and MW-60, with dip directions toward the East (MW-54) and the Southeast (MW-31 and MW-60). No ATV measurements were conducted at MW-50 or MW-61. At MW-61, no core was recovered between 156 feet bgs and 221 feet bgs. Collection of split spoon samples in this interval verified the presence of a clay-filled fault gouge. This boring likely intersected a steeply dipping North-South trending fault. The presence of this fault is consistent with faults previously mapped by Dames & Moore (1975). The near vertical orientation of the fault is further supported by observations of bedrock core from locations MW-66, advanced within 8 feet of MW-61. No fault gouge was observed in this boring. A fracture zone was noted between 136 and 145 feet bgs and is characterized by low RQDs, however, this fracture zone did not exhibit clay filled fault gouge and was more consistent with tightly spaced fractures.

Because the fault extends to the top of the bedrock, the question arises as to why we did not observe the fault zone above 156 feet bgs at MW-61. This is due to the geometry of the fault. The fault zone is sub-vertical, i.e. less than 90 degrees, but also may vary in orientation with depth. As the boring was advanced deeper into the bedrock, it intersected the fault zone at 156 feet bgs. The boring continued within the fault, in a near vertical portion of the fault, to the termination of the boring.

Furthermore, the rock core samples revealed several fracture zones ranging between approximately 0.5 feet and 110 feet thick. Significant zones of poor to no recovery are evident at MW-50, MW-61 and MW-66: boring MW-50 and MW-54 were aligned along or near the trace of historic faults mapped by Dames & Moore (1975). MW-49 and MW-61, may be aligned along the extension of a historic fault mapped by Dames & Moore (1975). The poor recovery observed at MW-50 and MW-61 is indicative of clay gouge that was washed out during the drilling process (which is consistent with, but not fully verified by, the split spoon samples containing clay, recovered in these borings). We further note the presence of this fault zone does not appear to materially alter groundwater flow directions or contaminant migration towards the Hudson River.

Figure 6.4 portrays faults mapped on the Site by Dames & Moore (1975). There are three major groups of faults with associated fractures identified at and in the vicinity of the Site. These groups have azimuths of approximately 45, 75, and 290 degrees. The East to N75E faults consist of conjugate faults where the sinistral set strikes West to N70W dipping southward, and the dextral set strikes East to N75E dipping southward. These faults are most often offset or truncated by younger faults. West striking faults in the Inwood Formation are typically characterized by breccias which have been healed by a re-crystallized calcite cement.

An additional fault or fracture zone appears (not shown on **Figure 6.4**) to extend from the Hudson River Southwest between Units 1 and 2, as expressed by fracture orientations and a low in the preconstruction bedrock contours. This appears be a zone of higher transmissivity as indicated by inflections in groundwater contours, tidal response measurements, and the shape of the contaminant plume.

6.4.8 Bedrock Structure Visualization

In order to aid in the visualization of the role bedrock structure plays on groundwater flow as well as show the apparent interconnectivity at the Site, GZA imported data collected throughout the various phases of investigation into a 3-dimensional visualization model. The Environmental Visualization Software (EVS) software suite, created by CTech Development Corporation, was the primary software application used for the development of this model. This software package provides real-time model rendering, animation/flyover capabilities, database and GIS interface utilities, and numerous image output options. EVS also provides the ability to interpolate variably spaced datasets via kriging, an established geostatistical technique. The EVS kriging process selects an optimal semi-variogram model for each kriged dataset in order to estimate unknown values, and provides statistical confidence for estimated values. The results of these analyses can then be rendered across three dimensions (x, y and z) to provide a spatially referenced visualization model.

GZA incorporated the borehole geophysical data provided by GA, the packer testing results, and the USGS evaluation of the HPFM data into the 3-dimensional visualization model. Our goal was to illustrate transmissive fracture locations. For many of the zones identified as transmissive, several fractures likely contribute to the estimated transmissivity. In these cases, a percentage of the estimated zone transmissivity was allocated to each contributing fracture based on the HPFM results and ATV/OTV logs. In addition, multiple fractures in close proximity and exhibiting similar planar characteristics were combined to present a single planar feature to avoid redundancy in the model. The fracture data set was imported into the 3-dimensional visualization model intact.

Figures 6.10 through **6.14** present the locations of transmissive fractures within each boring. Fractures are represented as disks with 50 foot radii. A single disk represents the strike direction and dip angle of a transmissive fracture feature. Fracture disks are also color coded to reflect the assigned transmissivity value. Boring designations and locations highlighted in yellow indicate the borings for which geophysical and transmissivity information was available. Boring designations and locations highlighted in white are lacking geophysical data; therefore, fractures are not presented. The transmissive fracture data set was divided into low transmissive (0.02 - 10 ft^2/day, **Figure 6.10**), moderate transmissive (10 – 50 ft^2/day, **Figure 6.11**) and high transmissive (50 – 250 ft^2/day, **Figure 6.12**) subsets. While there are limited geophysical data for borings located to the South and East of the Site, the available data do indicate that there appears to be a zone composed of more transmissive fractures within the center of the Site. This observation coincides with a low in the bedrock as elucidated by preconstruction bedrock contours (**Figure 6.4**). This historic depression may be the result of weathered or fractured bedrock being susceptible to glacial advance and retreat, indicating the potential for a fault to be present in this area. This is consistent with the observation of a lineament West of Unit 2 toward the Hudson River discussed above.

Figure 6.13 represents the same fracture data set, but with the fracture disk radius extended to 250 feet. A horizontal cutting plane has been extended across the Site at elevation 10 feet, identifying the strike direction of each fracture as it intersects the plane. For a selected diameter of disk, the width of the strike line has significance. A shallow dipping disk would have more contact with the horizontal cutting plane than a steeply dipping disk. Accordingly, a wider strike line indicates a fracture strike direction with a shallower dip angle. The East-West lineament is clearly visible in this figure, aligned approximately from Unit 2 toward the Hudson River, and comprised of moderate and high transmissive fractures. **Figure 6.14** represents the same horizontal slice concept; however, the slice plane is now placed at elevation -100 feet. There are no high transmissive fractures intersected at this elevation, indicating high transmissive fractures are more predominant at shallow depths. This is consistent with **Figure 6.13**, the Conceptual Site Model, hydraulic conductivity tests and previous reports (Tectonics, 2004). Because we observed no decrease in fracture spacing with depth (see **Section 6.4.6**), this suggests the hydraulic aperture of fractures decreases with depth.

While there are some localized trends in fracture strike direction, there is an abundance of intersecting fractures on a Site-wide scale occurring at all elevations. In addition, the fracture disk component of the 3-dimensional visualization model has been reviewed to identify potential fracture connections on a borehole-to-borehole scale. No significant interconnections were identified. These observations suggest that bedrock is highly fragmented on a Site-wide scale, high transmissive fractures are not continuous across IPEC, and groundwater flow through the Site may be modeled as flow through a non-homogeneous, anisotropic, porous media.

6.4.9 Bedrock Surface Elevations and Preferential Groundwater Flow Pathways

The results of the surface geophysical surveys are portrayed on **Figure 1.3**. The geophysical survey identified apparent bedrock at depths of between 2 and 18 feet below ground surface (bgs) within the IP2-TY. A depression in the bedrock surface exists in the vicinity of monitoring well MW-111. Bedrock in the depression was found at a depth of 16 to 18 feet bgs. Along the North side of the IP2-TB, apparent depth to bedrock was approximately 8 to 12 feet bgs and only intermittent groundwater associated with rainfall events has been encountered. This is likely the depth bedrock was cut in order to accommodate the service water lines. No discrete utility trenches were observed in the bedrock. Based upon the results of the geophysical survey it is more likely that bedrock was cut to a depth to accommodate deep subsurface utilities and potentially dewatering, rather than install utilities in individual trenches. On the eastern, western and southern sides of the Transformer yard, rock was encountered between 2 feet and 7 feet bgs. No groundwater was encountered in the overburden in these areas. However, groundwater was encountered in the backfill found along the western wall of the Discharge Canal, which forms the eastern boundary of the IP2-TY.

Within the IP3-TY, the approximate depth to bedrock ranged between 7.5 and 10.5 feet bgs. Generally the northern and southern ends of the survey area had the deepest and shallowest depths to bedrock, respectively. Again, the surveys did not exhibit evidence of individual utility trenches cut into bedrock. No groundwater was observed in overburden within borings advanced within the IP3-TY.

To assess the potential for contaminants to enter groundwater through leaking stormwater pipes (E-Series) and flow with groundwater towards the Hudson River within utility trenches cut into rock along the OCA access road on the South side of the Protected Area, the depth to bedrock and utility trenches cut into rock along this roadway was evaluated. The approximate depth to bedrock ranged between 8 and 16 feet bgs. Bedrock reflectors appeared to be less defined in this survey area compared to other areas at the Site. Many potential utilities were observed in the survey area, however it appears that one large bedrock trench was excavated to accommodate the utilities as well as the roadway. The bedrock appeared to be deeper near the "delta gate" along the East side of the survey area, reaching an apparent depth of 16 feet bgs. Further to the West the apparent bedrock surface was observed at a depth of approximately 8 feet bgs.

Seismic data collected around the warehouse on the South side of the Protected Area provided good subsurface information to a depth of approximately 50 feet bgs. In general, the apparent bedrock surface was found at depths of approximately ground surface on the East side of the survey area and sloped down to depths greater than 45 feet to the West. Near MW-48, the bedrock was located at 25 feet bgs. Topography of the bedrock interface ranged from flat to highly variable over relatively short distances and there were a few locations where the bedrock interface "disappeared" or was located greater than 40 to 45 feet bgs. Over most of the area, the bedrock interface was more gradual and slightly undulating along the profile lines. In general, the depth to bedrock was greater then 20 feet across most of the survey area, indicating that subsurface utilities would not be cut into bedrock trenches.

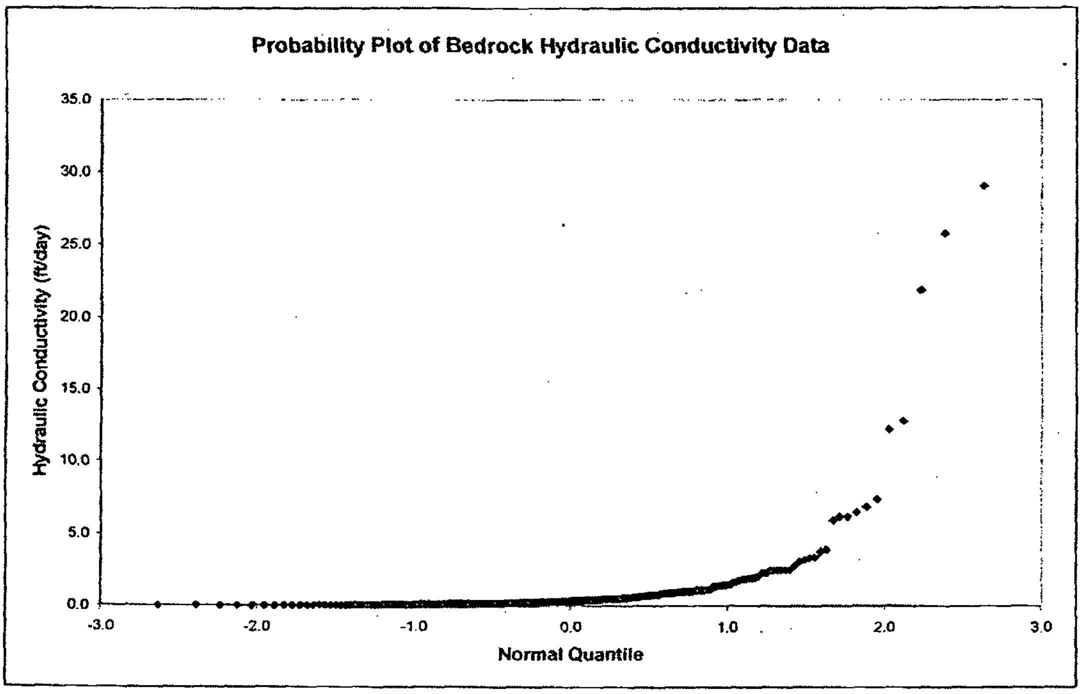
6.5 AQUIFER PROPERTIES

Our investigations demonstrate that, for the purposes of evaluating groundwater flux, bedrock beneath the Site can be modeled as flow in porous media. Following are the hydraulic properties we assigned to our equivalent conceptual porous media model.

6.5.1 Hydraulic Conductivity

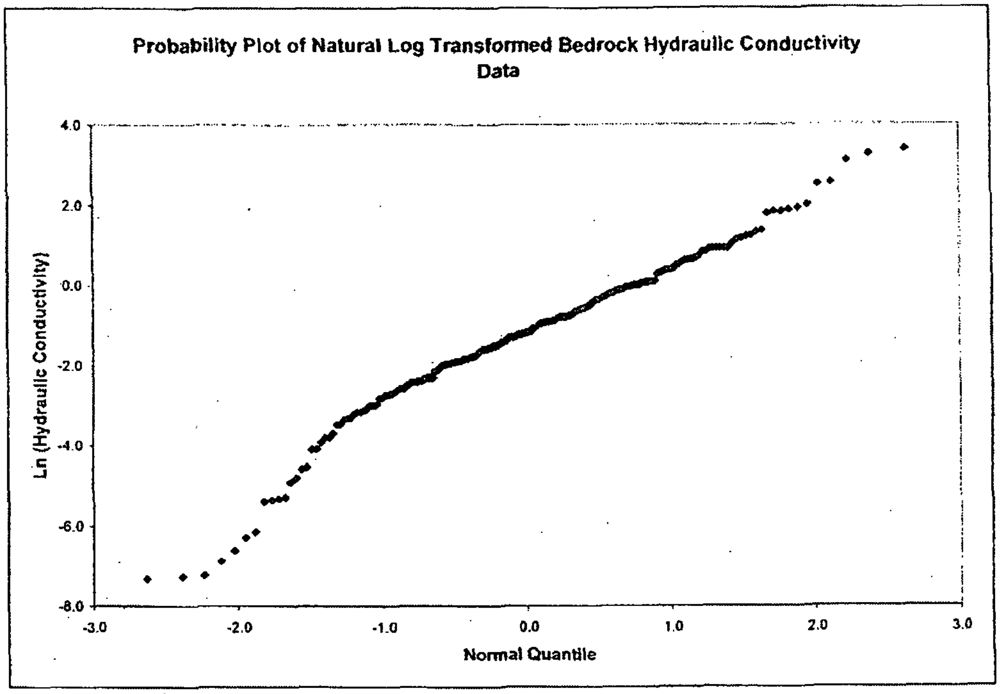
Transmissivity and hydraulic conductivity[32] data were collected as part of the hydrogeologic investigation in both the overburden and bedrock. The geometric mean of hydraulic conductivity in the overburden zone is 12.6 ft/day and the geometric mean in the bedrock is 0.27 ft/day. As indicated below, calculated hydraulic conductivities within the bedrock were found to be log-normally distributed.

GZA used probability graphs to evaluate the statistical distribution of the bedrock hydraulic conductivity data. As shown on the following two graphs, the log-transformed data better approximates a straight line. This indicates the log-transformed hydraulic conductivities are approximately normal and the hydraulic conductivity values are log-normal. This indicates that the geometric mean is a good approximation.



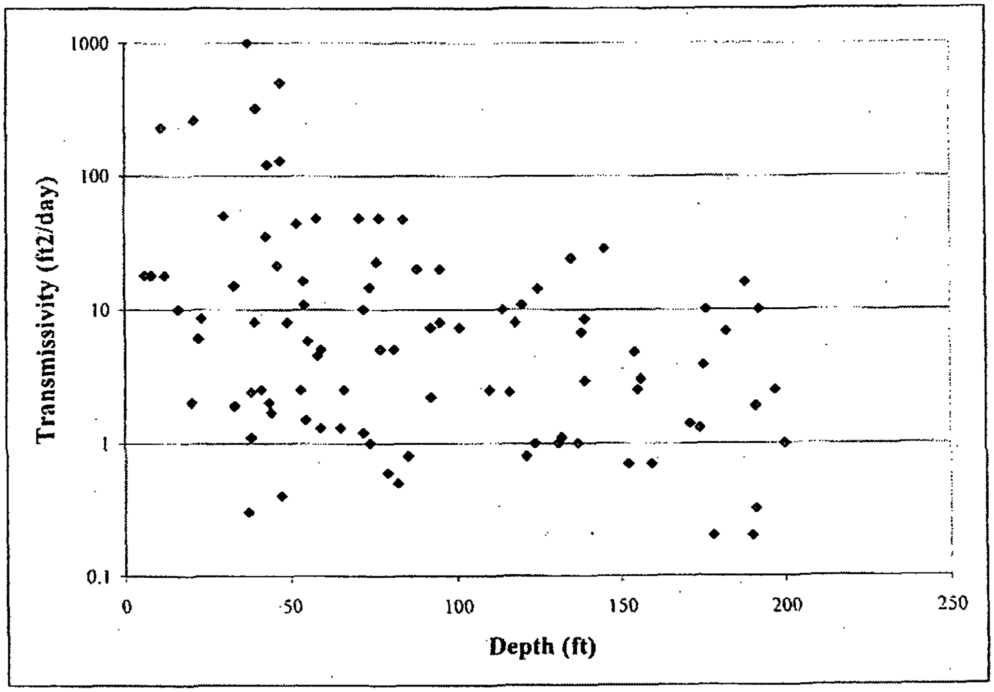
STATISTICAL ANALYSIS OF HYDRAULIC CONDUCTIVITY MAGNITUDE

[32] Transmissivity, as used here, is the property measured in the field and is the product of an equivalent hydraulic conductivity (K) and the test interval.



STATISTICAL ANALYSIS OF HYDRAULIC CONDUCTIVITY MAGNITUDE (NATURAL LOG TRANSFORMED)

As shown below, GZA also developed a graph of depth versus transmissivity of bedrock. In viewing that graph, note that all USGS[33] measured transmissivities of greater than 100 ft^2/day were found at depths of less than approximately 50 feet bgs.



TRANSMISSIVITY VS DEPTH

[33] Transmissivities shown were computed by the USGS from their heat pulse flow meter data which were in agreement with our packer test data.

It should be noted that the hydraulic conductivity values are based on aquifer tests conducted at specific locations and limited hydraulic loading, and are therefore only representative of the aquifer immediately adjacent to the subject borehole.

GZA also conducted a Pumping Test which imposed a larger hydraulic stress over a larger portion of the aquifer. We believe this test provides us with the most reliable estimate of transmissivity of the bedrock in the area of the Pump Test. However, the area of influence of the Pump Test did not encompass the zone of higher hydraulic conductivity within the fracture zone between Units 1 and 2. Depending on the methods used to evaluate the Pumping Test data, we estimate bedrock transmissivity values generally in the range of 30 ft^2/day to 50 ft^2/day[34]. This suggests an average hydraulic conductivity of between 0.2 and 0.4 feet/day.

To further evaluate the vertical distribution of the hydraulic conductivity, we computed the geometric mean of measured values in the upper 40 feet of the aquifer and the geometric mean of all values measured below that depth. This calculation resulted in values of 0.4 feet per day for the upper forty feet and 0.2 feet per day for the deeper aquifer.

6.5.2 Effective Porosity

Evaluation of Pumping Test data also allows calculation of storativity. Our Pumping Test results show the storativity of the bedrock aquifer is 0.0003. (Note: overburden wells were not present within the cone of depression and, therefore, storativity for the overburden could not be evaluated.) Because the bedrock aquifer is unconfined and the primary porosity of the marble is, essentially, zero, the effective porosity of the bedrock can be as small as the storativity. However, due to dead-end fractures, the effective porosity is likely to be higher.

To evaluate the reasonableness of estimated properties, we used the cubic equation, as shown below, to estimate the hydraulic aperture and storativity of the fracture system:

$$Q = \frac{\rho_w g b^2}{12\mu}(bw)\frac{\partial h}{\partial l}$$

Where:

Q = volumetric flow (ft^3)
ρ_w = density of water (62.4 lb/ft^3)
g = gravitational constant (32.2 ft/s^2)
b = aperture opening (ft)

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[34] The Pumping Test indicated the transmissivity of the rock was fairly isotropic, and only limited horizontal anisotropy was observed during the Pump Tests (e.g., in the drawdown observations at monitoring well MW 53-120). At the scale of the, Pumping Test we believe there are sufficient heterogeneities that the aquifer can be considered to be a non-homogeneous isotropic porous media.

μ = dynamic viscosity of water (0.0006733 lb/ft*s)

w = fracture width perpendicular to the flow direction (ft)

$\frac{\partial h}{\partial l}$ = groundwater gradient

From this, the concept of an equivalent hydraulic conductivity has been developed[35]:

$$K = \frac{\rho_w g n b^3}{12\mu}$$

Where:

Variables are as previously defined, and;

n = number of open features per unit distance across the rock face

Using a fracture spacing of one foot and an equivalent bulk hydraulic conductivity of 0.27 feet per day (9 x 10^{-5} cm/sec), this calculation indicates a hydraulic aperture of approximately 75 microns, and a theoretical minimum porosity of 2.4 x 10^{-4}. The calculated porosity is in good agreement with estimates of storativity developed from Pumping Test data (**Section 4.4.4**) and tidal responses (**Section 6.6**).

In summary, the measured effective porosity of the bedrock aquifer is approximately 0.0003.

6.6 TIDAL INFLUENCES

As discussed previously, the Hudson River, adjacent to the Site, rises and falls in response to ocean tides. Based on our measurements, this tidal variation (the numerical difference between low water and subsequent high water elevations) in 2006 ranged from approximately 1.4 feet to 4.3 feet, and averaged approximately 2.7 feet. This variation occurred between approximately elevation -1.5 feet to 3.7 feet NGVD 29 (i.e., the low tide elevations were typically above elevation -1.5 feet and the high tide elevations were typically below elevation 3.7 feet). These data are in good agreement with published information (see **Section 6.1**).

This natural variation produced measured effects that helped us better understand hydrogeologic information obtained at the Site. One such effect is water level changes in monitoring wells at the Site. The observed changes demonstrate that the bedrock aquifer is significantly fractured, and provided additional insight into aquifer properties.

Discharge of heated cooling water, in conjunction with tidal influences, produced a second effect; temporal temperature changes in groundwater in wells located near the Discharge

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[35] Snow, D.T. 1968. Rock Fracture Spacings, Openings, and Porosities. Journal of Soil Mechanics., Found. Div. Proc. Am. Soc. Civil Engrs., v. 94, p. 73-91.

Canal. We used that information to help explain water quality data collected from two specific wells (MW-38 and MW-48, originally proposed as southern boundary monitoring wells), which did not initially conform with our Conceptual Site Model (see **Section 6.6.2** below). These two effects are described in the following sections.

6.6.1 Groundwater Levels

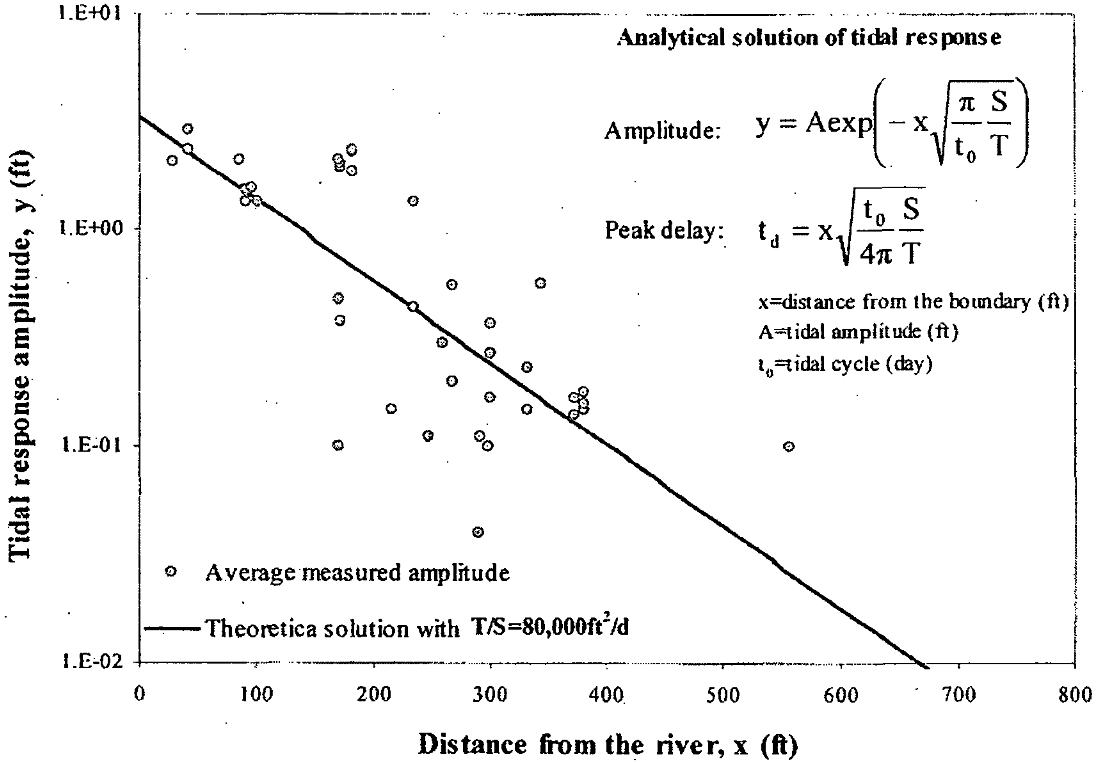
The tidal-induced variations in surface water levels near the edge of the Site's aquifer (in the river and intake structures and Discharge Canal[36]) induced pressure changes in groundwater that were observed in monitoring wells at the IPEC. As a general statement, these responses (as anticipated) varied over time as sinusoidal-like curves that decreased in amplitude and exhibited greater lag time with increased distances from the river/Discharge Canal[37].

At the time of our tidal response study, there were 87 transducers installed in 49 monitoring wells. As shown on the following graph, we observed measurable hydraulic responses to tidal variations at 43 of these transducer locations. In viewing that graph, note distances are measured from the edge of the Hudson River. We chose this as the boundary because data suggests the river has more influence on piezometric levels in the bedrock aquifer than do the intake structures and Discharge Canal. We further note that: 1) 41 of the 44 pressure transducers within 400 feet of the Hudson responded to tidal variations; 2) at greater distances, tidal responses may have occurred but were too small to be recorded because of the accuracy of the transducers; and 3) the tidal response in wells located in the higher hydraulic conductivity area between Units 1 and 2 was more pronounced than in other areas. Cumulatively, these data demonstrate:

- The aquifer is in strong hydraulic communication with the Hudson River; and
- The bedrock aquifer is well-fractured.

[36] The elevation of the water in the Discharge Canal rises and falls with the river elevation, but is maintained approximately 20 inches above the river level.

[37] Observed variations from this trend, in our opinion, are consistent with anticipated heterogeneities in an equivalent porous media model.



TIDAL RESPONSE VS DISTANCE FROM THE HUDSON RIVER

Fetter[38] provides an analytical solution for the theoretical piezometric response of an aquifer adjacent to a tidal boundary (see above graph). The assumptions upon which this solution is based are quite restrictive. In addition to the normal difficulties (aquifer heterogeneities, anisotropic properties, etc.) which limit the practical use of the solution in estimating aquifer properties, [39] it is not clear if water levels at the Site are responding to changes in the river level, changes in the Discharge Canal levels, or perhaps, a combination of both. Further complicating this issue, the concrete canal walls, and at some locations (not all) the concrete canal bottom, should clearly affect propagation of tidal fluctuations in the canal.

With these limitations noted, our review of data indicates that the hydraulic diffusivity[40] (transmissivity, T, divided by storativity, S) of the rock, as estimated by the tidal responses, is on the order of 80,000 ft^2/day. See the above graph and information in **Appendix K**.

As presented in **Section 6.5,** we believe the average transmissivity of the bedrock aquifer is typically in the range of 30 to 50 ft^2/day. Using a transmissivity of 40 ft^2/day and a diffusivity of 80,000 ft^2/day, it follows the storativity of the bedrock aquifer is on the order of 5×10^{-4}. This value is in good agreement with the values we computed from an evaluation of the Pumping Test data and from the cubic equation (see **Section 6.5.1**).

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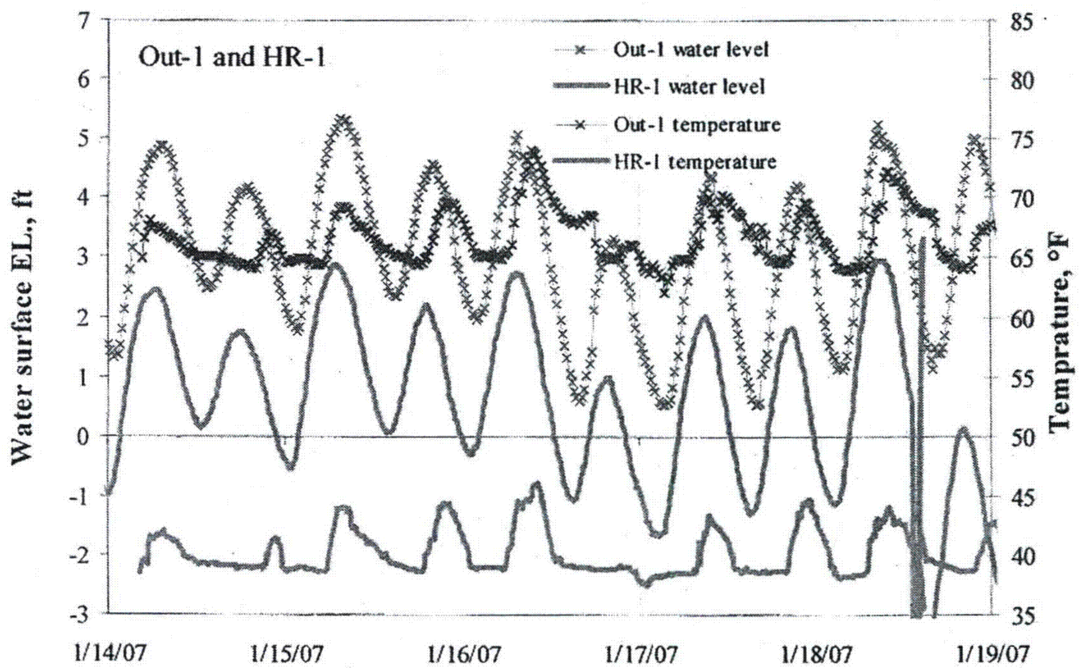
[38] C.W. Fetter, *Applied Hydrology*, Second Edition, Merrill 1988.
[39] Patrick Powers, *Construction Dewatering*, Second Edition.
[40] Freeze & Cherry, *Groundwater* Prentice-Hall 1979.

Another effect of river tidal changes is manifested in monitoring wells in close proximity to the river or Discharge Canal as follows. As the river approaches high tide, the groundwater gradients in proximity to the river become flatter, and at certain locations and tides, are reversed; that is, on a temporary basis, groundwater discharge to the river is generally slowed, and in at least some locations, groundwater flow normally to the river is reversed to then be from the river into the aquifer.

6.6.2 Groundwater Temperature

The cooling water intake structure is located North (upstream) of the cooling water discharge structure (see **Figure 1.3**). When the river is near high tide, the cooling water intake draws river water that contains discharge water[41] (i.e., river flow reverses and water begins to flow away from the ocean). At periods near low tide, the current in the river reduces or eliminates this circulation (within the river) of cooling water. A consequence of this tidal influence is that the temperature of water in the Discharge Canal, in addition to always being warmer than the river water, varies with tidal cycles. This is illustrated on **Figure 6.15** as well as the graph below, a double-axis graph to show the water level and temperature data collected in January 2007 from two stilling wells: Out-1, located at the southern end of the Discharge Canal, and HR-1, located in the cooling water intake structure of Unit 1[42].



WATER LEVEL AND TEMPERATURE RELATIONSHIPS FOR DISCHARGE CANAL AND HUDSON RIVER (JAN. 07)

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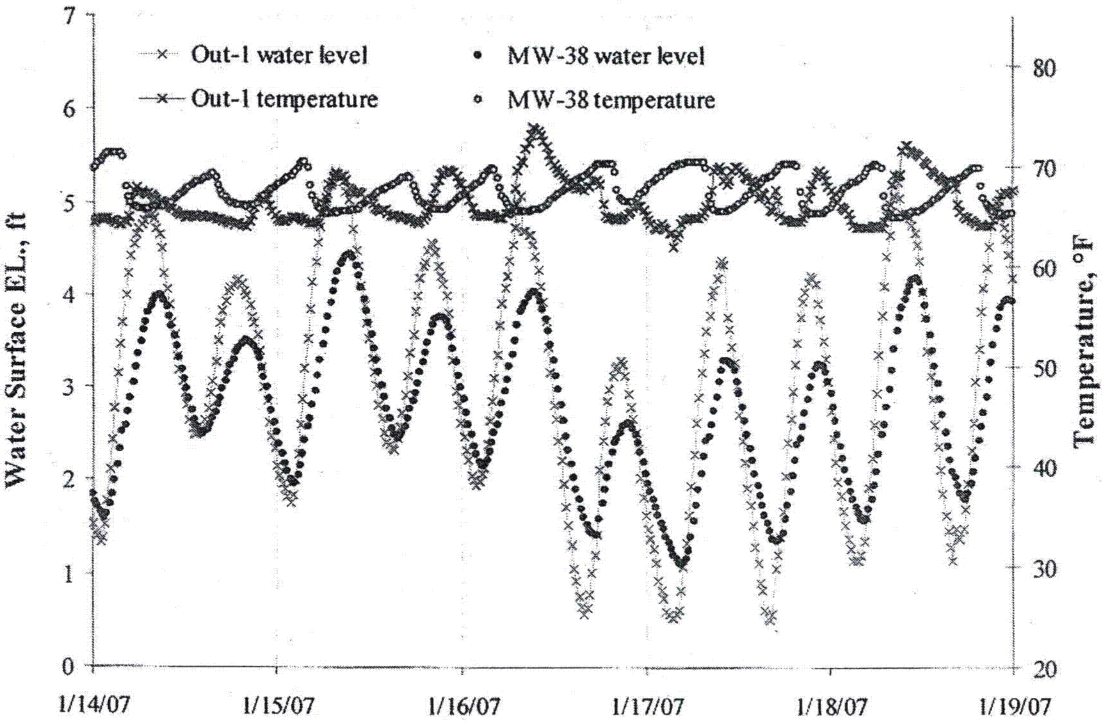
[41] The direction of the flow in the river is tidally influenced, which at periods near high tide, is to the North, away from the ocean.

[42] Unit 1 is inactive and this stilling well should provide a good measure of the river elevations with time.

Based on this information and water quality variations (see **Section 6.6.3**), we evaluated the potential for the Discharge Canal water to influence water quality at two locations originally proposed for southern property boundary monitoring[43], MW-38 and MW-48 (located adjacent to the canal and river respectively; see **Figure 1.3**).

6.6.2.1 Monitoring Well MW-38

Groundwater response to tidal influence of the cooling water Discharge Canal (at this location) is strong and appears to vary between tidal cycles. We note, however, that we observed responses from approximately 60% to at least 86% with an average of approximately 70%.



WATER LEVEL AND TEMPERATURE RELATIONSHIPS FOR DISCHARGE CANAL AND MW-38 (JAN. 07)

Additionally, at high tide the canal level is above the water level in MW-38 and at low tide the water level in MW-38 is above the level of the canal (see above graph). These data demonstrate the potential for water in the canal to migrate to the proximity of MW-38 during periods of high tide.

Groundwater temperature data collected from MW-38 indicate that canal water does in fact, at times, migrate to well MW-38. This is shown on the above graph

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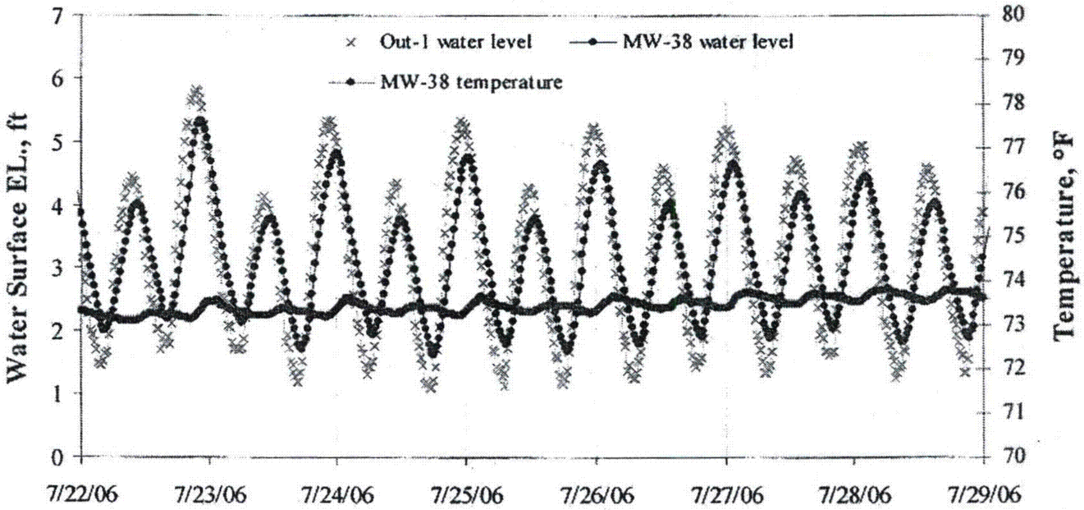
[43] The results of our analyses demonstrate that monitoring wells MW-38 and MW-48 are impacted by Discharge Canal water at various times. Therefore, these wells are not suitable for measuring southern boundary groundwater radiological conditions.

which shows water levels and temperatures collected in January 2007. In reviewing this graph, note that the temperature of groundwater in MW-38 is: 1) warmed significantly above ambient ground water temperatures (averaging approximately 70° F as compared to an ambient temperature of approximately 55° F); 2) on average, during this period, warmer than the canal water; 3) at its lowest temperature near high tide; and 4) increases in temperature while water levels in the well decline. These observations are consistent with groundwater discharge to the canal at low tide and canal water flow to the vicinity of well MW-38 during high tide.

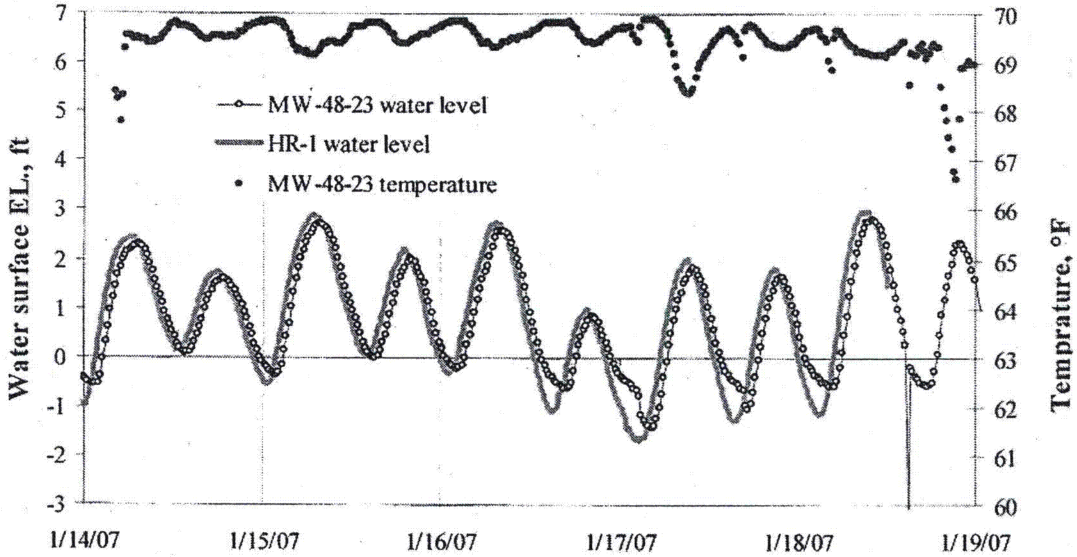


WATER LEVEL AND TEMPERATURE RELATIONSHIPS FOR DISCHARGE CANAL AND MW-38 (JULY 06)

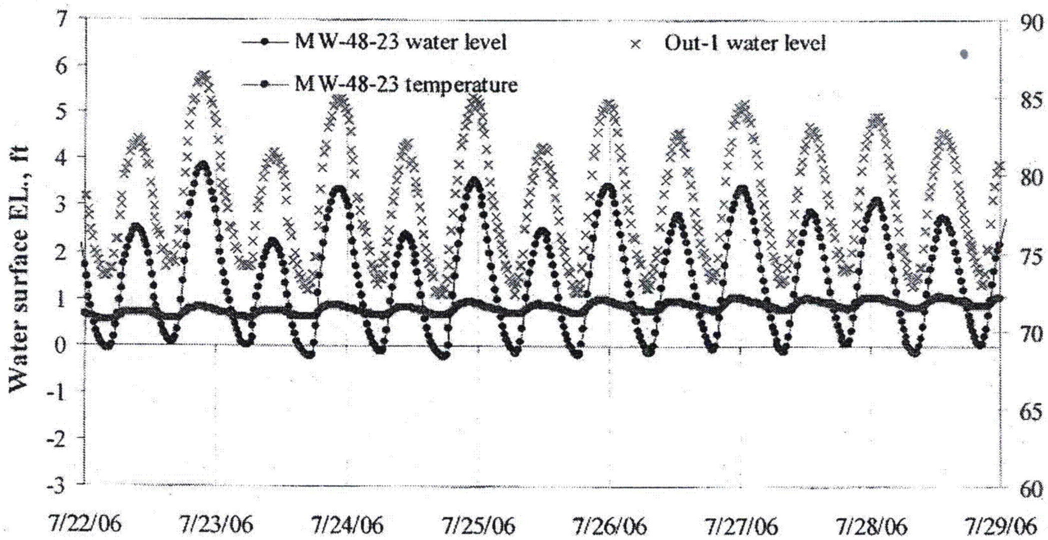
Data presented above, which is for MW-38 in the summer of 2006, while not as dramatic, supports our conclusion that groundwater in MW-38 is mixed, at times, with canal water. In reviewing this graph, note the canal water is significantly warmer than the groundwater, and that water temperature in the well water increases while the canal water level is above the level of water in the well.

6.6.2.2 Monitoring Well MW-48

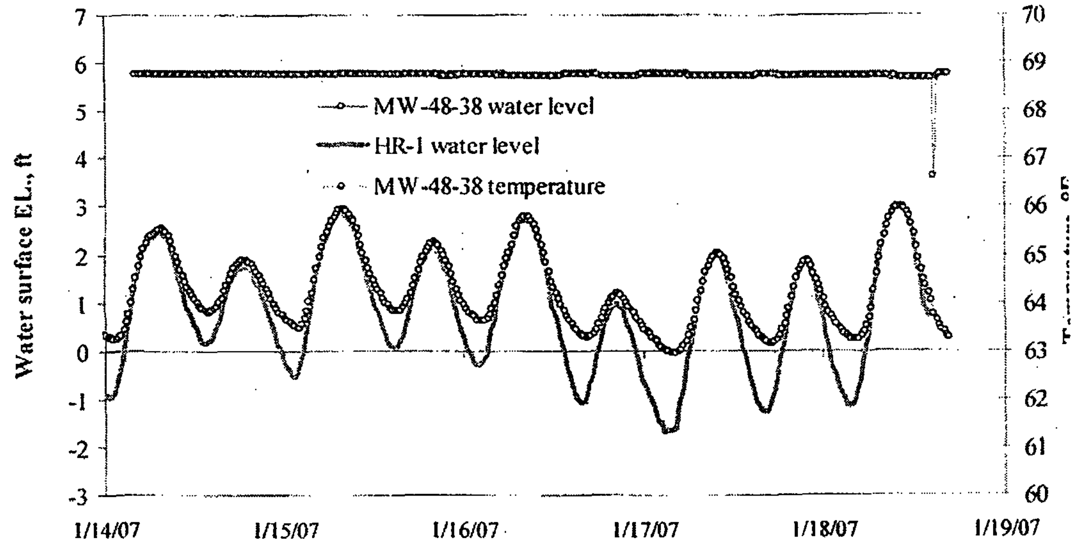
Water levels respond to tidal changes in both wells (MW-48-23 and MW-48-38) at the MW-48 location. The water levels and temperature variations in these two wells are presented and described below.



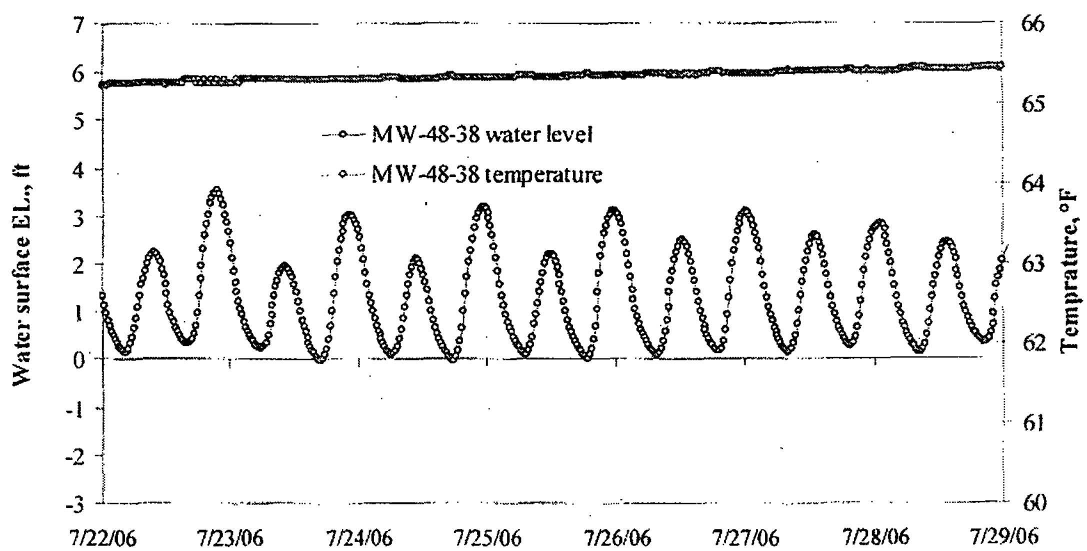
WATER LEVEL AND TEMPERATURE RELATIONSHIPS FOR HUDSON RIVER AND MW-48-23 (JAN. 07)



WATER LEVEL AND TEMPERATURE RELATIONSHIPS FOR DISCHARGE CANAL AND MW-48-23 (JULY 06)



WATER LEVEL AND TEMPERATURE RELATIONSHIPS FOR HUDSON RIVER AND MW-48-38 (JAN. 07)



WATER LEVEL AND TEMPERATURE RELATIONSHIPS FOR MW-48-38 (JULY 06)

At high tide, the level of water in both of these wells is very close to the river level, while at low tide, it is slightly above the river level and approximately 2 feet below the level of the Discharge Canal. The vertical gradient at this location is upward, with a stronger gradient at low tide. These data are consistent with anticipated trends, indicating groundwater discharge to the river occurs predominantly at low tide.

Note that the river water temperatures shown on graphs in this report are not representative of the temperature of the water in the river adjacent to monitoring wells MW-48. This is due to the location of river transducer HR-1, and tidal induced flows in the river. However, the elevated (above ambient) temperature of the groundwater at these locations (65 to 69° F) indicates it has been warmed by the Site's cooling water discharge.

The temperature of water in monitoring well MW-48-23 varies with some tide cycles, with the coolest temperature being near high tide in the winter, and the warmest temperature being near high tide in the summer. This pattern of temperature change is consistent with this monitoring well receiving river water at times of high tide.

The temperature of water in monitoring well MW-48-38 does not appear to vary with tidal cycles. We interpret these data to mean that physical water quality in monitoring well MW-48-38 is not typically influenced by large exchanges of river water[44]. The elevated groundwater temperature at this location, and the piezometric data, suggest, however, that flows created by purging of the well prior to sampling, at times of high tide, could induce river water flow to this location.

6.6.3 Aqueous Geochemistry

Routine groundwater monitoring indicated the presence of Tritium in a limited number of samples collected from monitoring wells MW-38 and MW-48. MW-38 was originally installed under the first phase of investigation to bound the southern extent of Tritium contamination at the Site along the cooling water Discharge Canal. However, subsequent sampling events indicated the presence of Tritium in groundwater at this location. The presence of Tritium in this well did not fit our CSM or what we knew of groundwater flow at the Site. A second well, MW-48, was installed at the southern Site boundary along the Hudson River to establish if any Tritium would potentially migrate off-Site. Tritium was detected intermittently in groundwater samples collected at this location as well. As neither of these locations was hydraulically downgradient of identified release areas, another mechanism other than groundwater migration from the release area was postulated. This mechanism involved releases from the legacy piping that conveyed contaminated water from the IP1-SFDS to the "E"-series stormwater piping that runs beneath the access road on the South side of the Protected Area and discharges stormwater to the cooling water Discharge Canal. While evaluating this hypothesis, we found evidence, as discussed in **Section 6.62**, that at certain tidal cycles, water from the Discharge Canal and the Hudson River may back flow into these groundwater monitoring wells. To help identify the source of Tritium in these two wells, we developed a focused water quality program specific to these wells. Generally, the water quality program involved analyzing select aqueous geochemical parameters in groundwater and surface water samples. Evaluation of these data can allow conclusions to be drawn regarding the source of the sampled water.

Both data sets (elevation and water chemistry) indicate that water collected from these wells may contain river or cooling water from the Discharge Canal. Based on these findings, we recommend that groundwater sample laboratory results from these well locations not be used to evaluate the extent of groundwater contamination or contaminant

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[44] Relatively large exchanges of water are required to overcome the thermal mass of the subsurface deposits surrounding the well bore. Therefore, while smaller exchanges of groundwater/river water may go undetected via temperature change, they may still be large enough to adversely impact radiological water quality, particularly in consideration of the data from the proximate well screens. Also see discussion in **Section 6.6.3**.

flux to the Hudson River and that these wells not be incorporated into the Long Term Monitoring Plan as Boundary Wells.

6.6.3.1 Sampling

Groundwater samples were collected from monitoring wells MW-38, MW-48-23, and MW-48-38 and from the Discharge Canal and Hudson River on January 19, 2007. These samples were analyzed for bicarbonate alkalinity (as $CaCO_3$), magnesium, sodium, calcium, sulfate, and chloride. The data was graphed on Stiff diagrams and is shown on **Figure 6.16**.

6.6.3.2 Water Quality Evaluation

GZA used the six water quality indicators (bicarbonate alkalinity [as $CaCO_3$], magnesium, sodium, calcium, sulfate, and chloride) to assess whether or not Discharge Canal and/or river water was present or mixed with groundwater at the two locations of interest (note that the MW-48 monitoring well location contains a shallow and a deep well). A summary of our findings follows.

- The river and canal samples are chemically similar and are dominated by sodium and chloride. The sodium and chloride contents are highest at the mid tide sampling event. These data indicate that at mid tide there was a greater vertical mixing of river water which caused the water to contain more sodium and chloride[45].
- The MW-48-23 samples collected at low, mid and high tide are all geochemically similar and are dominated by the sodium and chloride ions. However, the electrolyte concentration of these two ions is approximately half of that measured in the river or canal samples. Additionally, at low tide, there is slightly less sodium chloride and slightly more bicarbonate anion than at mid or high tide. We believe this indicates that at low tide, this location receives relatively more groundwater.
- Samples collected from MW-48-38 at low, mid, and high tide were generally all dominated by calcium and magnesium cations and chloride and bicarbonate anions. These samples also contained similar sodium, chloride, calcium, bicarbonate, magnesium, and sulfate electrolyte concentrations. However, at mid and high tide, there was somewhat more calcium, magnesium, and bicarbonate measured in these samples. It is further noted that the cation/anion imbalance for the MW-48-38 samples (except MW-48-38-L1) was greater than 5%. This indicates a lack of accuracy or the presence of unanalyzed ions in the groundwater samples. While samples from MW-48-38 currently appear more representative of groundwater than those from wells MW-38 and MW-48-23, it is not certain that they are always fully representative of groundwater only[46].

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[45] We believe the river and canal samples are similar (in part) because the river sample location was situated immediately down-river of the Discharge Canal outfall. In addition, the river sampling location visibly appears to remain within the discharge water heat plume. Therefore, the river samples are likely Discharge Canal water or at least mixed with what is being discharged from the canal.

[46] For example, 573 pCi/L of Tritium was detected in this interval on September 5, 2006. Tritium had never previously been detected and has since not been detected in this interval. It may be that this sample was misidentified in the field and the sample was actually obtained from the upper interval of this well where Tritium is routinely detected. However,

- The samples collected from MW-38 at low, mid and high tide are all geochemically similar and are dominated by the sodium and chloride ions. However, the electrolyte concentration of these two ions is less than half of that measured in the river or canal samples. Additionally, at low tide, there is slightly less sodium and chloride than at mid or high tide. We believe this likely indicates that at low tide, this location sees relatively more groundwater.

These data indicate that water samples collected from MW-38 and MW-48-23 are largely representative of the proximate surface water bodies at the Site. Recognizing the source of water in these wells, the other *chemistry data* (e.g., Tritium and Strontium) are suspect and should not be used for evaluation of groundwater contaminant migration or flux. Based on the available data, MW-48-38 may provide samples *more* representative of Site groundwater than MW-38 and MW-48-23. However, further analysis would be necessary to allow this well to be recommended as a southern boundary monitoring location, particularly in light of the above analysis pursuant to the proximate well screens and the potential for false positives. Given the demonstrated groundwater flow directions in this area[47], it is GZA's opinion that an additional southern boundary monitoring location (in addition to MW-51 and MW-40) is not required proximate to MW-48-38.

6.7 GROUNDWATER FLOW PATTERNS

A major purpose of this groundwater investigation was to identify the fate and level of groundwater contaminant migration. The contaminants of potential concern are soluble in groundwater, and at somewhat varying rates, move with it. This section provides a description of identified groundwater flow patterns in and downgradient of identified contaminant release areas. The piezometric data, shown in **Table 6.1**, which form the basis of this evaluation are independent of chemical data collected at the same monitoring locations. Consequently, our evaluation of piezometric data provides an assessment of where contaminants are expected to migrate in various time frames. Refer to **Section 9.0** for information on the observed distribution of contaminants and a discussion on discrepancies between anticipated and observed conditions.

Testing has indicated that the bedrock is sufficiently fractured to, on the scale of the Site, behave as a non-homogeneous, anisotropic, vertically porous media. This finding indicates that groundwater flow is perpendicular to lines of equal heads. This assessment appears particularly valid in horizontal (East-West & North-South) directions.

The nature of bedrock fracturing suggests the hydraulic conductivity is higher in the horizontal than in the vertical direction. Furthermore it appears the upper portions of the rock are more conductive than the deep rock except within the zone of higher hydraulic conductivity between Units 1 and 2. These findings suggest that the bulk of the

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it also is possible that this sample is reflective of river water induced into the well through sampling and/or the specific conditions existing at the time the sample was taken.

[47] While the representativeness of the chemistry data in these wells (MW-38, MW-48-23 and MW-48-38) is not certain, the groundwater elevation data is reliable for establishing flow direction.

groundwater moves at shallower depth, with small masses being reflected deeper into the rock mass than would be seen in anisotropic aquifer.

6.7.1 Groundwater Flow Direction

Groundwater elevations from pressure transducers at a representative low tide have been used to construct a potentiometric surface map of the aquifer beneath the Site (see **Figure 6.17**). We chose this data set after evaluating a number of piezometric data sets. More specifically we have mapped six groundwater conditions:

- Low tide during the drier portion of the year (2/12/07)
- High tide during the wetter portion of the year (3/28/07)
- Low tide during the wetter portion of the year (3/28/07)
- High tide during the drier portion of the year (2/12/07)
- Groundwater elevations at sample locations with the greatest Tritium impact during wet season
- Groundwater elevations at sample locations with the greatest Tritium impact during the dry season

Based on this evaluation, it appears that there is not a great deal of change in groundwater flow patterns over time (see **Appendix S**). However, as groundwater elevations have a smaller tidal response (amplitude) than the fluctuations of the river, low tide is a time with a relatively high degree of groundwater flux from the Site. Furthermore, low tide during the drier portion of the year likely represents a period of highest groundwater flux.

Groundwater flow is in three dimensions. A representative set of groundwater elevations was used to construct a cross-sectional groundwater contour map as shown on **Figure 6.18**. This figure is based on a 1:1 horizontal to vertical hydraulic conductivity. Because horizontal fractures transmit flow in only a horizontal direction, and vertical fractures transmit flow in both a horizontal and vertical direction, the aquifer is vertically anisotropic with a preference for horizontal flow. Conversely, if the vertical hydraulic conductivity decreases with depth, the groundwater flow should be driven deeper than shown on the figure, but would still ultimately discharge to the Hudson River. Based on the observed vertical distribution of piezometric heads, the deepest flow paths of potential interest for this investigation originate near Unit 2. Based on the observed vertical distribution of contaminants (see **Section 9.2**), these flow paths are limited to depths of between 200 and 300 feet below ground surface.

As discussed previously, groundwater flow patterns are also influenced by anthropogenic sources and sinks. The groundwater sources/sinks are shown on **Figure 1.3** and are summarized below:

- Unit 1 Chemical Systems Building (IP1-CSB) Foundation Drain: This drain discharges into the Sphere Foundation Drain Sump (SFDS) and is designed to maintain groundwater elevations beneath IP-1-CSB subbasement to an elevation of approximately 12 feet NGVD 29. The reported groundwater extraction rate from this drain is approximately 10 gallons per minute (gpm).

- IP1-NCD: This drain is designed to maintain groundwater elevations beneath the Unit 1 containment building (IP1-CB) and the Unit 1 Fuel Handling Building (IP1-FHB) at an elevation ranging from 33 to 42 feet NGVD 29. The reported groundwater extraction rate from this drain is approximately 5 gpm.
- Unit 2 Footing Drain: This drain is designed to maintain groundwater elevations beneath the Unit 2 Vapor Containment (IP2-VC) at an elevation ranging from approximately 13 to 42 feet NGVD 29. The long term flow rate from this drain is not known, but short term measurements made prior to and during the Pumping Test indicate it is likely on the order of 5 gpm.
- Unit 3 Footing Drain: IP3-VC is known to have a Curtain Drain. However, specifics of its construction were not available. It is known that a pipe that connects to the Unit 3 Curtain Drain is currently under water in a manhole Northeast of Unit 3. Due to this condition, it is unknown how much or whether or not this drain is removing groundwater.
- Unit 1, 2, and 3 storm drains: The storm drains surrounding Units 1, 2, and 3 were constructed of corrugated metal piping. These pipes and associated utility trenches have been shown to allow at least some infiltration/exfiltration. That is, depending on rainfall and location, these structures may either receive groundwater or recharge the aquifer.

6.7.2 Groundwater Flow Rates

In the interest of evaluating conditions when a relatively large amount of groundwater (and associated constituents) flux to the Hudson River occurs, our discussion of lateral groundwater flow direction focuses on the low tide potentiometric surface contours as shown on **Figures 6.19** and **6.20**. These groundwater contours show that groundwater generally flows toward the Site from the North, East and South, with a generally westerly flow direction across the Site with a gradient averaging about 0.06 feet per feet.

6.7.2.1 Seepage Velocities

We used Darcy's Law to estimate the average groundwater seepage velocity across the Site:

$$V = K * \frac{dh}{dl} * \frac{1}{n_e}$$

Where:

V = average linear groundwater velocity

K = hydraulic conductivity (0.27 feet/day [see **Section 6.50**])

$\frac{dh}{dl}$ = groundwater gradient (0.06)

n_e = effective porosity (assumed to be 0.0003 based on specific yield measured during Pumping Test)

Based on this equation and Site data, we computed the average groundwater seepage velocity to be on the order of 55 ft/day. This is an upper end estimate in that it does not account for the effect of dead-end fractures and irregularities in fracture apertures. That is, we believe the effective porosity is larger than that indicated by hydraulic testing. Also note that this is an average velocity with flow rate in individual fractures being controlled by the local gradient and hydraulic aperture of the fracture. Based on the tracer test (see **Section 7.3.2**), actual measured average seepage rates were substantially less than 55 ft/day.

6.7.2.2 Groundwater Flux

To estimate groundwater flows (i.e., groundwater mass flux) beneath the IPEC, a calibrated analytical groundwater flow model was constructed. This model was based on two independent equations, both of which provide groundwater flow estimates. The first of these equations is based on a mass balance. That is, on a long term average, the groundwater discharging from the aquifer is equal to the aquifer recharge. The second equation is "Darcy's Law", which states the flow per unit width of aquifer is equal to the transmissivity of the aquifer multiplied by the hydraulic gradient.

As discussed in the following subsections using Site-specific data for the governing parameters, both of these independent methods provided similar results. Because we were conservative (that is, we chose values for both equations that we believe may somewhat overestimate flows), we believe the model is appropriate for its intended use for estimating the mass of groundwater discharging to the Hudson River as part of dose impact computations[48]. Please note, this model is not, therefore, conservative for all purposes. For example, we believe it would likely overestimate the yield of extraction wells should they be developed at the facility.

While the calculated groundwater flux from the Site directly to the river (approximately 13 gpm) may intuitively seem small, it is consistent with our Conceptual Site Model and the identified hydrogeological setting.

Mass Balance

The mass balance approach recognizes that the only substantial source of recharge to aquifer is areal recharge derived from precipitation. Precipitation in the area reportedly varies from 49 inches per year (30-year average) to 36 inches per year (10-year average) at the IPEC Meteorological Station. Areal recharge is that portion of precipitation that reaches the water table (total precipitation minus run-off, evaporation and transpiration). The average areal recharge is dependent on total precipitation, the nature and timing of individual storm events, soil types, topography, plant cover, the percentage of impervious cover (roads, buildings, etc.) and precipitation recharge through exfiltrating

[48] It is noted that the dose impact computations reported for 2006 were based on the mass balance model only. These analyses were completed prior to obtaining sufficient data to implement the Darcy's Law model. It is recommended that future dose impact computations also be based on the mass balance model, but with upgrades based on Darcy's Law analyses.

stormwater management systems. Based on our review of available information, we believe that the areal recharge at the IPEC is greater than 6 inches per year and less than 12 inches per year. For the purposes of this study, an average of 10 inches per year was used (see **Appendix S** for information on how we arrived at this average).

Topographic divides were used to defined the recharge area (see **Figure 3.1**). This provides a recharge area of approximately 4,000,000 square feet (92 acres) and a calculated recharge rate of 38 gpm. From this value, the 20 gpm extracted by pumping from foundation drains was subtracted (see **Section 8.0**). This approach, therefore, indicates that the groundwater discharge to the cooling water Discharge Canal and the Hudson River is approximately 18 gpm.

<u>**Darcy's Law**</u>

Darcy's Law is presented below:

$$Q = K * A * \frac{dh}{dl} = T * W * \frac{dh}{dl}$$

Where:

Q = volumetric flow (ft^3)
T = transmissivity (ft^2/day)
W = width of the streamtube

To estimate transmissivities, the aquifer was divided into two layers or zones: the upper forty feet; and between depths of 40 feet and 185 feet, the identified bottom of the significant groundwater flow field. In each of the zones, transmissivities were calculated using the geometric mean of hydraulic conductivity testing. The facility was further divided into 6 flow zones representing areas beneath pertinent Site features; and data East (upgradient) of the Discharge Canal was reviewed independently of that West (downgradient) of the Discharge Canal. This process, shown on the following four tables, provides an estimate of the groundwater flux passing beneath structures of interest that discharge to the cooling water Discharge Canal and the Hudson River. In reviewing these calculations, note the resulting total groundwater flow East of the canal is approximately 18 gpm, which indicates that the long term areal recharge to the aquifer is 10 inches per year, or 28% of the 10-year average precipitation recorded at the IPEC.

Unit	Transmissivity (ft^2/day)	Width (ft)	Hydraulic Gradient (ft/ft)	Volumetric Flow Rate (gpm)
Northern Clean Area	0.36	209	0.600	0.23
Unit 2 North	1.59	294	0.014	0.03
Unit 1/2	31.97	215	0.007	0.26
Unit 3 North	29.87	324	0.054	2.74
Unit 3 South	16.02	338	0.038	1.07
Southern Clean Zone	24.34	879	0.037	4.12
			Total→	8.45

SHALLOW ZONE BEFORE CANAL (OVERBURDEN AND TOP 40 FEET OF BEDROCK)

Unit	Transmissivity (ft^2/day)	Width (ft)	Hydraulic Gradient (ft/ft)	Volumetric Flow Rate (gpm)
Northern Clean Area	0.36	209	0.600	0.23
Unit 2 North	1.59	221	0.038	0.07
Unit 1/2	31.97	146	0.022	0.52
Unit 3 North	29.87	316	0.013	0.61
Unit 3 South	16.02	248	0.011	0.24
Southern Clean Zone	24.34	879	0.037	4.12
			Total→	5.79

SHALLOW ZONE AFTER CANAL (OVERBURDEN AND TOP 40 FEET OF BEDROCK)

Unit	Transmissivity (ft^2/day)	Width (ft)	Hydraulic Gradient (ft/ft)	Volumetric Flow Rate (gpm)
Northern Clean Area	10.77	209	0.068	0.80
Unit 2 North	10.77	294	0.030	0.49
Unit 1/2	62.15	215	0.023	1.61
Unit 3 North	37.65	324	0.022	1.41
Unit 3 South	22.02	338	0.040	1.55
Southern Clean Zone	19.66	879	0.043	3.83
			Total→	9.69

DEEP ZONE BEFORE CANAL (FROM 40 TO 185 FEET BELOW TOP OF BEDROCK)

Unit	Transmissivity (ft^2/day)	Width (ft)	Hydraulic Gradient (ft/ft)	Volumetric Flow Rate (gpm)
Northern Clean Area	10.77	209	0.068	0.80
Unit 2 North	10.77	294	0.023	0.29
Unit 1/2	62.15	215	0.018	0.83
Unit 3 North	37.65	324	0.018	1.09
Unit 3 South	22.02	338	0.016	0.45
Southern Clean Zone	19.66	879	0.043	3.83
			Total→	7.25

DEEP ZONE <u>AFTER</u> CANAL (FROM 40 TO 185 FEET BELOW TOP OF BEDROCK)

GZA's groundwater flux calculations are used by Entergy to calculate radiological dose impact. Entergy currently estimates this dose based upon the precipitation mass balance approach alone. Refinements to this dose model are feasible utilizing the hydrogeologic data presented above. These refinements will improve the overall data fit of the flow model in concert with the long term monitoring program being implemented by Entergy.

The resultant dose assessments are expected to remain close to, or be somewhat lower than, what has already been estimated. It is recommended that Entergy evaluate the refinements to the existing model for inclusion in the next annual effluent assessment report.

7.0 GROUNDWATER TRACER TEST RESULTS

A tracer test was conducted to help assess groundwater migration pathways from IP2-SFP. As discussed in the following sections, the test also helped to confirm migration pathways from Unit 1. The test was designed to simulate a leak from IP2-SFP, in that the tracer (Fluorescein) was released directly to the bedrock at the base of the structure, immediately below the shrinkage cracks associated with the 2005 release. The bedrock surface at this location is approximately elevation 51 feet, and thus approximately 40 feet above the water table (as measured in the immediately adjacent MW-30 - see **Figure 7.1**). This approach was taken (recognizing it would complicate tracer flow paths relative to injection directly into the groundwater) to provide better understanding of the role of unsaturated bedrock in storing and transporting Tritium.

A major difference in the test, as compared to possible releases at IP2-SFP, is the rate of the injection. The 2005 Tritium release was measured at a peak rate of approximately 2 liters per day (0.005 gpm), as opposed to the tracer injection that occurred relatively instantaneously (as compared to the Tritium release) at a rate of approximately 3.5 gpm over approximately an hour. This higher injection rate was used to insure that a sufficient mass of Fluorescein was released at a known time. As anticipated, and discussed in subsequent sections, this practice appears to have enhanced the lateral spreading of the tracer in the unsaturated zone.

7.1 TRACER INJECTION

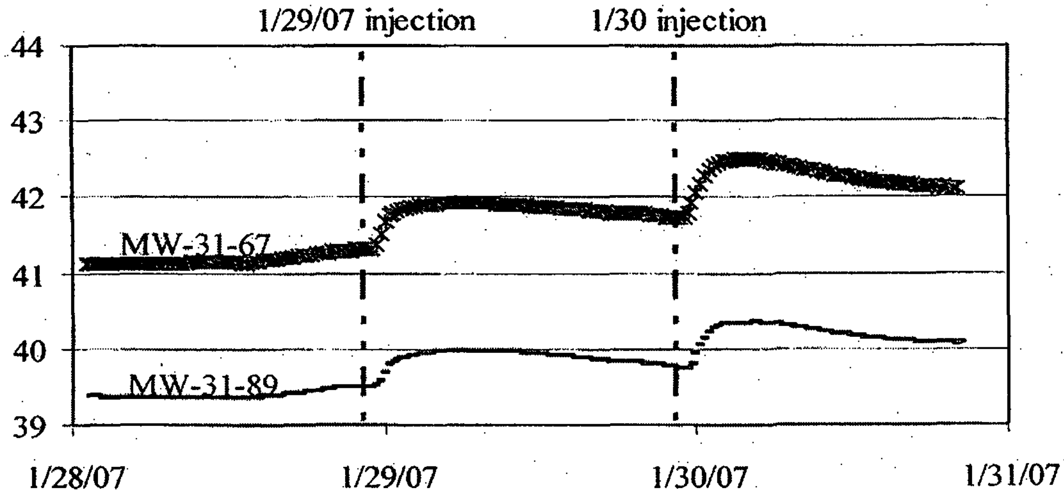
Preparation for the injection began on January 29, 2007 with the injection of potable water to test the ability of the injection point[49], T1-U2-1, to accept water and to pre-wet fractures. The first potable water injection was conducted on January 29, 2007. Five hundred gallons of water (measured using an inline totaling water meter) was introduced as fast as the water source would permit (approximately 8.5 gpm). The water level in the well did not rise significantly. The second potable water injection was conducted on January 30, 2007. A total of 1,012 gallons of tap water was introduced at a mean rate of approximately 8.3 gpm.

The piezometric data collected during that period from wells MW-30, MW-31, MW-33, MW-34 and MW-35 were reviewed for evidence of groundwater mounding. (Note: transducers were not installed in RW-1 and MW-32 on that date.) Mounding, on the order of 0.5 to 1 foot, was recorded at MW-31. No response was noted at the other four nearby monitored locations. Note that MW-31 is located upgradient of the injection point from a *saturated* zone groundwater flow perspective, and unsaturated zone flow in this direction is

[49] The injection point as shown on **Figure 7.2** is constructed from two-inch steel pipe that ends in a tee and perforated piping running directly on the bedrock surface, well above the water table. This perforated piping was covered with approximately 0.5 feet of crushed stone extending from the bedrock excavation face to the South face of the SFP, over a length of approximately 8 feet. The crushed stone was covered with filter fabric prior to placing the concrete mud-mat for gantry crane foundation construction; the mud-mat covers the entire bedrock excavation "floor" adjacent to the South side of the SFP.

consistent with the bedrock strike/dip directions. Based on the shape of the time response curve at MW-31, GZA believes that:

1. The center of the release to the water table was at some distance from MW-31 (see time lag), and;
2. Injected water was released to the water table over a longer duration than the two hour injection test. This opinion is based on the relatively slow decay of the mound at MW-31. This response is shown on the figure below:



PIEZOMETRIC GROUNDWATER RESPONSE TO WATER INJECTION

We have insufficient information to render an opinion on the shape or height of the tracer injection-induced groundwater mound. We note, however, because of the lower rate of the tracer injection, the short duration of the injection (see below), and the groundwater flow velocities, as derived from the tracer test, GZA believes mounding had relatively little effect (compared to unsaturated flow) on the lateral spreading of the tracer. That is, the life of the mound was not of sufficient duration to cause long term, widespread lateral migration in the groundwater.

The tracer injection was performed on February 8, 2007. It consisted of the release of 7.5 pounds of Fluorescein with 210 gallons of water. More specifically, prior to Fluorescein injection, 30 gallons of potable water was released to the well, this was followed by 10 gallons of a Fluorescein-water mixture, followed by 170 gallons of potable water (to flush the Fluorescein out of the well). This procedure resulted in a minimum initial average tracer concentration of 4,300,000 ppb.

7.2 TRACER CONCENTRATION MEASUREMENTS

The concentrations of Fluorescein in groundwater were routinely measured between February 8, 2007 and August 21, 2007[50] at 63 locations. This resulted in the collection analysis of 4,488 samples, including background samples, charcoal samplers and water samples. These data are tabulated and presented on time-concentration graphs in **Appendix N**.

Measurements of Fluorescein concentrations were made by two methods. The first is through aqueous sample analysis (1,969 individual samples). These water sample analyses provide direct concentration measurements, at the time of sampling, with a detection limit of less than 1 ppb.

A second method entailed desorbtion of Fluorescein from packets of activated carbon (carbon samplers) suspended in the groundwater flow path at multi-level sampling locations. This method provides a measure of the mass of Fluorescein moving through a monitoring well screen over the period the activated carbon is in the well. However, the actual concentration of Fluorescein in the groundwater is not determinable from this test. Among other things, carbon sample analyses are useful in establishing that the Fluorescein mass being transported by groundwater did not pass sampling locations between discrete sampling events. This was important for this study because of the potential for high transport rates (see **Section 6.0**).

7.3 SPATIAL DISTRIBUTION AND EXTENT OF FLUORESCEIN IN GROUNDWATER

The groundwater tracer test was developed primarily to identify groundwater migration pathways. We have divided our discussion on observed pathways into three subsections: unsaturated zone migration, the lateral distribution of Fluorescein, and the vertical distribution of Fluorescein.

Unsaturated Zone Transport

By design, Fluorescein was released atop the bedrock, in the unsaturated zone. The bedrock structure (strike and dip direction of bedrock fractures) therefore played a dominant role in controlling tracer migration to the water table. This is witnessed by the significant Fluorescein concentrations observed in the upgradient monitoring well MW-31 and MW-32 (see below) and at lower concentrations in the more distant and upgradient Unit 1 monitoring well MW-42.

The observed unsaturated zone migration to the South and East is consistent with the observed bedrock fracturing (see **Section 6.0**). This mechanism is also evidenced by data showing the highest Fluorescein concentration (49,000 pico-curies per liter - pCi/L)[51]

[50] In addition to the routine sampling, specific wells were sampled for a longer period of time as part of short term variability testing (see **Section 9.0**).
[51] pCi/L is a standard unit of radiation measurement.

being found in well MW-32, located 60 feet to the South of the injection location, and not in MW-30, located immediately below the injection location.

In reviewing tracer test results, it should be recognized that the Fluorescein released at a single location on the bedrock was not released to the water table at a single location, rather, it reached the water table over an undefined area that likely extends to the East of MW-31, to the South to MW-42, and likely not far to the North of the injection well. As discussed in **Section 7.5**, this limits our ability to evaluate migration rates, but increases our ability to understand likely Tritium migration pathways from IP2-SFP.

The spreading of Fluorescein in the unsaturated zone was likely more pronounced than the spreading of Tritium because of the higher release rate. The tracer test, however, supports data that shows the Unit 2 plume to extend upgradient of the source area and laterally to Unit 1 to the South of IP2-SFB.

Lateral Distribution

Two conditions were selected to show the lateral distribution of Fluorescein in a manner illustrating conditions influencing the migration of groundwater in the vicinity of IP2-SFB. These are:

1. The maximum observed concentrations; and,
2. Conditions just prior to, and including, June 14, 2007.

While the maximum observed concentrations do not illustrate an actual condition, the resulting figure is useful in highlighting migration pathways. We chose June 14th because it represents conditions approximately 4 months after the injection. With estimated Fluorescein transport rates on the order of 4 to 9 feet per day (see **Section 7.4**), conditions proximate to that date clearly illustrate the effects of subsurface storage on both Fluorescein and Tritium[52].

Lateral Distribution – Maximum Observed Concentrations

The distribution of the observed maximum concentrations of Florescein, at any depth, in groundwater is shown on **Figure 7.2**. This figure was developed based on both the observed concentrations and our understanding of groundwater flow directions (inferred from groundwater contours). This figure does not show conditions at any single time; rather it represents our interpretation of the highest tracer concentration, at any time during the test, at a location. In reviewing that figure please note:

- The maximum observed tracer concentration was 49,000 ppb; approximately 1% of the calculated average injection concentration. We interpret these data to mean that there is considerable spreading and mixing of the tracer in the unsaturated and shallow saturated zones.

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[52] Later dates were not selected because of the associated reduction in the sampling frequency and/or number of sampling locations.

- The 50 ppb contour represents approximately 1/100,000 the concentration of the injected tracer. Because Tritium concentrations in IP2-SFP are approximately 20,000,000 pCi/L this contour (50 ppb Fluorescein) represents the detection limit of a release of Tritium from IP2-SFP (at the injection well).
- The general shape of the resulting plume is strikingly similar to the observed Unit 2 plume, see **Figure 8.1**. This supports our interpretation of contaminant migration from IP2-SFP.
- Because tracer was detected in MW-42 and MW-53, the test can be used to help assess migration pathways from Unit 1. The observed distribution of Fluorescein in the vicinity of Unit 1 supports our interpretation of the migration of Strontium, with a westward migration towards the Hudson River in a fairly narrow zone (see **Figure 7.2**).
- The low concentrations to the West (downgradient) of the cooling water Discharge Canal (as compared to East of the canal) indicate the canal received a significant mass of the tracer, as opposed to direct discharge to the river.
- Concentrations found in Manhole Five (MH-5) indicate the IP-2 Curtain Drain received tracer (see **Section 7.5**).

Lateral Distribution – June 14, 2007

GZA's interpretation of the distribution of Fluorescein in groundwater proximate to June 14, 2007 is shown on **Figure 7.3**. Again, concentrations are the highest measured at any depth. While not ideal for the observed concentrations, the contour interval was selected to match the contour intervals shown on **Figure 7.2**. In reviewing that figure, please note:

- The shape of the plume is more representative of an ongoing release than of a four-month-old instantaneous release in a strong groundwater flow field. This supports other data which indicate water is stored in the unsaturated bedrock (and potentially within the upper water bearing zone) and is released to the groundwater flow field over time.
- The center of the Fluorescien mass in groundwater, in the release area, shifted to the North. (See data for wells MW-30 and MW-32 on **Figures 7.2** and **7.3**). GZA interprets these data to mean:
  - There is more storage in the unsaturated zone in proximity to IP2-FSB, than to the South or West; and
  - The relatively high injection rate resulted in more lateral spreading of the tracer than would have resulted from a slow, long duration release.

Vertical Distribution

The table provided below presents data on the vertical distribution of Fluorescein along the center line of the tracer plume (see **Figure 7.2** for well locations). It presents the maximum observed concentration at each depth and the approximate concentration[53] proximate to June 14, 2007.

[53] Data estimated for the June 14th date are based on time concentration graphs (see **Appendix N**).

FLUORESCEIN CONCENTRATIONS

MW-31		MW-32		MW-30		MW-33		MW-111		MW-37	
Depth	**Conc.**	**Depth**	**Conc.**	**Depth**	**Conc.**	**Depth**	**Conc.**	**Depth**	**Conc.**	**Depth**	**Conc.**
53	1600 / 0.5	62	49,000 / 2	74	5690 / 2600	18	6.6 / 1	16	2.9 / 2.9	22	47 / 10
67	12,700 / 200	92	24,300 / 500	88	167 / 110					32	1.3 / ND
89	1810 / 3	140	15,300 / 6								
		165	4160 / 16								
		197	621 / 56								

1600 / 0.5 = Max. conc. / conc. proximate to 6/14/07 in μg/L
Depth = Below Ground Surface (Feet)
ND = Not Detected

The available data indicate the bulk of the Fluorescein was migrating at fairly shallow depths, although not always at the water table. As anticipated (consistent with the Conceptual Site Model), it also suggests the pathway becomes somewhat deeper downgradient of the injection point, likely being below the well screens at MW-33 and MW-111. The comparatively low concentrations at MW-111, as compared to Tritium concentrations, likely highlights the importance of unsaturated zone migration in groundwater contaminant distributions.

7.4 TEMPORAL DISTRIBUTION OF FLUORESCEIN IN GROUNDWATER

Groundwater samples were collected at regular intervals between February 8 and August 21, 2007[54]. These data are shown on graphs provided in **Appendix N** with selected information shown below. Interpretation of these graphs is complicated, beyond the normal difficulties associated with interpreting tracer test data in fractured rock. This is because the tracer was *not* injected directly to the water table, as would be more typical. Rather, the tracer was released at the top of the bedrock, in the unsaturated zone, so as to better mimic the behavior of the Tritium release from the cracks in the fuel pool wall; as was the primary objective of the tracer test. Therefore, the tracer then entered the groundwater regime at numerous locations due to unsaturated zone spreading from the release point. In addition, these numerous release points remained active over an extended period of time (months) due to storage in the unsaturated zone; see the previous subsection and **Section 8.1.2** for further discussion.

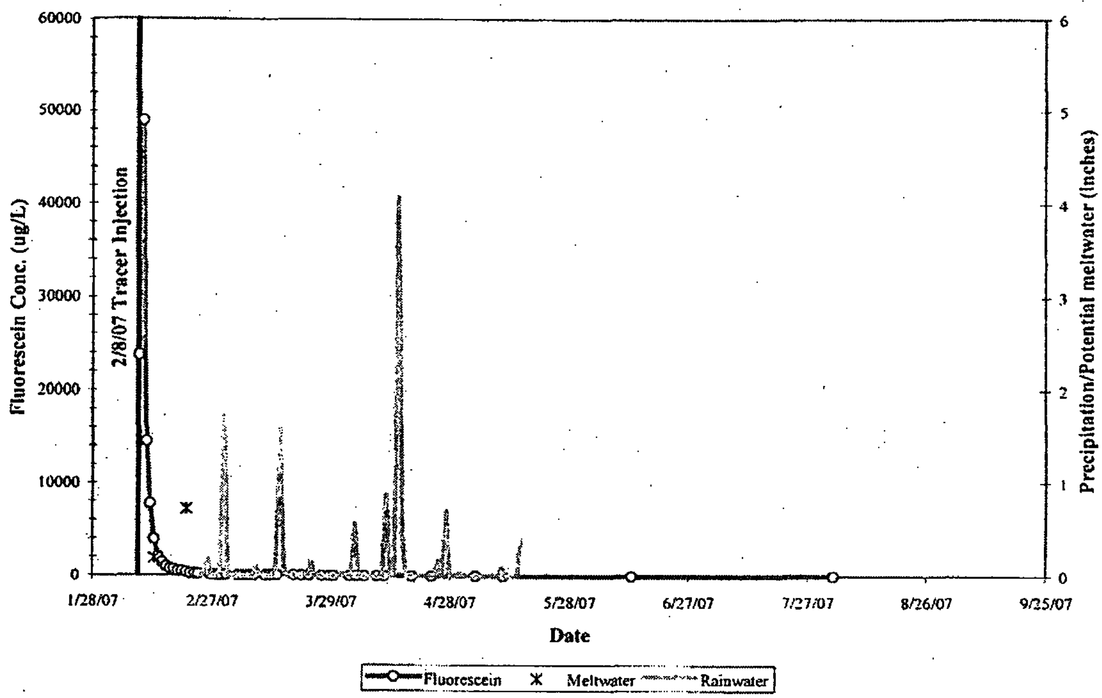
With these limitations noted, the following observations/interpretations are provided:

- At some locations, the release to the water table was rapid. For example, at monitoring well MW-32-62, located approximately 60 feet to the South of the injection point, the tracer arrival time[55] was approximately one day. Conversely, at MW-30-74, located adjacent to the injection well, the arrival time was approximately 25 days. See the following figures.

---

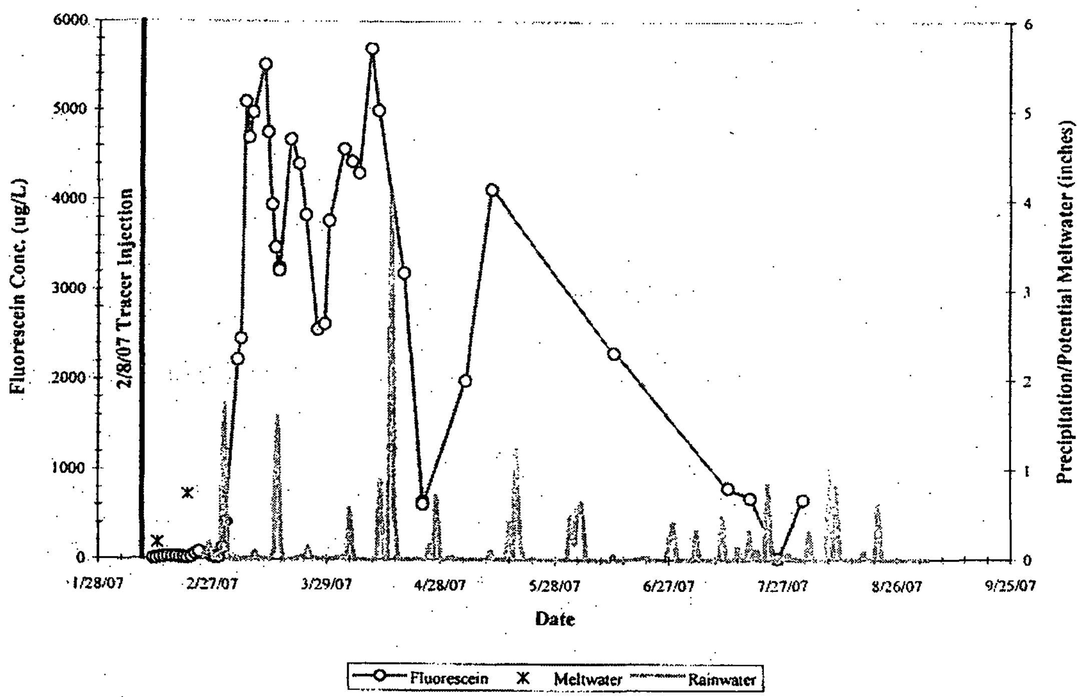
[54] In addition to the routine sampling, specific wells were sampled for a longer period of time as part of short term variability testing (see **Section 9.0**).
[55] Arrival times are generally established as the center of mass (often the peak) of the concentration vs. time graph.

MW-32-62



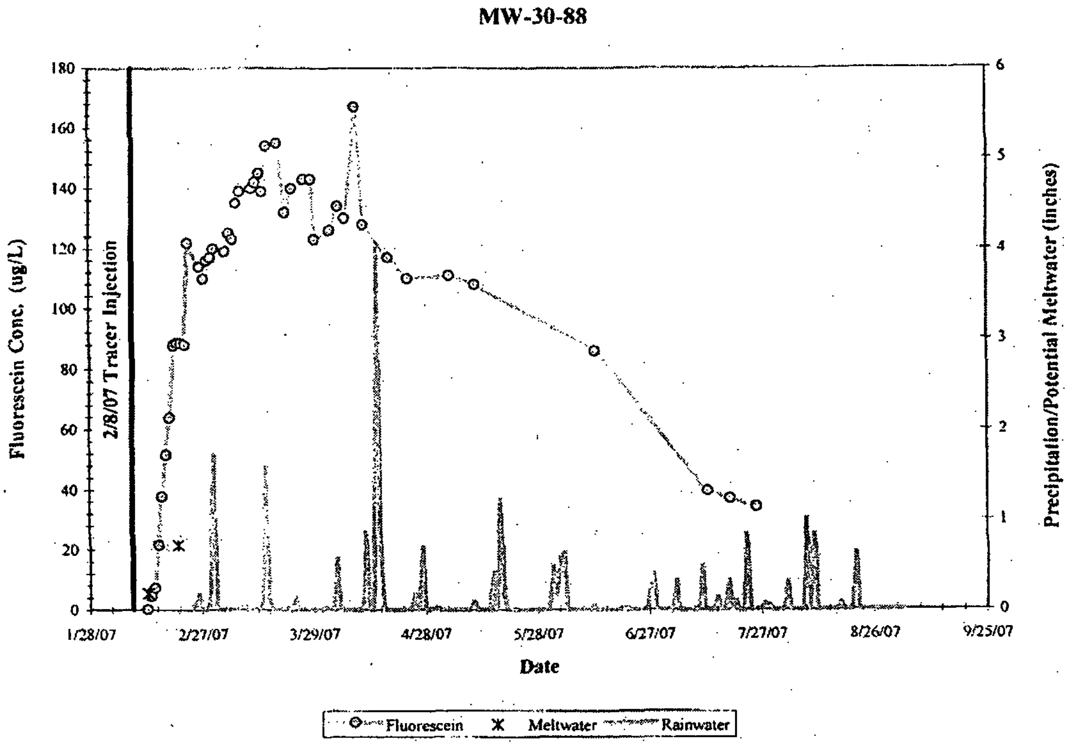
MW-32-62 FLOURESCEIN AND PRECIPITATION VS TIME

MW-30-69



MW-30-69 FLOURESCEIN AND PRECIPITATION VS TIME

- In mid-June 2007, there was still an ongoing source of Fluorescein to the water table in the vicinity of IP2-FSP. This is evidenced by the time-concentration graphs for MW-30 -74 (see previous figure) and MW-30 -88, presented below:



MW-30-88 FLOURESCEIN AND PRECIPITATION VS TIME

- Because the locations and times of releases from the unsaturated zone to the water table are not known, it is difficult, at best, to estimate tracer transport velocities. However, as shown below, the average value appears to be on the order of 4 to 9 feet/day.

Well Location	Time of Arrival Date	Time (Days)	Distance (Feet)	Velocity (Ft/Day)
MW-33	3-5-07	25	110	4.4
MW-111	3-14-07	34	145	4.3
MW-37-22[56]	4-10-07	61	300	4.9
MW-55[57]	3-28-07	48	240	5 to 9

FLOURESCEIN ARRIVAL TIMES AND TRANSPORT VELOCITIES

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[56] The source of the Fluorescein observed in MW 37-22 is uncertain. It may be entirely from migration in the bedrock slightly to the North of that location, or may be due, in part or in whole, to transport via storm drains and in the backfill around the Discharge Canal walls. See **Section 4.5**.

[57] The calculated velocity depends on which flow path is selected. Using a flow path from MW-32 (day of release) to MW-55, the calculated velocity is approximately 5 feet/day. Using a flow path between MW-53 and MW-55 (the Strontium flow path) the calculated velocity is 9 feet/day.

Also note, the carbon sampler data supports these estimates to the extent that no evidence of significant Fluorescein migration between aqueous sampling events was found.

The observed tracer migration rates are approximately 1/5 to 1/10 the calculated groundwater velocity of 55 ft/day, see **Section 6.7.2**. GZA attributes the difference between the "observed" and the "computed" transport velocities primarily to the effective porosity of the bedrock. That is, we believe the actual effective porosity is considerably larger (more on the order of 0.003) than that computed from our analyses of the Pumping Test (see **Section 6.5.1**); the aquifer response testing (see **Section 6.6.1**); or the hydraulic aperture of the bedrock (see **Section 6.5.2**). This slower transport velocity helps to explain the observed long term temporal variations in both tracer and Tritium groundwater concentrations, and supports the use of a porous media flow model. As a practical matter, this slower transport velocity encourages the use of conventional groundwater monitoring frequencies (quarterly or longer); and reduces concerns over the possibility of high concentrations of contaminants migrating by a monitoring location between sampling events.

7.5 FLUORESCEIN IN DRAINS, SUMPS AND THE DISCHARGE CANAL

Fluorescein was also detected within storm drain catch basins, foundation drain sumps, and the Discharge Canal. Fluorescein was detected in manholes MH-4, MH-5 and MH-6. In reviewing these data, note:

- MH-5 receives discharge from the IP2-VC Curtain Drain system. The presence of tracer in this manhole indicates that tracer entered the Curtain Drain system due to lateral spreading at the release point during injection. Once in the Curtain Drain system, the tracer migrated to MH-5.
- Water in MH-5 flows towards the cooling water Discharge Canal passing through MH-4, discharging at MH-4A.
- The concentrations detected in MH-4 are very similar to the Fluorescein concentrations detected in samples collected from MH-5, while Fluorescein was not detected in samples collected from the downstream manhole MH-4A. This suggests that either dilution in MH-4A reduced Fluorescein to below method detection limits, and/or the tracer is lost via exfiltration from piping between MH-4 and MH-4A. This loss (if it occurs) in conjunction with flow in the canal backfill, could explain the Fluorescein observed in MW-37. Available data are not adequate to fully address this issue. In any event, the test further demonstrates the need to account for the Tritium being transported in the IP2-VC Curtain Drain (see **Section 7.6**).
- In reviewing data, note that the tracer concentrations in MH-6 are lower than the concentrations observed in MH-5 (peak in MH-6 of 14.4 ppb as opposed to a peak in MH-5 of 43.1 ppb). We attribute the concentrations in MH-6 to groundwater infiltration in the area of the identified tracer plume. Also note the flow from MH-6 is to MH-5.

Fluorescein was also detected in the IP1-NCD, the IP1-SFDS, and the Containment Spray Sump (CSS). We have attributed the presence of tracer at these locations to unsaturated zone migration to the vicinity and West of MW-42. The concentration and arrival times at these three locations are not easily explained but, taken as a whole, are consistent with the observed migration of Tritium.

Fluorescein was detected at low concentrations, at various times, in carbon samples collected from the cooling water Discharge Canal. Because of the substantial dilution in the canal, the extended release of tracer to the canal and the low concentrations of tracer found in the samples, we believe these data represent background conditions[58], and cannot be used to evaluate the tracer test.

7.6 MAJOR FINDINGS

As an overview, the tracer test, supports our CSM and the observed distribution of contaminated groundwater. GZA also concludes that:

- Unsaturated zone flow is important to the migration of contaminants released above the water table in the vicinity of Unit 2. Bedrock fractures induce this flow to the South and East of the release.
- There is significant storage of contaminated groundwater above the water table or in zones of low hydraulic conductivity (homogeneities) in the saturated zone. These features allow a long-lived release of contaminants to the Site groundwater flow field.
- Observed tracer migration rates are lower than calculated theoretical migration rates. As a practical matter, this "migration" indicates that the use of the estimated average hydraulic conductivity (0.27 ft/day or $1x10^{-4}$ cm/sec) will overestimate the volume of groundwater migrating through a given area. That is, we attribute the lower transport velocity to be due, in part, to a lower average hydraulic conductivity.
- In our opinion, the tracer test, in conjunction with the Tritium release, indicates that the existing network of monitoring wells can be used to monitor groundwater at IPEC.

[58] It is noted that Fluorescein is the primary colorant in automobile coolant anti-freeze. Therefore, leaks from cars to parking lot/road surfaces can impact surface water bodies via storm drain systems and/or direct runoff. Fluorescein was detected in the Discharge Canal prior to initiation of the tracer injection, further indicating its presence as background.

8.0 CONTAMINANT SOURCES AND RELEASE MECHANISMS

GZA conducted a review of available construction drawings, aerial photographs, prior reports, and documented releases, and interviewed Entergy personnel to assess potential contaminant sources. The primary[59] radiological sources identified were the Unit 2 Spent Fuel Pool (IP2-SFP) located in the Unit 2 Fuel Storage Building (IP2-FSB) and the Unit 1 Fuel Pool Complex (IP1-SFPs)[60] in the Unit 1 Fuel Handling Building (IP1-FHB. These two distinct sources are responsible for the Unit 2 plume and the Unit 1 plume, respectively.

No release was identified in the Unit 3 area. The absence of Unit 3 sources is attributed to the design upgrades incorporated in the more recently constructed IP3-SFP. These upgrades include a stainless steel liner (consistent with Unit 2 but not included in the Unit 1 design) and an additional, secondary leak detection drain system not included in the Unit 2 design.

The identified specific source mechanisms associated with the IP2-SFP and the IP1-SFPs are discussed in the following sections. We have segregated this source discussion based on primary contaminant type; those classified as primarily Tritium sources, as associated with the Unit 2 plume, and those classified as primarily Strontium sources, as associated with the Unit 1 plume. While the groundwater plumes emanating from their respective source areas can clearly be characterized using each plume's primary constituent, radionuclides other than Tritium and Strontium also exist to a limited extent and are fully addressed within the context of the Unit 2 and Unit 1 plume discussions[61].

Discussion of the two primary source types will be parsed further as follows:

- The Unit 2 (Tritium) plume source analyses will be split into: 1) "direct sources" defined as releases to the exterior of Systems Structures and Components (SSCs); and 2) "indirect storage sources" related to natural hydrogeologic mechanisms in the unsaturated zone (such as adsorption and dead-end fractures) and potential anthropogenic contaminant retention mechanisms (such as certain subsurface foundation construction details);
- The Unit 1 (Strontium) plume source analyses will be split into the mechanisms specific to the individual plume flow paths identified.

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[59] In addition to sources that directly impact groundwater, atmospheric deposition from permitted air discharges was also identified as a potential source of diffuse, low level Tritium impact to the groundwater.

[60] All of the pools in the IP1-SFPs contained radionuclides in the past. However, only the West pool currently contains any remaining fuel rods and all of the other IP1 pools have been drained of water. It is also noted that the Unit 1 West pool has been undergoing increased processing to significantly reduce the amount of radioactive material in the pools. Once fuel is removed, the IP1-SFPs will no longer constitute an active source of groundwater contamination.

[61] Contaminants associated with the Unit 2 leak were found to be essentially comprised of Tritium. The Unit 1 plume is comprised primarily of Strontium, but also includes Tritium and sporadic observation of Cesium-137, Nickel-63 and Cobalt-60 at low levels in some wells downgradient of the IP1-SFP (see **Figure 8.3**). Entergy accounts for all radionuclides that can be expected to reach the river in their required regulatory reporting of estimated dose impact.

8.1 UNIT 2 SOURCE AREA

The majority of the Tritium detected in the groundwater at the Site was traced to IP2-SFP. This pool contains water with maximum Tritium concentrations of up to 40,000,000 pCi/L[62].

The highest Tritium levels measured in groundwater (up to 601,000 pCi/L[63]) were detected early in the investigation at MW-30. This location is immediately adjacent to IP2-SFP and directly below the 2005 shrinkage cracks. As shown on **Figure 8.1**, the Tritium contamination ("the plume[64]") then tracks with downgradient groundwater flow[65] through the Unit 2 Transformer Yard, under the Discharge Canal and discharges to the river[66] between the Unit 2 and Unit 1 intake structures. During review of the following sections, it is important to recognize that only small quantities of pool leakage (on the order of liters/day) will result in the Tritium groundwater plume observed on the Site.

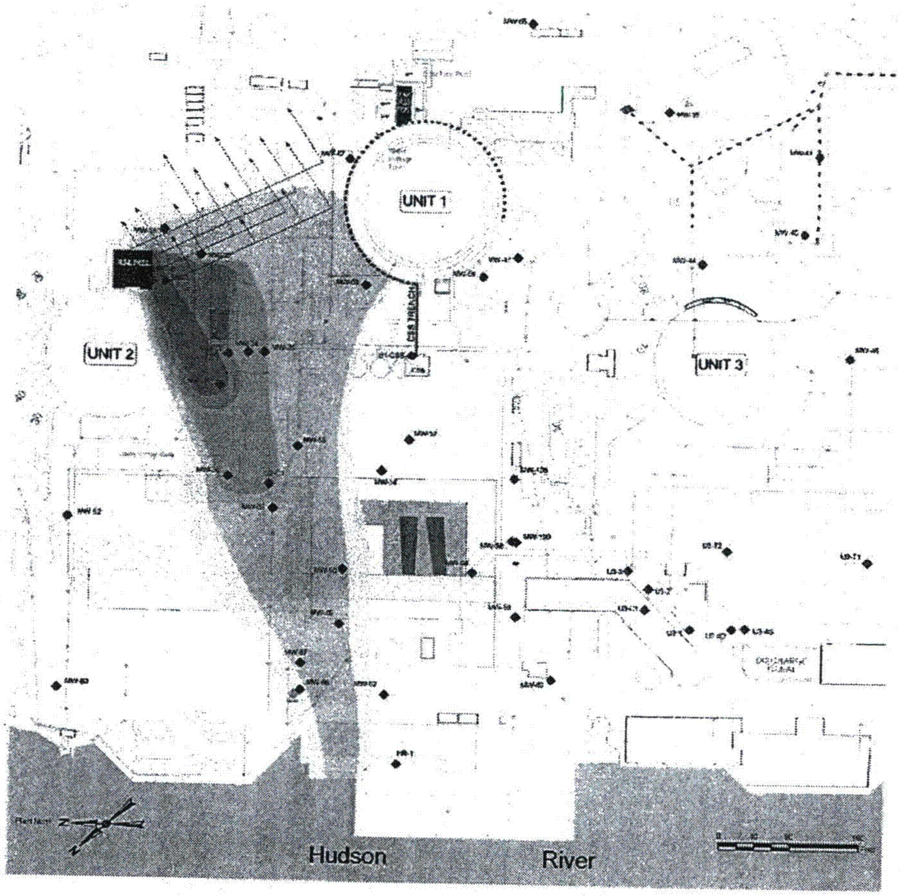
[62] In contrast, the levels of Tritium in the Unit 1 West pool are only on the order of 250,000 pCi/L. Strontium concentrations in IP2-SFP are on the order of 500 pCi/L.

[63] The 601,000 pCi/L Tritium concentration was measured during packer testing of the open borehole prior to multi-level completion. This value is therefore actually a *lower bound* estimate for depth-specific Tritium concentrations at that time. If the multi-level sampling instrumentation could have been completed prior to obtaining these data (not possible because the packer testing was required to design the multi-level installation), samples would have yielded *equal or higher concentrations*. This conclusion reflects the limited standard length and temporary emplacement of the packers used during the packer testing, and thus the greater potential for mixing and dilution between zones, as compared to the numerous packers permanently installed in the multi-level completions.

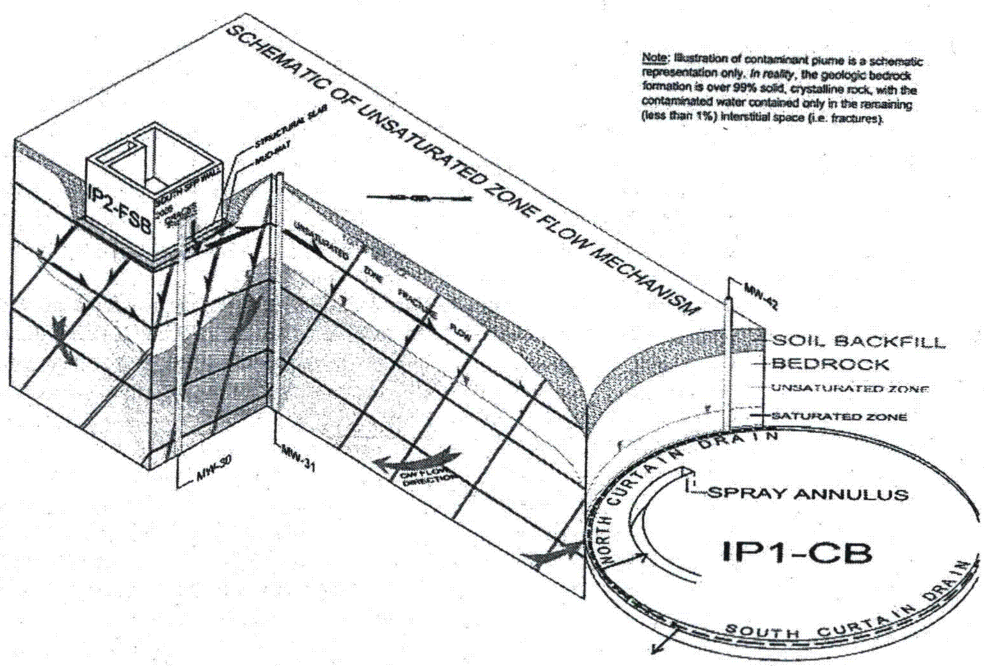
[64] It is noted that **Figure 8.1** does *not* show an actual Tritium plume; the isopleths presented contour upper bound concentrations for samples taken at *any time* and *any depth* at a particular location, rather than a 3-dimensional snapshot of concentrations at a single time. As such, this "plume" is an overstatement of the contaminant levels existing at any time. It should also be noted that the lightest colored contour interval begins at one-quarter the USEPA drinking water standard. While drinking water standards do not apply to the Site (there are no drinking water wells on or proximate to the Site), they do provide a recognized, and highly conservative, benchmark for comparison purposes). Lower, but positive detections outside the colored contours are shown as colored data blocks. See figure for additional notes.

[65] It is recognized that low concentrations of Tritium likely extend to the South, all the way to Unit 1. This conclusion is supported by: 1) the low Tritium concentrations remaining in IP1-SFPs (250,000pCi/L); 2) the data from MW-42 and MW-53; and 3) the Tritium balance between that released by the IP1-SFPs leak and that collected by the NCD. The transport mechanism is through *unsaturated* zone flow which follows bedrock fracture strike/dip directions rather than groundwater flow direction (see schematic of unsaturated zone flow mechanism included below). The levels of Tritium detected *upgradient* of IP2-SFP in monitoring wells MW-31 and MW-32 are also due to unsaturated zone transport from IP2-SFP along the generally southerly striking and easterly dipping bedrock fractures (see structural geology analysis in **Section 6.0** and tracer test discussions in **Section 7.0**).

[66] As the Tritium moves under the Discharge Canal, a significant amount discharges directly to the canal before the plume reaches the Hudson River.



UNIT 2 BOUNDING ACTIVITY ISOPLETHS



IP2-SFP UNSATURATED ZONE FLOW MECHANISM

The IP2-SFP contains both the fuel pool itself as well as its integral Transfer Canal. IP2-SFP is founded directly on bedrock which was excavated to elevation 51.6 feet for construction of this structure. As such, this pool's concrete bottom slab is located approximately 40 feet above the groundwater (as measured directly below the pool in MW-30[67]). During construction, a grid of steel "T-beams" was embedded in the interior surface of the 4-to 6-foot-thick concrete pool walls. These T-beams provided linear weld points for the 6 by 20 foot stainless steel liner plates. Given this construction method, an interstitial space exists between the back of the ¼-inch-thick stainless steel pool liner and the concrete walls. The space is expected to be irregular[68] and its exact width is unknown, but nominal estimates of a 1/8 to ¼ inch are not unreasonable for assessing potential interstitial volume. Using these estimates, the volume of the space behind the liner could be on the order of 1500 gallons. In addition, the degree of interconnection between the spaces behind the individual liner plates is also expected to be highly variable given the likely variability of weld penetration into the "T beams." Therefore, the travel path for pool water that may penetrate through a leak in the liner is likely to be highly circuitous.

8.1.1 Direct Tritium Sources

Two confirmed leaks in the IP2-SFP *liner* have been documented, as well as the 2005 shrinkage crack leak through the IP2-SFP concrete wall[69]. The first liner leak dates back to the 1990 time frame, under prior ownership. This legacy leak was discovered and repaired in 1992. With the more recent discovery of the concrete shrinkage cracks in September 2005, Entergy undertook an extensive investigation of the IP2-SFP liner integrity. Within areas accessible to investigation, no additional leaks were found in the liner of the pool itself. However, after draining of the IP2-SFP Transfer Canal in 2007 for further liner investigations specific to the Transfer Canal, a single small weld imperfection was detected in one of these liner plate welds. This was the only leak identified in the Transfer Canal where the entire surface and all the welds could be and were inspected. This second liner leak is expected to have released tritiated pool water into the interstitial space behind this area of the liner plates whenever the Transfer Canal was filled above the depth of the imperfection (the Transfer Canal is currently drained and this imperfection will be welded leak-tight prior to refilling the Transfer Canal). All identified leaks have therefore been terminated. While additional active leaks can not be completely ruled out, if they exist, the data[70] indicate they must be very small and of little impact to the groundwater[71].

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67 While similar and lower groundwater elevations persist downgradient to the West, the shallow groundwater elevations are much higher (up to approximately elev. 45 feet) within only 50 feet to the East (MW-31) and Southeast (MW-32) of the pool.

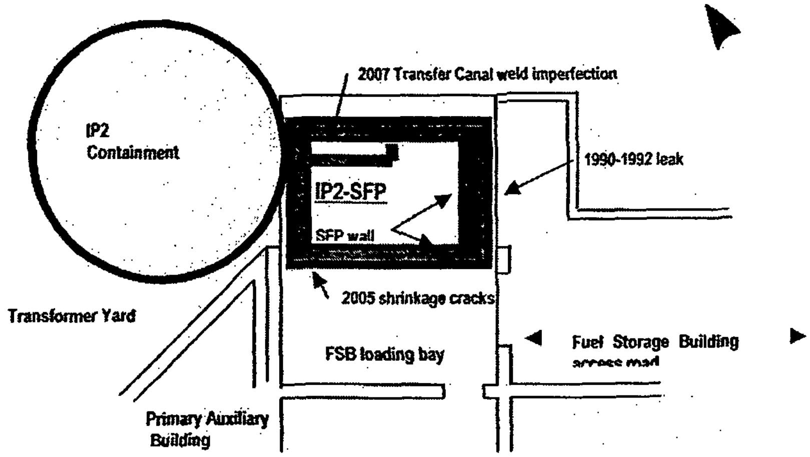
68 The interstitial space width and uniformity will be related to the degree to which the concrete wall surface falls within a single plane. Because of the practicalities of forming and pouring concrete walls, we believe the surface is unlikely to be planer.

69 While the 2005 leak from the shrinkage cracks does not appear to be related to a specific leak in the pool liner, it is considered a "direct source" because it still resulted in a release to the exterior of one of the plant's SSCs.

70 These data include: monitored water levels in the SFP, with variations accounted for based on refilling and evaporation volumes; the mass of Tritium migrating with groundwater is small; and the age of the water in the interstitial space.

71 For example, the 2005 shrinkage cracks still intermittently release small amounts of water; on the order of 10 to 20 ml/day. This water could represent a transient active leak, or it may just be due to residual water trapped behind the liner plates above the 2005 crack elevation still working its way slowly to the cracks. While this water is contained and prevented from reaching the groundwater, other such small leaks may exist which do reach the groundwater.

The three identified direct sources are discussed individually in the following paragraphs and shown on the figure below.



UNIT 2 FUEL POOL DIRECT SOURCE LOCATIONS

<u>IP2-SFP 1990-1992 Legacy Liner Leak</u> – This leak was first documented on May 7, 1992 when a small area of white radioactive precipitate was discovered above the ground surface on the outside of the IP2-SFP East concrete wall. This boron deposit exhibited radiological characteristics consistent with a potential leak from the pool. A camera survey was then conducted within the IP2-SFP to identify the location of the associated leak(s) in the liner. The survey initially revealed no damage to the liner. However, to further investigatory efforts, divers were utilized to visually inspect accessible portions of the liner. The divers found indications that the liner had been gouged when an internal rack had been removed on October 1, 1990. Two hundred and forty linear feet of the North and West IP2-SFP wall welds were then inspected and vacuum-tested to verify that the identified damage was isolated to this one case. No other leaks were identified, and on June 9, 1992, the leak was repaired.

Subsequent analyses conducted by the previous plant owner indicate that approximately 50 gallons per day could have leaked through the liner. This leak rate and the time scale of the release event would be expected to fill all the accessible interstitial space behind the liner[72]. Once the space behind the liner was filled to elevation 85 feet (the elevation of the 1990 cracks), water then began to leak out of the cracks in the concrete wall, with a maximum total release volume of up to 50,000 gallons. Given the very slow release rate (0.035 gal/min), the porous, hydrophilic nature of concrete, and the location of the leak at approximately five feet above the ground surface, a significant portion of the released water likely evaporated prior to entering the soils. However, given that the soils

[72] While the interstitial space was filling up to elevation 85 feet, any other cracks or joints in the concrete wall below this elevation, such as those identified in 2005, likely released contaminated water to the environment. As discussed below, it is hypothesized that with time, these subsurface cracks/joints may have become sealed due to precipitation of dissolved compounds, either carried with the pool water or derived from the concrete pool wall. This would have been required to allow retention of pool water in the interstitial space below elevation 85 feet after the liner leak was repaired in 1992, and thus subsequent leakage of the 2005 shrinkage cracks.

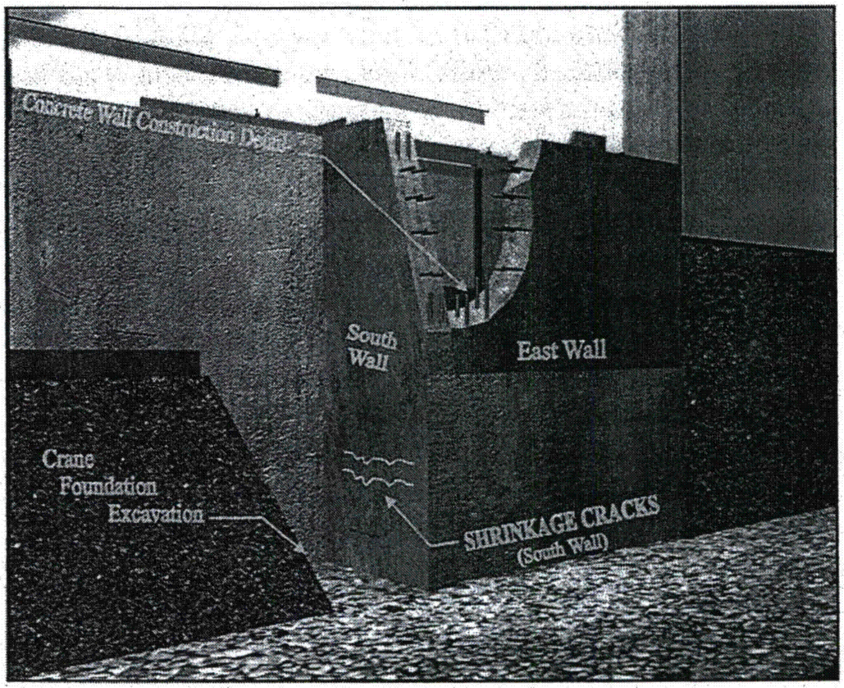
below the leak were found to be contaminated[73], it is clear that some portion of this release entered the subsurface. While Strontium and Cesium could have largely partitioned out of the pool water to the shallow soils, tritiated water would be expected to have continued to migrate downward to the groundwater.

IP2-SFP 2007 Transfer Canal Liner Weld Imperfection – As part of the recently completed liner inspections initiated by Entergy in 2005, the IP2-SFP Transfer Canal was drained in 2007 to facilitate further leak-detection efforts including vacuum box testing of the welds. These inspections discovered a single small imperfection in one of the liner plate welds on the North wall of the Transfer Canal at a depth of about 25 feet, which is approximately 15 feet above the bottom of the pool. All of the welds and the entire liner surface area of the Transfer Canal have been inspected by one or more techniques and no other leaks were found. Engineering assessments indicate this wall imperfection is likely from the original construction activity since there is no evidence of an ongoing degradation mechanism.

Given that the Transfer Canal is now drained, this weld imperfection is no longer an active leak site. However, the historic practice of maintaining water in the Transfer Canal likely resulted in a generally continuous release of pool water into the interstitial space behind the liner over time, and then potentially through the concrete pool walls and into the groundwater.

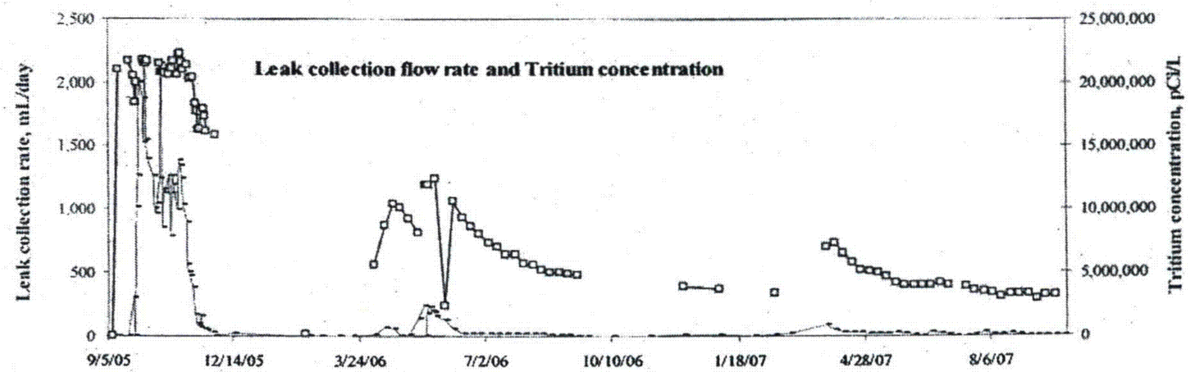
IP2-SFP 2005 Concrete Shrinkage Crack Leak - During construction excavation in September 2005 for the dry cask storage project, the South wall of the IP2-SFP was exposed and two horizontal "hairline" shrinkage cracks were discovered (see schematic below). These cracks exhibited signs of moisture, though fluid flow was not observed emanating from the cracks. To promote collection of adequate liquid volumes for sampling and analysis, the cracks were subsequently covered with a plastic membrane to retard moisture evaporation and enhance water vapor condensation. The trapped fluid was drained to a sample collection container. This temporary collection effort not only provided leak rate measurement capability and sufficient water for analysis, it also prevented further release to the groundwater.

[73] Approximately 30 cubic yards of radionuclide contaminated soils were excavated from the area in 1992.



UNIT 2 SFP 2005 SHRINKAGE CRACKS IDENTIFIED IN SEPTEMBER 2005

Initially, the two cracks were found to be leaking at a combined average rate typically as high as 1.5 l/day (peak of about 2 l/day) from the time of crack discovery/initial containment through the fall of 2005. In early 2006, a permanent stainless steel leak containment and collection device was installed. This containment was also piped to a permanent collection point such that any future leakage from the crack could be monitored and prevented from reaching the groundwater. Subsequent monitoring through 2006 and into 2007 has indicated that the leakage rate had fallen off rapidly and become intermittent with an average flow rate of approximately 0.02 l/day, when flowing (see figure below presenting shrinkage crack flow rate and Tritium concentration over time). This small amount of leakage is permanently being contained and it therefore is not impacting the groundwater.



UNIT 2 2005 SHRINKAGE CRACK LEAK RATE AND TRITIUM LEVELS

Based upon two years of flow and radiological and chemical sample data, it appears that excavation of the backfill from behind the pool wall caused the shrinkage cracks to begin releasing water trapped in the interstitial space dating back to 1992. This release mechanism is hypothesized to have developed as follows:

- During the original construction, the fuel pool walls developed shrinkage cracks in the concrete upon curing, as is not atypical for concrete.
- When the pool walls were backfilled with soil, they flexed inward slightly in response to the soil pressures developed during backfill placement and compaction[74].
- The pool was then filled with water which exerts an outward pressure against the walls. However, little outward flexure would be expected given the stiffness of the compacted soil backfill, which assists the concrete walls in resisting outward bending motion due to the water pressure.
- The stainless steel pool liner was punctured in 1990 and began leaking. Over time, this leak filled the interstitial space between the liner and the concrete walls. tritiated pool water then likely first leaked out of the lower-most cracks/joints, such as those responsible for the 2005 leak (elevation 62 to 64 feet), and successively leaked out of higher imperfections until it reached the cracks at elevation 85 feet. At this point, leakage was detected and the leak was fixed in 1992.
- At some point during the leakage, the subsurface cracks apparently became plugged with precipitate which stopped the leakage. This allowed pool water to remain trapped behind the liner at an elevation above the 2005 shrinkage cracks, potentially as high as elevation 85 feet. To the extent that the subsurface cracks/joints in the concrete did not all become completely leak-tight, the interstitial space behind the liner was likely recharged by leakage from the Transfer Canal weld imperfection (up until Transfer Canal drainage in July 2007) and/or other small leak sites in the liner.
- With excavation of the soil backfill from behind the southern pool wall, the pressure exerted by the backfill material was sequentially removed from the top to the base of the concrete wall. The elimination of this inwardly focused backfill pressure allowed the outwardly directed water pressure in the pool to flex the wall outward. It is hypothesized that this motion, while limited, was sufficient to initiate leakage from the 2005 shrinkage cracks at a rate of approximately 1.5 l/day during the fall/winter of 2005.
- The released water is believed to be primarily residual water derived from the 1990-1992 liner leak. However, laboratory results for water samples initially collected from the crack in the September 2005 time frame yielded Cesium-137 to Cesium-134 ratios indicating that the age of the water was approximately 4 to 9 years old. This age does not directly correlate with the 1990-1992 release timeframe. Conversely, the water clearly had exited the pool many years ago. A potential explanation for this intermediate age water is the mixing of water from a then-current small leak in the liner with 1992 age water.
- Over time, the shrinkage crack leak reduced the elevation of the residual water trapped behind the liner to the elevation of the cracks. Beginning in 2006 and through 2007, the leak rate was observed to have quickly become intermittent with typical leak rates, when leaking, of only approximately 0.02 l/day. These

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[74] While the 4-to 6-foot-thick concrete walls are stiff, some flexure is required for the walls to develop bending stresses.

subsequent water samples did not contain Cesium-134, indicating that this more recent crack water could, in fact, be old enough to be from the 1990-1992 leak[75].

- As a corollary to the above conceptual model, the intermediate-aged crack water may be partially comprised of leakage from the Transfer Canal weld imperfection. This release pathway could potentially explain the measured intermittent and variable leakage collected in the permanent containment system after 2005. The variations in water elevation and temperature in the Transfer Canal are consistent with this hypothesis. While the Transfer Canal leak water would be recent, it is likely that it would take a substantial amount of time to flow from the North wall of the Transfer Canal to the South wall of the IP2-SFP[76]. This hypothesis is therefore consistent with the lack of short-lived isotopes (as associated with SFP water) currently being found in the water from the shrinkage crack. A more significant leak rate with shorter transit times (e.g., the magnitude of the 1990-92 leak) would be expected to, and did previously show, short-lived radionuclide signatures.
- Although several additional theories have also been postulated and investigated, a definitive explanation of the apparent discrepancy in Cesium age ratios could not be definitively determined. This discrepancy from the early sample data when the crack location was first investigated was an important factor in Entergy's decision to perform intensive pool and ongoing Transfer Canal liner inspections.
- It can also be concluded from the above data and analysis that any ongoing active leak in the pool liner, if one exists, must be quite small. Otherwise, the limited volume of the interstitial space between the liner and the concrete wall would transport a more substantial leak to the shrinkage cracks in a short time and the water would thus show a young age[77].

8.1.2 Indirect Storage Sources of Tritium

The extensive testing of the IP2-SFP liners to date by Entergy provides evidence that all <u>direct sources</u> (i.e., releases from SSCs) of Tritium have been identified and are currently no longer contributing radionuclides to the groundwater[78]. However, the Unit 2 plume, while decreased in concentration relative to the samples taken just after

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[75] Cesium-137 was present at sufficient concentrations that if the water was "young", Cesium-134 would have also been present at concentrations above method detection limits. It is further noted that the two isotopes of Cesium should partition to solids at the same ratios. Therefore, preferential removal of the Cesium-134 due to partitioning to the concrete is not an explanation for the lack of this isotope in the more recent crack water samples.

[76] It is noted that the seepage path(s) from the liner leak on the North wall of the Transfer Canal to the shrinkage cracks on the southern pool wall is likely to be particularly circuitous. The interstitial space between these two liners can only be connected (if they are connected at all) at the gate from the Transfer Canal to the fuel pool and/or through imperfections in the concrete wall/floor waterstops or in the concrete itself (given the five-foot-thick concrete wall separating the Transfer Canal from the SFP itself).

[77] As a benchmark, pool water from a one-tenth of a gallon per minute leak would be expected to reach the shrinkage crack in less than two weeks given the estimated volume of the interstitial space.

[78] However, some <u>small</u> amount of leakage could still be ongoing from other potential imperfections in the liner and/or concrete pool wall; large ongoing leaks would result in conditions inconsistent with the measurements of both leak rate and water age collected from the 2005 shrinkage crack. A large leak would also be inconsistent with the reductions observed in the Tritium concentrations in the groundwater.

identification of the 2005 shrinkage crack leak[79]; still exhibits elevated concentrations. If all of the releases to the groundwater were terminated, it would be expected that the Unit 2 plume would attenuate more quickly than observed[80]. As such, a subsurface mechanism appears to exist in the unsaturated zone under the IP2-FSP that can retain substantial volumes of pool water for substantial amounts of time. The existence of such a "retention mechanism" is also supported by both the results of the tracer test and the recent evaluation of contaminant concentration variability trends over short timeframes and precipitation events.

The tracer test results, discussed more fully in **Section 7.0**, indicate that:

- Tracer injection directly to the top of bedrock below the IP2-SFP above MW-30 did not result in arrivals at MW-30 in time frames expected for vertical transport through the fractured bedrock vadose (i.e., unsaturated) zone. In fact, the earliest arrivals and maximum tracer concentrations were detected in MW-31 and MW-32 at distances of greater than 50 feet from the injection location;
- Tracer concentrations in MW-30 took longer than expected to reach peak concentrations from the time of first arrival;
- The tracer concentration vs. time curves exhibit a "long tail;" and
- The tracer concentrations exhibit significant variation over short periods of time, which may be related to precipitation events moving tracer out of storage.

It is, therefore, apparent that once tracer, and thus tritiated water, is released from directly below the IP2-SFP, it does not flow directly down to the groundwater but can be "trapped" (held in storage) for substantial periods of time.

The Tritium concentrations in MW-30 were measured on a weekly basis between August 8 and August 30, 2007 (see **Section 9.3.1**). These data show significant variability in concentrations over these short timeframes. This variability appears to far exceed that which can be attributed to variation inherent in groundwater sampling or radionuclide analyses. Aliquots submitted for tracer concentration testing also showed similar trends. It appears that these variations may be the result of the displacement of water, as evidenced by both tracer and Tritium, from this storage mechanism by infiltration such as associated with precipitation events.

Based on the above summarized information, two indirect storage mechanisms are postulated to explain the persistence of the Unit 2 plume. The first is the storage of tritiated water in dead-end fractures in the unsaturated zone. The second is the potential for tritiated water from the SFP to be trapped in the blast-rock backfill above the "mud-mat[81]"

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[79] The earliest samples taken from directly below the SFP in MW-30 (open borehole and packer testing samples) yielded Tritium concentrations over 600,000 pCi/L. More currently, maximum concentrations detected have been below one-half of those initial concentrations.

[80] Rapid attenuation of the Tritium plume would be expected based on 1) Tritium's lack of partitioning to solid materials in the subsurface; and 2) the crystalline nature, low storativity and high groundwater gradients associated with the bedrock on the Site.

[81] Prior to constructing a structural base slab (typically 2 to 5 feet thick) for the fuel pool, a 6-to 8-inch-thick, lean concrete "mud-mat" is typically constructed over blasted bedrock to even out the irregular rock surface and provide a

which was placed prior to construction of the SFP structural base slab. A combination of these two indirect storage mechanisms, as discussed separately below, is a conceptual model that explains the observed Unit 2 plume behavior in the context of the termination of the identified direct release mechanisms[82].

Dead-Ended Bedrock Fracture Storage - Naturally occurring bedrock fractures, as discussed in **Section 6.0,** are seldom long, continuous linear features. Rather, they are more typically networks of interconnected, discontinuous fractures. These networks often contain many dead-ended fractures. While dead-ended fractures are not subject to advective groundwater flow, they still can contain high contaminant concentrations. Contaminants enter these fractures through osmotic pressures set up in the subsurface by concentration gradients (initially high concentrations at the fracture "mouth" and low concentrations within the fracture). Over time, these concentrations equilibrate through liquid-phase diffusion. Therefore, under conditions of high Tritium groundwater concentrations, such as likely occurred during the two year timeframe of the 1990-1992 liner leak, the dead-ended fractures would be expected to end up containing high Tritium concentrations. Once the liner leak was repaired, the input of Tritium to the groundwater would subside and the concentrations in the advective fractures would start to decrease. However, the high Tritium concentrations within the dead-ended fractures would then start to diffuse back out of the dead-ended fractures into the groundwater flowing past them, thus maintaining higher than otherwise expected Tritium concentrations in the groundwater.

Our computation of the volume of the naturally occurring dead-ended fractures in the unsaturated zone below the IP2-SFP yields fracture volumes which are unlikely to support the observed Unit 2 plume for the required time frames (years). However, two additional considerations substantially increase the dead-ended fracture volume: 1) the observed unsaturated flow to the East and Southeast (this migration pathway exposes many more fractures to the Tritium due to the bigger area involved); and 2) construction blasting (which creates more fractures in the bedrock remaining below the structure).

As demonstrated vividly during the tracer test, contaminants released to the bedrock at the bottom of the SFP travel at least 50 to 75 feet to the East and Southeast as evidenced by the high tracer concentrations quickly detected in the upgradient monitoring wells

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hard, flat surface upon which to set the reinforcing rod "chairs" (these chairs elevate the lowest layer of rods to provide sufficient concrete corrosion prevention cover).

[82] It is noted that we originally believed that the groundwater in the Unit 2 Transformer Yard was uncontaminated with Tritium prior to February of 2000. If true, this finding would be inconsistent with the storage mechanisms proposed. Our original conclusion was based on the sampling results at that time from MW-111; this well was sampled as part of the due diligence for property transfer to Entergy and was found not to contain Tritium above detection limits (900 pCi/L). However, interviews with facility personnel revealed that the sample was collected from the upper surface of the water table with a bailer. There was no attempt to purge the well to obtain samples representative of deeper aquifer water because the samples were taken primarily to look for floating oil in the well. Because this sample was collected from the upper groundwater surface (which will be most subject to infiltration by rain water) without adequate well purging, it is likely that this sample result was biased low. As discussed in **Section 9.0**, this well is subject to wide variations in Tritium concentrations due to rainfall events. Therefore, it is entirely plausible that no Tritium was detected above laboratory method detection limits even if Tritium were present at much higher concentrations deeper in the aquifer. As such, this February 2000 groundwater sample result should not be used to assess Tritium groundwater conditions at that time. See supporting data in **Section 9.3.1**.

MW-31 and MW-32[83]; the same behavior would be expected for Tritium. This wide areal distribution would substantially increase the volume of dead-ended fractures available for storage of contaminants.

In addition to naturally occurring fractures, the founding elevation of the SFP was achieved through construction blasting of the bedrock. While the bulk of the blasted rock was removed to allow construction, a zone of much more highly fractured bedrock typically remains after the founding elevation is reached. While these blast-induced fractures may be interconnected, they may not be fully connected to tectonic fractures that intersect the groundwater, and thus would be dead-ended. Therefore, contaminated water may be stored in these fractures and periodically escape in response to precipitation events.

Blast-Rock Backfill Storage - Following blasting of the bedrock to accommodate the IP2-SFP foundation, standard construction practice would have been to pour a mud-mat[84]. Based on construction photographs, it appears that the areal extent of the blasting was not much bigger than the dimensions of the structural slab for the SFP; this would be typical given standard contracting specifications and the cost of blasting. Therefore, it would be expected that the mud-mat was poured directly against the face of the bedrock excavation, without the use of forms. This hypothesis was confirmed visually during the 2005 excavation alongside the IP2-SFP for dry cask gantry crane foundation construction.

The concrete for a mud-mat is typically placed in a relatively fluid state to enhance self-leveling properties. As this fluid concrete is placed, it is typically pushed up against the perimeter forms, or in this case the bedrock face. This placement procedure would be expected to coat and seal off the fractures in the lower portion of the bedrock sidewalls. While the height above the surface of the mud-mat to which this seal would be formed is highly variable and occurrence-specific, it would not be unreasonable to find a 2-to 6-inch high "lip" of concrete against the bedrock. The net effect would have been to create storage volume above the mud-mat, between the sides of the subsequently constructed structural floor slab and the bedrock sidewalls directly at the base of the SFP. While this space was likely filled with blast-rock fill, the pore volume of this material available for pool water storage could easily be over 30 percent of the total volume. This results in a substantial storage volume when compared to that required to "feed" and maintain the Unit 2 plume over time.

During the 1990-1992 liner leak, a large volume of highly tritiated water appears to have been released from the pool, thereafter traveling down the exterior of the SFP concrete wall. This travel path would place the pool water directly into the hypothesized storage containment. Once full, additional pool water would overtop the containment, migrate into fractures that were not sealed off by concrete, and then travel through the unsaturated zone. Once in the unsaturated bedrock, some tritiated water would quickly

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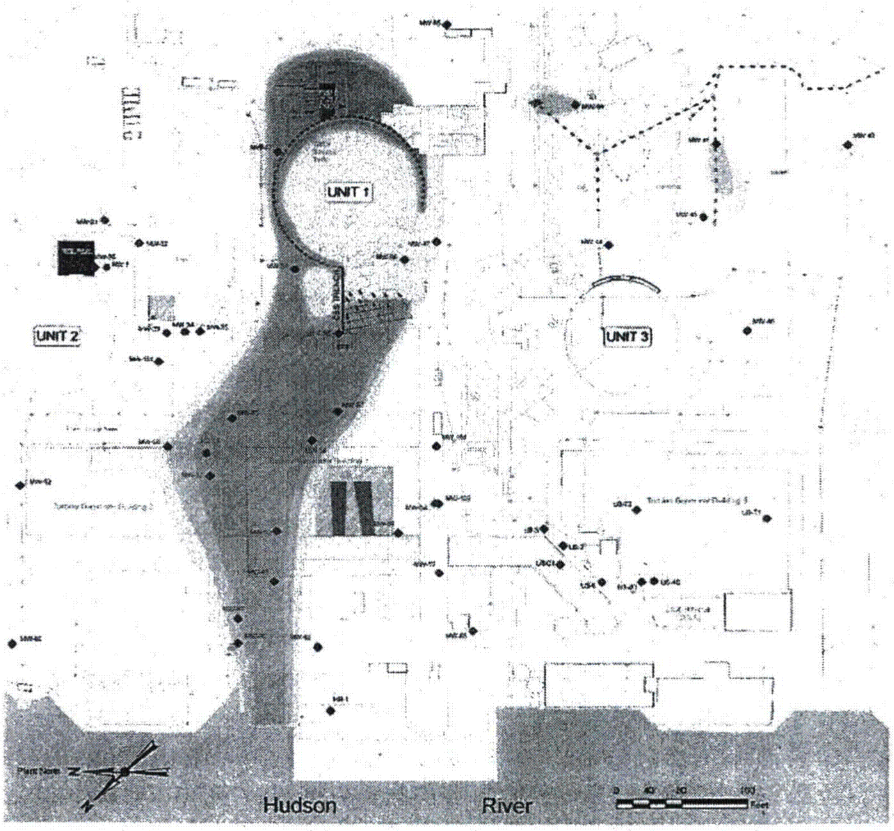
[83] Tracer reached MW-31 and MW-32 in less than four hours (time of first sample), thus supporting the conclusion of unsaturated zone transport to these locations.

[84] A 6-to 8-inch, lean concrete "mud-mat" is typically constructed over blasted bedrock to even out the irregular surface and provide a hard flat surface upon which to set the reinforcing rod "chairs" (these chairs elevate the lowest layer of rods to provide sufficient concrete cover for corrosion prevention).

reach the groundwater and some would be retained in dead-ended fractures, as discussed above. Over time, rainfall events would be expected to repeatedly displace pool water out of the containment and into the bedrock fractures. Contaminated water would therefore continue to impact the groundwater even if all active leaks from the pool were terminated. We believe this process could continue over substantial periods of time[85].

8.2 UNIT 1 SOURCE AREA

The Unit 1 contamination, as shown on **Figure 8.2** and the figure included below, is often referred to as the Strontium "plume"[86]. This is because the other radionuclides detected, including Tritium, Cesium-137, Nickel-63 and Cobalt-60, have a smaller radiological impact when compared to Strontium-90 and the Strontium is found in the entirety of the plume's areal extent, while the other contaminants are found only sporadically and in smaller subsets of the plume's area. The Tritium data for the Unit 1 plume is included on **Figure 8.1** and the Cesium-137, Nickel-63 and Cobalt-60 data are presented on **Figure 8.3**.



UNIT 1 BOUNDING ACTIVITY ISOPLETHS

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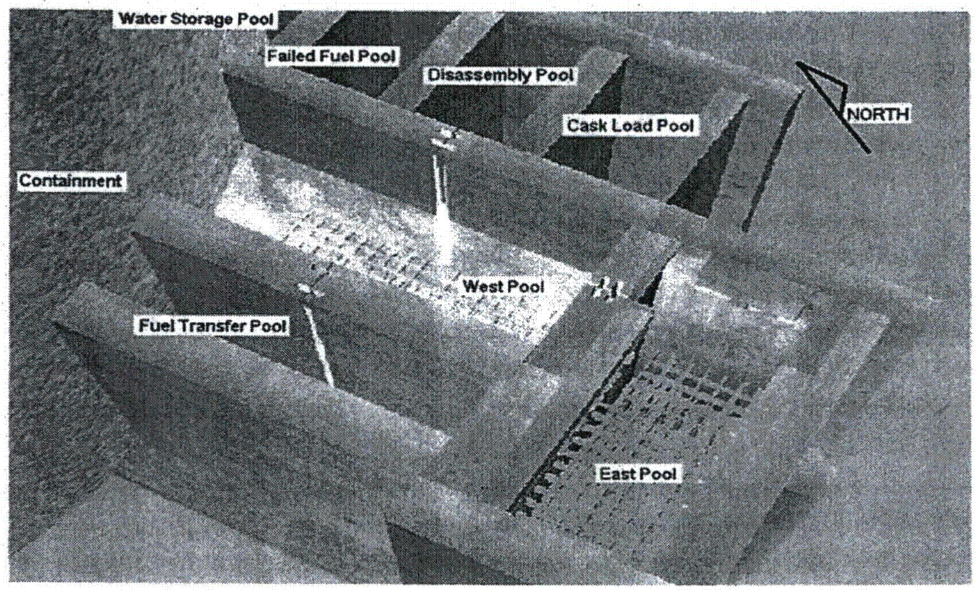
[85] See footnote No. 58 above relative to the reported Tritium results for MW-111 as sampled in May of 2000.

[86] It is noted that **Figure 8.2** does <u>not</u> show an actual Strontium plume; the isopleths presented contour upper bound concentrations for samples taken at *any time* and *any depth* at a particular location, rather than a 3-dimensional snapshot of concentrations at a single time. As such, this "plume" is an overstatement of the contaminant levels existing at any time. It should also be noted that the lightest colored contour interval begins at one-quarter the USEPA drinking water standard. While drinking water standards do not apply to the Site (there are no drinking water wells on or proximate to the Site), they do provide a recognized, and highly conservative benchmark for comparison purposes). Lower, but positive detections outside the colored contours are shown as colored data blocks. See figure for additional notes.

The highest levels of Strontium (up to 110 pCi/L) were originally found adjacent to the North side of IP1-SFPs in MW-42[87]. However, since Entergy began processing the pool water to remove the Strontium, the levels of Strontium (and other radionuclides) in this well have decreased. From MW-42, the Unit 1 "plume" tracks downgradient with the groundwater along the North side of the Unit 1 Superheater and Turbine Buildings[88]. As this plume approaches and moves under the Discharge Canal, it commingles with the Unit 2 plume, and discharges to the river[89] between the Units 1 and 2 intake structures, as does the Unit 2 plume. As discussed in **Section 6.0**, the plume track appears to follow a more fractured, higher conductivity preferential flow path in this area.

The source of all the Strontium contamination detected in groundwater beneath the Site has been established as the IP1-SFPs. The IP1-SFPs were identified by the prior owner as leaking in the mid-1990's, and are estimated to currently be leaking at a rate of up to 70 gallons/day. A schematic of this pool complex is included below.



UNIT 1 FUEL POOL COMPLEX

The IP1-SFPs were constructed of reinforced concrete with an internal low permeability coating[90]; stainless steel liners were not included in the design of these early fuel pools. The pool wall thickness ranges from 3 to 5.5 feet thick. The bottom of the IP1-SFPs is

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[87] The highest concentrations of the other contaminants associated with the Unit 1 plume, including Cesium-137, Nickel-63 and Cobalt-60 were also found in well MW-42. This location is very close to the IP1-SFPs and it is therefore not unexpected to find these higher concentrations of less mobile radionuclides near the source.

[88] This general introductory discussion of the Unit 1 plume is focused specifically on the "primary Unit 1 plume." Further more detailed discussion of the other "secondary Unit 1 plumes," which all originate from the IP1-SFPs, is provided in subsequent subsections.

[89] As is the case with the Tritium from the Unit 2 plume, some Strontium discharges directly to the Discharge Canal before the plume reaches the Hudson River.

[90] The original coating failed and was subsequently removed.

founded directly on bedrock, generally at elevation 30 feet[91]. As such, there is no significant unsaturated zone below the IP1-SFPs. While all of the pools have been drained except the West Pool, the other pools have all contained radionuclide at various times in the past. The West pool, which is approximately 15 feet by 40 feet in area, currently contains the last 160 Unit 1 fuel assemblies remaining from prior plant operations. This plant was retired from service in 1974.

The IP1-SFPs are contained within the IP1-FHB. The foundation system of the FHB and IP1-CB complex contains three levels of subsurface footing drains (see figure included below). The design objective of these drains, with the potential exception of the Sphere Foundation Drain (SFD)[92], appears to be permanent depression of groundwater elevations to below the bottom of the structures[93].

North and South Curtain Drains - The uppermost IP1-FHB drain encircles the Unit 1 FHB and IP1-CB. This footing drain, typically referred to as the Curtain Drain, is divided into two sections, the North Curtain Drain (NCD) and the South Curtain Drain (SCD). Each of these drains starts at a common high point (elevation of 44 feet) located along the center of the eastern wall of the FHB. These drains then run to the North and South, respectively, and wrap around the Unit 1 FHB and CB. The NCD then discharges to the spray annulus in the IP1-CB[94] at an elevation of 33 feet. From the annulus, the water is pumped for treatment and then discharged. The NCD flows at a yearly average of about 5 gpm carrying a Strontium concentration of 50 to 200 pCi/L (concentrations measured prior to reductions in Unit 1 pool water radionuclides via accelerated demineralization). The SCD pipe remains as originally designed with discharge to the Discharge Canal; however, the SCD is typically dry[95].

Chemical Systems Building Drain - The lowest level of the IP1-CSB (contained within the FHB) is also encompassed by a footing drain. The eastern portion of this drain begins at a high point elevation of 22 feet at its northernmost extent, located proximate to the IP1-CB, and then slopes to elevation 11.5 feet at its low point on the southern side of the IP1-CSB. The western portion of this drain begins at a high point elevation of 12.5 feet at its northernmost extent, again located proximate to the IP1-CB, and then slopes to elevation 11.5 feet at its low point on the southern side of the IP1-CSB. Both portions of the drain join at the southern side of the IP1-CSB where the common drain line runs below the floor slab and drains into the IP1-SFDS (bottom elevation of 6.5 feet). This drain typically flows

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[91] The bottom elevation of the individual pools range from a high elevation of 36 feet for the Water Storage Pool to a low of 22 feet for the Transfer Pool.

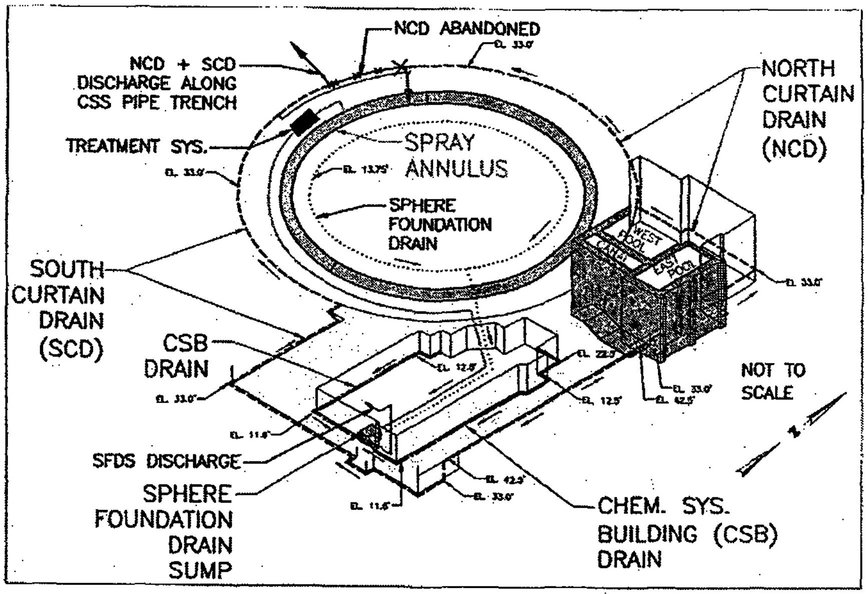
[92] The SFD is constructed at an elevation of 16.5 feet. It is above the bottom of the Sphere (elevation -11 feet) and completely encapsulated in either concrete or grout.

[93] The elimination of hydrostatic uplift pressures allows a "relieved design" to be used for the bottom concrete slabs of the structures. The alternative to a relieved slab design is a "boat slab design." In this case, the slab is heavily reinforced to resist hydrostatic uplift pressures. Boat slabs are more expensive to construct than relieved slabs, and thus are typically only used when it is not feasible to relieve the hydrostatic uplift pressures.

[94] This design modification within the IP1-CB, to allow storage of the footing drain water prior to treatment, was implemented by the former owner once the water was found to contain radionuclides. The initial Unit 1 design connected the two 12-foot perforated footing drain lines into a common 15-inch tee and drain pipe at the entrance to the Nuclear Service Building. This 15-inch footing drain pipe was collocated in the bedrock trench containing the spray annulus to CSS drain line.

[95] The lack of water in the SCD is consistent with the expected impact of the CSB drain given its proximity and lower elevation.

at a yearly average of 10 gpm carrying a Strontium concentration of not detected (ND) to 30 pCi/L.



UNIT 1 FOOTING DRAINS AND DISCHARGE SUMP

Sphere Foundation Drain - The third foundation drain below the IP1-FHB and IP1-CB complex is the SFD. This drain is located directly around the bottom portion of the Sphere and consists of: 1) nine perforated pipe risers spaced around the sphere and tied into a circumferential drain line at elevation 13.75 feet; 2) each vertical riser is surrounded by a graded crushed stone filter; and 3) all of which are within a clean washed sand which encompasses the Sphere from elevation 25 to 16.5 feet (the "sand cushion"). The sand cushion is "sandwiched" between the concrete foundation wall, the Sphere and the grout below the Sphere; it is open at the top, proximate to the annulus. As such, it appears that this drain does not interface with the groundwater, except to the extent that some leakage may occur through imperfections in joint seals. This drain is also connected to the SFDS through a valve.

During the development of the initial Conceptual Site Model, it was understood that the IP1-SFPs were currently leaking, but it was concluded that the footing drainage systems would contain any releases from the IP1-SFPs. This was also the conclusion of a previous analysis performed for the prior owner in 1994[96]. This conclusion was based on:

- The proximity of the drains to IP1-SFPs; in fact, the NCD runs along the North and East walls, and in conjunction with the SCD, completely encompasses the IP1-SFPs;
- The generally downgradient location of the drains relative to the IP1-SFPs;
- The elevation of the drains relative to the bottom of the IP1-SFPs;

[96] *Assessment of Groundwater Migration Pathways from Unit 1 Spent Fuel Pools at Indian Point Power Plant, Buchanan, NY*; The Whitman Companies, July 1994

- The elevation of the drains relative to the surrounding groundwater elevations[97];
- The continuous flow of the drains, even during dry periods; therefore, the groundwater surface does not drop below, and thus bypass, the drains;
- The reported predominant southerly strike and easterly dip of the bedrock fractures relative to the southerly location of the CSB footing drain; this expected anisotropy should extend the capture zone of this drain preferentially to the North towards the IP1-SFPs; and
- The existence of IP1-SFPs pool water constituents in the drain discharge[98].

In February 2006, Strontium was detected in the downgradient, westerly portion of the IP2-TY (downgradient of IP2-SFP). Given that Strontium could not reasonably be associated with a release from the Unit 2 SFP, the most plausible source remaining was the retired Unit 1 plant where: 1) the SFPs historically contained Strontium at approximately 200,000 pCi/L (prior to enhanced demineralization[99]); and 2) legacy leakage was known to be occurring. Based on this finding, we concluded that either: 1) an unidentified mechanism(s) must be transporting IP1-SFPs leakage beyond the capture zone of the footing drains[100]; or 2) other sources of Strontium existed on the Site. A number of plausible hypotheses potentially explaining each of these two scenarios were therefore developed, and then each was investigated further. During these investigations, additional detections of Strontium were also identified, including some relatively low concentrations in the area of Unit 3. However, with completion of the investigations and associated data analyses, it was concluded that *all of the Strontium detections could be traced back to leakage from the IP1-SFPs*. These Strontium detections can be grouped into five localized flow paths, each associated with a different IP1-SFPs release area. Collectively, these flow paths define the overall Unit 1 "plume[101]" as listed below:

- The primary IP1 flow path;
- The eastern IP1-CB flow path;
- The southwestern IP1-CB flow path;
- The IP1-CSS trench flow path; and
- The legacy IP1 storm drain flow path.

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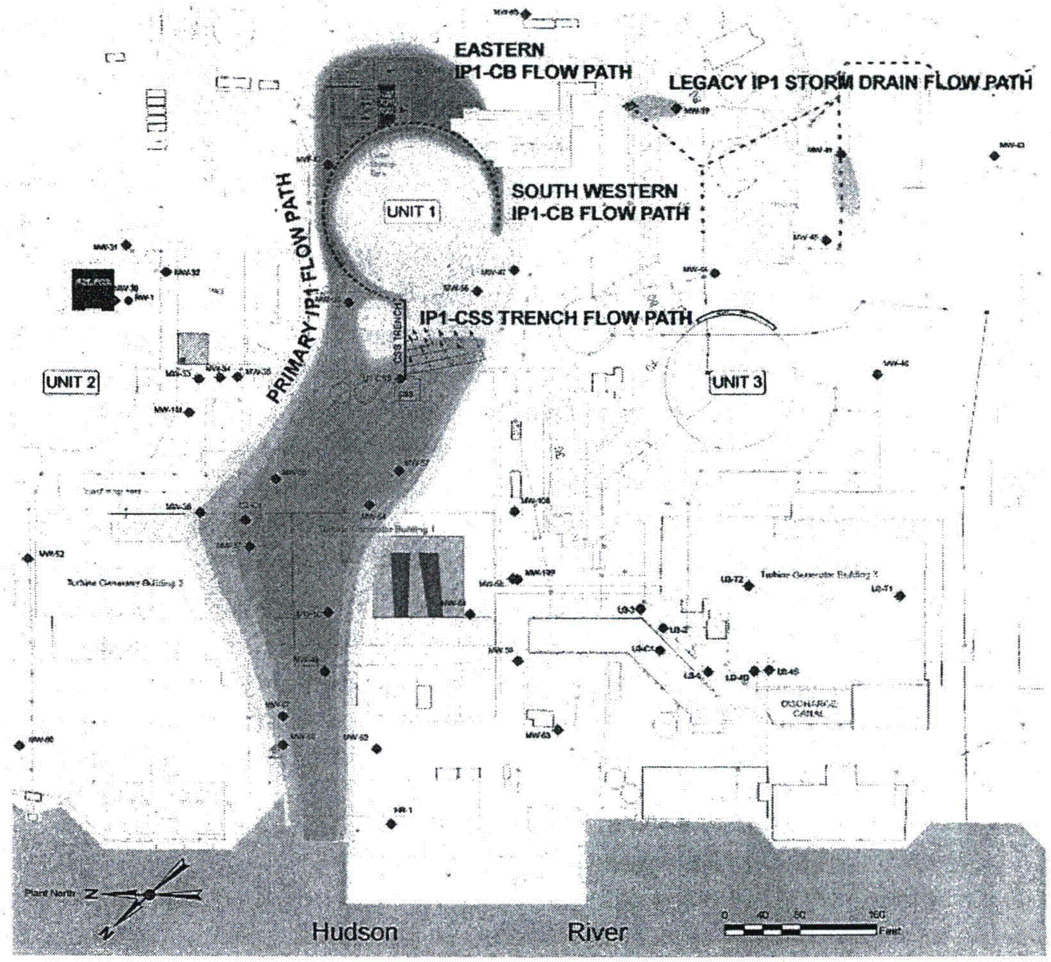
[97] This line of evidence remained supportive of the initial conclusion until the installation of MW-53, which occurred during the third phase of borings (after the discovery of Strontium in the groundwater).
[98] Drain water is treated prior to discharge as permitted monitored effluent.
[99] Strontium levels in IP1-SFPs have been more recently reduced to approximately 3,000 pCi/L under accelerated filtering through demineralization beds. Tritium concentrations in IP1-SFPs are on the order of 250,000 pCi/L.
[100] Once Strontium-contaminated pool leakage enters the groundwater, it is transported in the direction of groundwater flow; Strontium, as well as the other potential radionuclides, do not migrate in directions opposing groundwater flow (with the exception of diffusive flow which is insignificant as compared to advective flow under these hydrological conditions). Therefore leakage entering the groundwater within the capture zone of the footing drains is captured by those drains.
[101] The grouping of Strontium detections into contiguous "plumes" may be an over-simplification, and the detections may, in reality be due to small, isolated individual groundwater entry points and flow paths from the IP1-SFPs. This is likely to be particularly true pursuant to the IP1 Legacy Piping "flow path."



INDIVIDUAL UNIT 1 STRONTIUM FLOW PATH LOCATIONS

The discussions below are focused on the discovery and characterization of these individual flow paths, and the final mechanisms that best explain their existence. Other initially plausible mechanisms were also investigated as part of the Observational Method approach employed[102], but they did not remain plausible in light of the subsequently developed data and analyses, and are therefore not discussed herein. In addition, portions of the discussions below also relate to the concurrent investigation of other potential source areas across the Site. During review of the following sections, it is important to recognize that only small quantities of leakage are required to result in the groundwater plumes observed on the Site.

Primary IP1 Flow Path – Monitoring well MW-42 was initially installed to investigate the premise that contaminants may be leaking into the subsurface from the IP2-Reactor Water Storage Tank (RWST). However, the sample analysis made it clear that IP1-SFPs water was present in the groundwater at MW-42; the radiological profile was consistent with

[102] As indicated above, multiple initially plausible hypotheses potentially explaining the genesis of these flow paths were developed and investigated. These investigations proceeded in a step-wise, iterative manner consistent with the Observational Method, whereby various aspects of the Conceptual Site Model (CSM) were modified to develop an overall CSM that better fit all of the data. Not all mechanisms investigated remained plausible in light of all the data and analyses developed as part of this hypothesis-testing.

Unit 1 fuel pool water (low Tritium, high Strontium and Cesium). While IP1-SFPs leakage was known to be ongoing, this conclusion was *not* consistent with the CSM at the time which was predicated, in part, on containment of IP1-SFPs leakage by the footing drains (North and South curtain Drains, and the Chem. Sys. Building Drain).

An additional monitoring well, MW-53, was subsequently installed downgradient of MW-42 (on the Northwest side of the IP1-CB). Groundwater in this well was also apparently impacted by IP1-SFP water, thus resulting in the initial steps in the identification of the Unit 1 primary Strontium flow path. The groundwater elevations measured in MW-53 proved even more enlightening than the radiological profile. In the case of a *continuously flowing* footing drain such as the NCD, groundwater would generally be expected to be flowing into the drain over the entire length of the drain; the corollary to this conclusion is that the groundwater elevation would be above the drain invert along its entire extent. Otherwise, water flowing into the drain along its eastern, upgradient extent would exfiltrate the drain along its western, downgradient extent and thus, water would no longer discharge out of the end of the drain into the IP1-CB Spray Annulus; it would therefore *not* typically be *continuously flowing*. However, the groundwater elevation in MW-53 was measured at approximately elevation 9 to 10 feet, substantially lower than the water table elevation in MW-42 (35 feet) and the elevation of the NCD invert (33 feet). Therefore, it was found that only a portion of the groundwater which infiltrated the drain to the East was observed as continuous flow at the Spray Annulus collection point. The remainder of the water was exfiltrating along the drain further to the West[103], where groundwater elevations were below the drain invert and thus outside the capture zone of the drain.

Therefore, leakage from the IP1-SFPs was initially being captured by the NCD, but then during transport to the Annulus for collection and treatment, a portion of this leakage was discharging to the groundwater outside the capture zone of the drain. This leakage then migrates downgradient to the West with the groundwater and establishes the Unit 1 primary Strontium flow path.

Eastern IP1-CB Flow Path - A Strontium plume is shown on **Figure 8.2** as existing below the entire IP1-SFPs. With the exception of MW-42, there are no monitoring wells in this area to verify that this plume actually exists. However, it is known that the IP1-SFPs have and continue to leak, and the NCD and CSB footing drains have been shown to contain radionuclides consistent with that expected from IP1-SFPs' leakage. The locations of the specific release points are not known, but could be anywhere along the walls and bottom of the IP1-SFPs.

Once leakage from any of the above postulated points enters the groundwater, it will migrate either to the NCD or the CSB drain, depending on where the specific release point is located relative to these drains. Leakage located along the northeastern portions of the IP1-SFPs is likely to migrate to the NCD (elevation 33 feet), whereas leakage located more to the South and West is more likely to migrate to the lower CSB drain (elevation 22 to

[103] It is hypothesized that, in the past, the drain likely did not flow continuously. However, over time, the exfiltration rate has been reduced through siltation such that the drain can no longer release water over its western extent as fast as it infiltrates into the drain further to the East.

11.5 feet). These scenarios, when considered for multiple potential release points, should result in Strontium flow paths that are all contained within the plume boundaries shown on the figure.

Southwestern IP1-CB Flow Path - As part of the investigations to identify other potential releases to the groundwater across the Site, low levels of Strontium (less than 3 pCi/L) were detected in monitoring wells MW-47 and MW-56. Groundwater contamination in this area was inconsistent with the known sources and the groundwater flow paths induced by the IP1-CSB footing drains. A summary of the investigations and analyses undertaken to identify the release mechanism responsible for this Strontium flow path follows.

Construction drawings indicate that the IP1-CB and the IP1-FHB were constructed with an inter-building seismic gap and stainless steel plate between the two structures. This construction detail creates a preferential flow path for any pool leakage through the western walls of the IP1-SFPs, as well as leakage from other locations which migrates to the western side of the IP1-SFPs[104]. While this "plate/gap" separates the structures all the way down through the structural foundation slabs, it likely would not have penetrated the mud-mat[105]. In addition, it would not be uncommon for the surface of the mud-mat to *not* be completely cleaned prior to pouring of the structural slab. Even small amounts of soil, mud, dust, etc. between the mud-mat and the structural slab above would result in a preferential flow path along the top of the mud-mat. Therefore, it is expected that pool leakage in this zone (between the structural slab and the mud-mat) could flow laterally and would still be isolated from the fractured bedrock below. It would then, in turn, also be isolated from the influence of the footing drains (both the NCD and the IP1-CSB drain). To the extent that the above hypotheses are correct, this leakage could then build up and flow along the plate and above the top of the mud-mat. With sufficient input of leakage from the pool, the elevation of this flowing water could also rise above the top of the IP1-CB footing[106].

With the above hypothesized conditions, pool leakage may migrate along the plate all the way around the IP1-CB to the South and West until it reaches the end of the plate (at the intersection of the perimeter of the IP1-CB with the IP1-FHB). At that location, the water would follow the top of the mud-mat (and/or top of footing) along the IP1-CB bottom slab further to the West[107]. This leakage flow path is highlighted on **Figure 8.2**. The leakage water would not be constrained to flow into the SCD given that this footing drain is dry. Once past the end of the plate, the pool leakage could enter the bedrock at multiple points, wherever it encounters bedrock fractures. Thereafter, the leakage would enter the groundwater and thus be constrained to migrate in the direction of groundwater flow.

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[104] This hypothesis is further supported by the presence of weeps of contaminated water (SFP leakage) in the eastern wall of the IP1-CB at the footing wall joint.

[105] While not shown on the constructions drawings reviewed "as required", construction photos show that a mud-mat was placed prior to rebar cage construction (also see discussion of rationale under Tritium source areas above). Given the consistent bottom elevations of both the VC and the SFPs structural concrete slabs, a single mud-mat was likely constructed.

[106] Leakage flow above the top of the footing (elevation 33 feet) to the East and Southeast of the VC would not be captured by the SCD given that this drain is dry.

[107] See discussion of likely mud-mat/bedrock excavation wall configuration and the impact of precipitation events in the section above under Tritium source areas.

As shown on the figure, pool leakage entering the groundwater along the South side of the IP1-CB would be expected to mound the groundwater somewhat. This is particularly true in this case given the leakage entry point within the "flat zone" encompassing the groundwater divide between flow to the river to the West and flow to the East to the CSB footing drain[108]. The portion of the pool leakage which flows West would form the southwestern IP1-CB Strontium flow path and thus explain the low levels of Strontium found in MW-47 and MW-56. From this point, the "plume" continues to flow West and joins the primary Strontium flow path.

IP1-CSS Trench Flow Path - During the course of the investigation for potential sources, MW-57 exhibited significant Strontium concentrations. Strontium was also detected in the upgradient IP1-CSS, located in the Unit 1 Superheater Building. This sump was investigated to evaluate the extent to which it may be associated with the contamination identified to the West, near the Discharge Canal. A retired subsurface pipe, designed to drain water from the Unit 1 Spray Annulus to the CSS, was determined to be the input source path for water observed within the sump. During Unit 1 construction, this pipe was installed within a 3-foot-wide trench cut up to 20 feet into bedrock, which slopes downward from the Spray Annulus to the CSS[109]. Construction drawings further indicate that this trench was backfilled with soil. This pipe had been temporarily plugged in the mid-1990's when contaminated water from the NCD was routed to the Spray Annulus. However, the temporary inflatable plug was later found to be leaking and the pipe was then permanently sealed with grout.

As part of our investigations, a monitoring well (U1-CSS) was installed horizontally through the East wall of the CSS at an approximated elevation of 4 feet. This horizontal well is connected to a vertical riser which extends to above the top of the CSS. Water levels in this well typically range from elevation 12 to 18 feet and respond rapidly to precipitation events.

Based upon available data, we believe the IP1-CSS is not a source of contamination to the groundwater. Inspections of the sump indicate the likely entry point for water periodically found in the sump is the pipe from the IP1 Spray Annulus, the joint between the concrete sump wall and the sump ceiling (the floor of the Superheater Building), and/or the joint in the sump wall where the pipe penetrates from the rock trench into the sump. These conclusions are based on:

- The groundwater elevations measured in U1-CSS are above the bottom of the CSS which is generally nearly empty (bottom elevation of 1.0 feet);
- The results of the tracer test confirmed that contaminated groundwater can enter the CSS when it is empty; and
- Visual inspections of the interior of the sump and associated piping.

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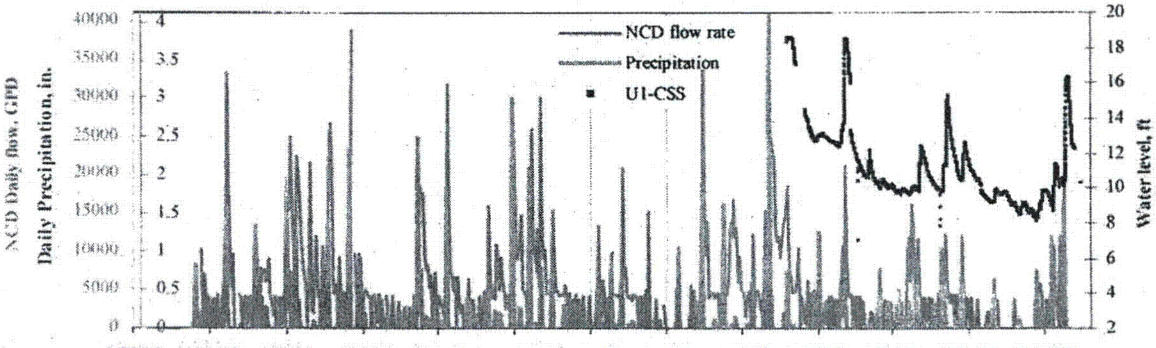
[108] While a groundwater divide must exist between the CSB footing drain and river to the West, the exact location of the divide is unknown.

[109] The trench bottom starts at elevation 22.75 feet at the Spray Annulus and slopes gradually to elevation 21.75 feet at a point 9 feet from the CSS. From this point, the trench slopes steeply to elevation 13 feeet at the CSS.

This sump is no longer in service as the system it supported is retired.

While the CSS itself does not appear to be a release point, we believe the associated bedrock trench between the Spray Annulus and the CSS is a source of contamination to the groundwater. As indicated above, the Spray Annulus is used to store releases collected from the IP1-SFPs by the NCD, which contains contaminants. The Annulus water has been historically documented as leaking into the pipe and surveys indicate that the pipe itself likely leaks into the trench. While the leak into the pipe from the Spray Annulus was sealed, other leakage inputs to the trench also likely exist. One such likely leakage path is for water to flow directly from the NCD through the drain backfill and abandoned piping[110] to the pipe trench. This flow path is supported by the trends in U1-CSS water elevation variation as compared to the NCD discharge rate (see figure included below).



UNIT 1 NCD FLOW, U1-CSS GROUNDWATER ELEVATION AND PRECIPITATION RELATIONSHIPS

These hypothesized leakage paths are highlighted on **Figure 8.2**. Once leakage enters the trench, it should flow along the sloped bottom until it finds bedrock fractures through which to exfiltrate. This leakage will then flow through the unsaturated zone along the strike/dip of the fractures until it encounters the saturated zone, and thereafter will follow groundwater flow.

Because of these hypothesized, but probable conditions, we concluded that leakage has exited the trench and impacted groundwater. Impacts directly to the groundwater below the pipe trench are characterized by Strontium concentrations in monitoring well U1-CSS. In addition, source inputs to the groundwater from the trench are also envisioned to have occurred farther to the South, where the groundwater flow would then carry contamination to MW-57, thus explaining the Strontium concentrations found in that well[111]. While southerly flow in this area is inconsistent with groundwater flow direction, source inputs can migrate from the bedrock trench to the South in the *unsaturated* zone near the

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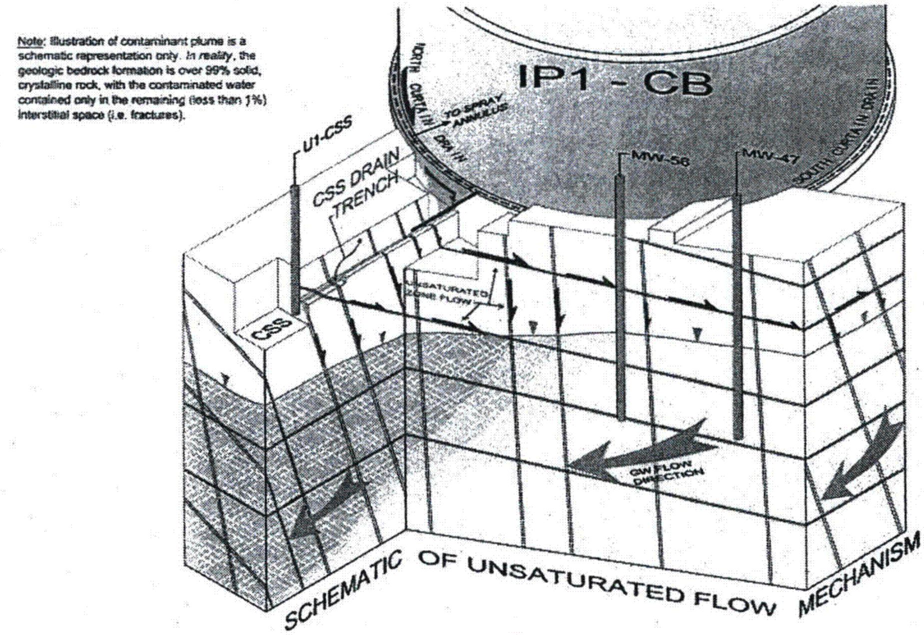
[110] As noted above, the NCD discharge was rerouted into the Spray Annulus when the NCD was found to contain contaminants by the previous owner. Prior to this modification, the footing drain was routed to a 15-inch drain line collocated in the CSS pipe trench. The abandoned piping and permeable backfill still exist and likely act as an anthropogenic preferential flow path.

[111] Monitoring wells U1-CSS and MW-57 do not appear to be in the groundwater flow path of the primary Unit 1 "plume."

CSS, where the unsaturated zone is relatively deep[112]. This hypothesized unsaturated zone flow path is shown on **Figure 8.2,** as well as the schematic included below.



IP1-CSS TRENCH UNSATURATED ZONE FLOW MECHANISM

In addition, the construction details of the Superheater East wall may also channel saturated flow to the South, depending on variation in groundwater elevations. These less direct leakage inputs then establish the southern portion of the source area for the CSS trench flow path such that the groundwater flow carries the "plume" through monitoring well MW-57, thus explaining the Strontium found in samples collected from this well[113].

<u>**Legacy IP1 Storm Drain Flow Path**</u> – As summarized above, the CSB footing drain collects groundwater from the vicinity of the IP1-SFPs; this water has been documented to contain radionuclides. The contaminated water is then conveyed to the SFDS, located at the southern end of the CSB. In addition, historical events, including CSB sump tank overflows in Unit 1, have impacted the SFDS.

Prior to construction of Unit 3, water collected in the SFDS was pumped up to elevation 65 feet and discharged to the stormwater system on the South side of the Unit 1 CSB. The discharge was conveyed by these drains to the South towards catch basin U1-CB-9 (currently under the access ramp to Unit 3), and then West (U1 CB-10) under what is now the IP3-VC toward the Discharge Canal. This pathway was re-routed during construction of Unit 3 in the early 1970s to flow South from catch basin U1-CB-9, then further South towards catch basin U3-CB-A4 and subsequently to the Discharge Canal through the

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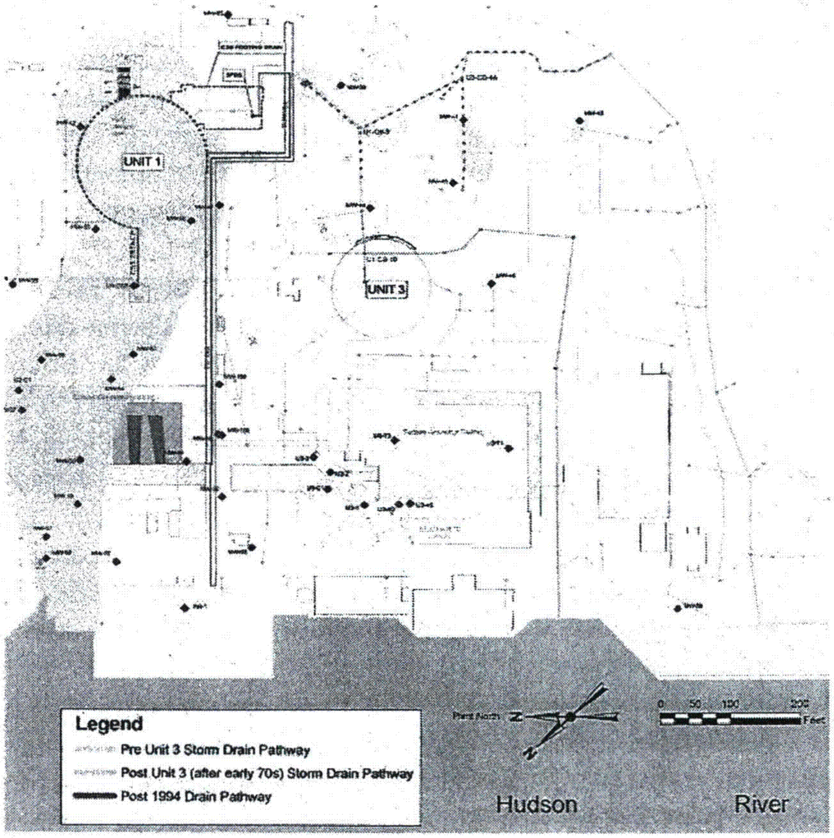
[112] The hypothesized southerly flow of a portion of the trench leakage to the South through the unsaturated zone is consistent with: 1) the strike/dip direction of major joint sets found on Site; and 2) the groundwater flow path from the resulting unsaturated zone input to the wells which identified this Strontium flow path.

[113] This well appears to be located outside, and upgradient of, the primary Unit 1 Strontium flow path to the North.

E-Series storm drains. (See figure included below and **Figure 8.2** where these pathways are also highlighted.)



DIFFERING SPHERE FOUNDATION DRAIN SUMP DISCHARGE PATHWAYS OVER TIME

A recent inspection of the storm drain system, including smoke tests and water flushing, has revealed that a number of pipes along these sections have been compromised and are leaking. Strontium found in groundwater on the South side of the Unit 1 FSB, and upgradient of Unit 3, is coincident with the locations of these stormwater pipes. Therefore, we concluded that some of the contaminated water discharged into these pipes exfiltrated, and then migrated downward through the unsaturated zone and contaminated the groundwater, thus resulting in the "legacy" storm drain flow path[114]shown on **Figure 8.2**.

In 1994, this discharge route was changed again, when contamination was detected in the effluent from the Unit 1 SFDS. The pipe leading from the SFDS towards Unit 3 was capped, and discharges were thereafter routed directly to the Discharge Canal through a series of interior pipes as well as a radiation monitor. As such, the storm drain lines to the

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[114] Three discrete isopleths have been drawn around MW-39, MW-41 and MW-43 given the measured concentrations greater than 2 pCi/L. However, it is expected that similar concentrations exist at other locations along the legacy piping alignment in addition to those shown on the figure. During the historic active discharge to the storm drains, it is expected that the individual leak areas would have resulted in commingling of the groundwater contamination into a single "plume" area. This "plume" would have then migrated downgradient across the Unit 3 area. With the cessation of discharge to the storm drains, the "plume" attenuated over time, leaving downgradient remnants which are still detectable as low level Strontium contamination in Unit 3 monitoring wells such as MW-44, 45 & 46, U3-T1 & 2, and U3-2.

South of Unit 1 no longer carry this contaminated water and they are therefore no longer an active source of contamination *to the groundwater*.

However, from a contaminant plume perspective, these historic releases still represent an ongoing legacy source of Strontium *in the groundwater* to the South side of Unit 1. This is because Strontium partitions from the water phase and adsorbs to solid materials, including subsurface soil and bedrock. The Strontium previously adsorbed to these subsurface materials then partitions back to, and continues to contaminate, the groundwater over time, even after the storm drain releases have been terminated.

As shown on **Figure 8.2**, low level residual evidence of this legacy pathway was identified in monitoring wells installed to South of Unit 1 during the course of the investigations proximate to potential sources associated with Unit 3. Strontium, Cesium and Tritium were detected in these wells at levels below the EPA drinking water standard. Three monitoring wells to the South of Unit 1 show "Legacy Storm Drain flow paths" drawn around them. These wells have yielded samples at one time/depth with Strontium concentrations greater than 2 pCi/L, or one-quarter of the Strontium-90 drinking water standard. While the actual extent of these Strontium concentrations is not known given that each has been drawn around a single point, they appear to be limited in extent (based on the data from the surrounding monitoring wells). It is also important to recognize that the specific locations of the historic releases from the storm drain lines are not known. In addition, once water has exfiltrated from the drain line, it moves generally downward in the unsaturated zone as controlled by the strike/dip direction of the specific bedrock fractures encountered. Therefore, legacy groundwater contamination does not have to be located immediately downgradient of the storm drain system (as exemplified by the Strontium found in MW-39 and tracer in MW-42). While three isopleths are shown on **Figure 8.2**, we believe it is possible that other areas in the general vicinity of this piping may exhibit similar groundwater concentrations. We have also concluded that the lower concentrations of Strontium detected in monitoring wells further downgradient, in the Unit 3 area, are also due to these historic, legacy storm drain releases.

9.0 GROUNDWATER CONTAMINATION FATE AND TRANSPORT

Strontium (the Unit 1 plume) and Tritium (the Unit 2 plume) are the radionuclides we used to map the groundwater contamination. The investigation focused on these two contaminants because they describe the relevant plume migration pathways, and the other Site groundwater contaminants are encompassed within these plumes.

While radionuclide contaminants have been detected at various locations on the Site, both the on-Site and off-Site analytical testing, as well as the groundwater elevation data, demonstrate that groundwater contaminants are not flowing off-Site and do not flow to the North, East or South. Groundwater flow and thus contaminant transport is West to the Hudson River via: 1) groundwater discharge directly to the river; 2) groundwater discharge to the cooling water canal, and 3) groundwater infiltration into storm drains, and then to the canal.

The primary source of groundwater Tritium contamination is the IP2-SFP. The resulting Unit 2 plume extends to the West, towards the river, as described in subsequent sections.

The source of the Strontium contamination is the IP1-SFPs. Previous conceptual models, based on information presented in prior reports, indicated that releases from the IP1-SFPs were likely captured through collection of groundwater from the Unit 1 foundation drain systems. However, based upon groundwater sampling and tracer test data, we now know that the Unit 1 foundation drain system, particularly the NCD, is not hydraulically containing *all* groundwater contamination in this area (see **Section 8.0**).

GZA's understanding of the Tritium source and Strontium source are discussed in more detail in **Section 8.0**. The plumes described on the figures in the following subsections are based on: 1) the isopleths bounding the maximum concentrations, as representative of "worst case conditions"[115] (**Figures 8.1** and **8.2**); and 2) the most recent laboratory data collected through August 2007, as representative of current conditions (**Figures 9.1, 9.2, 9.3** and **9.4**). While the figures showing upper bound isopleth concentrations do not show actual conditions, we believe these graphics are useful in developing an understanding of groundwater and radionuclide migration pathways.

In reviewing this section please note the plumes show our current understanding of how anthropogenic features influence groundwater flow patterns, in particular the various footing drains and backfill types used during construction. Also note that flow in the

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[115] It is noted that these figures (**Figures 8.1** and **8.2**) do *not* show actual plumes; the isopleths present contoured upper bound concentrations for samples taken at *any time* and *any depth* at a particular location, rather than a 3-dimensional snapshot of concentrations at a single time. As such, these "plumes" are an overstatement of the contaminant levels existing at any time. It should also be noted that the lightest colored contour interval begins at one-quarter the USEPA drinking water standard. While drinking water standards do not apply to the Site (there are no drinking water wells on or proximate to the Site), they do provide a recognized, and highly conservative benchmark for comparison purposes). Lower, but positive, detections outside the colored contours are shown as colored data blocks. See figure for additional notes.

unsaturated zone plays an important role in both the timing of releases to the water table and in the spreading of contaminants.

Based upon the results of GZA's geostructural analysis, the extent of contaminated groundwater, the 72 hour Pumping Test, the tracer test and tidal response tests, we believe that the bedrock underneath the Site is sufficiently fractured and interconnected to allow the Site to be viewed as a non-homogenous and anisotropic porous media. Based on this finding, and because advection is the controlling transport mechanism, groundwater flow, and consequently contaminant migration in the saturated zone, is nearly perpendicular to groundwater contours on the scale of the Site.

9.1 AREAL EXTENT OF GROUNDWATER CONTAMINATION

Based on measured tracer velocities (4 to 9 feet per day; see **Section 7.4**), the limited distances between release areas and the river (typically less than 400 feet), the age of the plumes (years), and recent interdictions, we believe contaminant plumes have reached their maximum size and are currently decreasing in size. Consequently, our reporting in this section focuses on observed, "current" conditions (the summer of 2007). That is, we saw no need to mathematically predict future conditions.

9.2 DEPTH OF GROUNDWATER CONTAMINATION

Because of the location of Indian Point on the edge of the Hudson River, the width of the river, and the nature of contaminants of potential concern, groundwater flow patterns (and, consequently, contaminant pathways) are relatively shallow. Furthermore, as discussed in **Section 6.0**, the upper portion of the aquifer (typically, the upper 40 feet of the bedrock) has a higher average hydraulic conductivity than the deeper portions of the bedrock. Consequently, the center of mass of the contaminated groundwater is shallow.

Figures 9.1 and **9.2** are cross sections which show the approximate vertical distribution of Tritium and Strontium, near the center lines of the Unit 1 and Unit 2 plumes, in the summer of 2007 ("current conditions"). In reviewing these figures, note that Strontium was not found below a depth of 105 feet in MW-67. We attribute the low concentrations of Tritium below a depth of 200 feet at this location, at least in part, to the downward migration of Tritium during our investigations. For example, by necessity, well RW-1 was an open wellbore for a period of time[116] which allowed vertical groundwater migration, along an artificial preferred pathway, deeper than would occur along ambient flow paths.

9.3 UNIT 2 TRITIUM PLUME BEHAVIOR

As shown on **Figures 8.1** and **9.3**, the Unit 2 plume exhibits Tritium concentrations originating at the IP2-SFP. The higher concentration isopleths are shown around the entire

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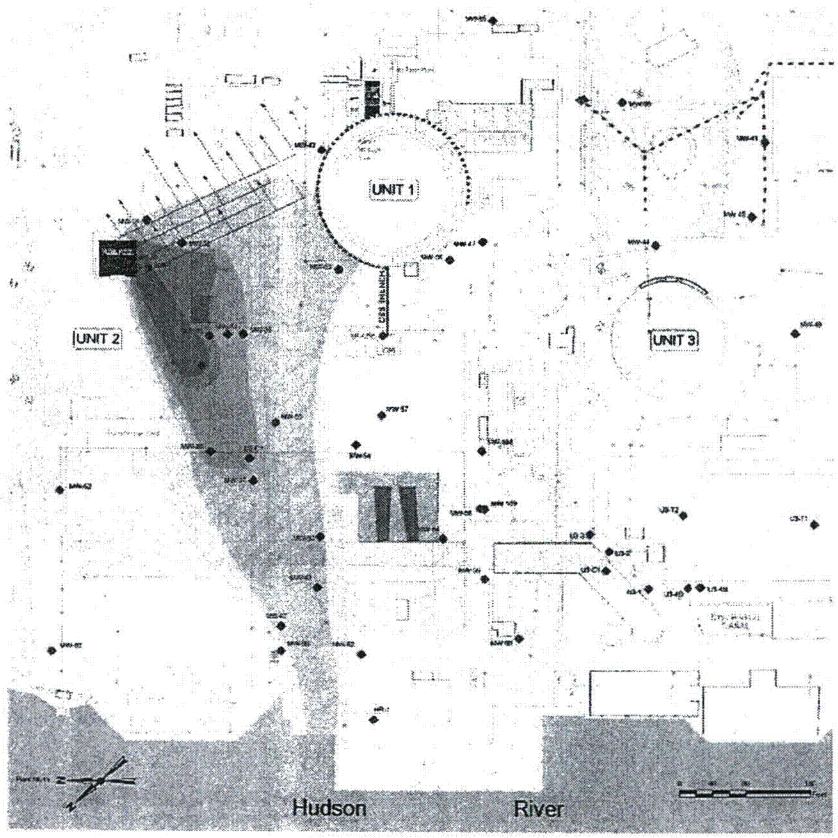
[116] RW-1 is located immediately below the 2005 shrinkage crack leak (high Tritium concentrations in shallow groundwater). This well had remained as an open wellbore for periods of time in preparation for and during: 1) the drilling of the wellbore; 2) the packer testing; 3) the geophysical logging; and, 4) the Pumping Test. During these times, vertically downward gradients likely moved some Tritium to levels deeper than it would otherwise exist. When possible, this wellbore has been sealed over its entire length using a Flute Liner System.

pool area so as to include the location of the shrinkage crack leak in the South pool wall, the location of the 1992 leak on the East wall, and the location of the weld imperfection in the North wall of the IP2 Transfer Canal. We believe the core of the plume, as shown, is relatively narrow where Tritium flows downgradient (westerly) to MW-33 and MW-111 in the Transformer yard[117]. This delineation is based on: 1) the degree of connection[118] observed from MW-30 to MW-33 (as compared with that from MW-30 to MW-31 and/or MW-32) as being indicative of a zone of higher hydraulic conductivity limiting lateral dispersion; and 2) the localized increased thickness of the saturated soil in the vicinity of MW-111 (see **Figure 1.3**) which likely behaves as a local groundwater sink/source for westerly bedrock groundwater flow, prior to entering the associated backfill of the Discharge Canal.



BOUNDING UNIT 2 ACTIVITY ISOPLETHS

Tritium has been detected in MW-31 and MW-32, both of which are upgradient of the IP2-SFP. As evidenced by the tracer test (see **Section 7.0**) and hydraulic heads, this

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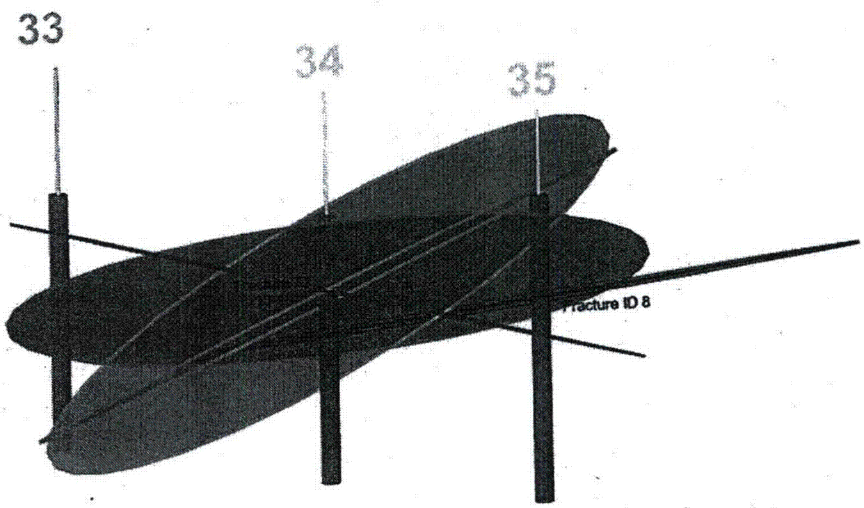
[117] The bedrock in this area was excavated via blasting to allow foundation construction. As such, the upper portions of the bedrock are likely highly fractured in this area. In addition, the pre-construction bedrock contours (see **Figure 1.3**) indicate that the particularly deep depression in the bedrock in the Transformer yard in the vicinity of MW-111 (filled with soil down to elevation 0 feet) was likely excavated to serve as a dewatering sump. The associated deeper blasting-induced fracturing and the saturated soil backfill are also likely to further increase the transmissivity in this area.

[118] The degree of connection is inferred based on both the similar static water levels in MW-30 and -33 (separated by over 100 feet), as contrasted to the much higher water levels in MW-31 and -32 located about 65 feet from MW-30, and the rapid change in water elevation in MW-30 in response to water level perturbations in MW-33 (e.g., during drilling/sampling), with little or no response in MW-31 and -32.

occurrence involves gravity flow along bedrock fractures in the unsaturated portion of the bedrock beneath the IP2-SFP. This unsaturated flow direction is consistent with the dominant foliations (which strike to the Northeast and dip to the Northwest). This behavior is shown on the figure by dashed arrows and the isometric insert (see **Section 8.1**). This mechanism also accounts for some of the Tritium found near Unit 1 and is also supported by the results of the tracer test (see **Section 7.3**). However, once the contaminated water enters the local groundwater flow field, it migrates via advection in a direction generally perpendicular to the groundwater contours (i.e., with the groundwater flow).

In the IP2-TY, the plume is drawn as more dispersive in response to the concentrations measured in MW-34 and -35 as well as the high degree of connection observed between MW-33, -34 and -35 along an orientation transverse to the general groundwater flow direction. See the figure below for a schematic of the three dimensional fracture orientations in this area that account for the observed lateral dispersion. In this general area, the Unit 2 plume is bounded to the South by MW-54 and to the North by MW-52.



Transmissive Fractures in MW-34 and MW-35
at Approximately Elevation 3

3 - DIMENSIONAL BEDROCK FRACTURE ORIENTATIONS

At the western boundary of IP2-TY, Tritium flows into the highly conductive soil backfill found along the eastern wall of the Discharge Canal (see **Figure 1.3**). This conclusion is supported by both the groundwater elevations and Tritium concentrations in MW-36.

The groundwater elevations with depth in MW-36 indicate that once in the Discharge Canal backfill, the groundwater flows downward below the canal wall and, subsequently, into both the Discharge Canal (lower water elevation in the canal) as well as under the canal through the bedrock fractures (see **Section 6.7.2.2** for an estimate of the relative flows to these two discharge locations). Once on the western side of the Discharge Canal, as evidenced by groundwater elevations and Tritium concentrations in MW-37, -49, and

-67, groundwater flow and Tritium migration is to the Hudson River, via both bedrock and unconsolidated material along the riverfront.

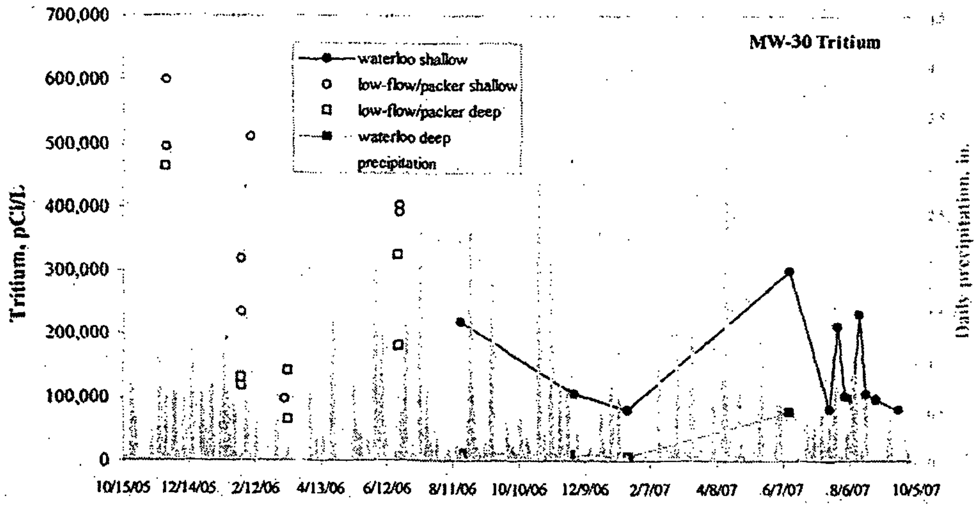
The specific flow path for the Tritium detected in MW-37-22 (located in the fill on the West side of the canal) is not certain. It is however associated with either: 1) upward groundwater flow into the backfill from the bedrock beneath the canal, as supported by the upward vertical hydraulic gradients; 2) groundwater flow into the blast rock fill on the West side of the canal, with northerly flow in the fill to, and around the North end of the canal and then southerly along the East side of the canal to MW-37; and/or 3) exfiltration from the stormwater piping between MH-4 and MH-4A into the fill on the western side of the canal, with a similar flow path as described in 2). See **Section 7.5** for additional information. Regardless of the upstream flow path to MW-37-22, the groundwater flow direction from this location is westerly toward the Hudson River. Also note that the exact pathway to this location does not change the results of the groundwater flux calculations to be used in radiologic dose impact assessments.

Both **Figures 8.1** and **9.3** show a southern component of flow as the Tritium migrates West towards the river. This pathway corresponds with the location of several East-West trending fractures zones and a fault zone. It is likely that this area is characterized by a zone of higher transmissivity that induces the contaminated groundwater to migrate as shown on these figures. We also note that it appears groundwater flow from higher elevations to the North also impedes a more northerly contaminant migration pattern.

9.3.1 Short Term Tritium Fluctuations

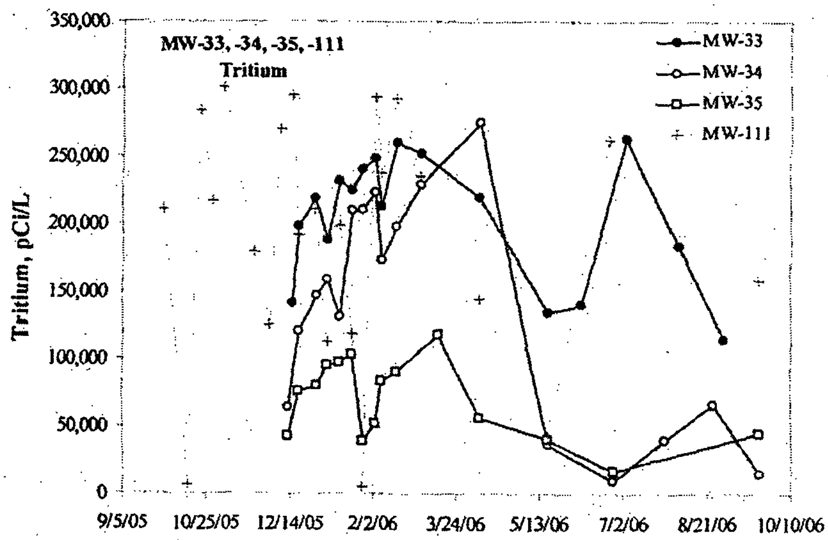
During our investigation, we observed short term fluctuating Tritium concentrations that we cannot reasonably attribute to a continuous release[119] (see **Table 5.1**). These fluctuations make drawing an accurate representation of a plume, on any single date, difficult because any single sample may not be representative of the overall water quality in proximity to the sampling location. In the case of Tritium associated with the IP2-FSB, we believe the fluctuations are associated with temporal variations in the release of Tritium-contaminated groundwater from the unsaturated zone to the water table. That is, we believe the unsaturated zone acts as an intermittent, ongoing source to the groundwater flow regime (see **Section 8.0**). The following graph shows the results of Tritium vs. time in samples collected from MW-30, located adjacent to the IP2-SFP.

[119] In addition, our review of sampling procedures and laboratory methods did not explain the variations observed in samples collected from monitoring well MW-30.



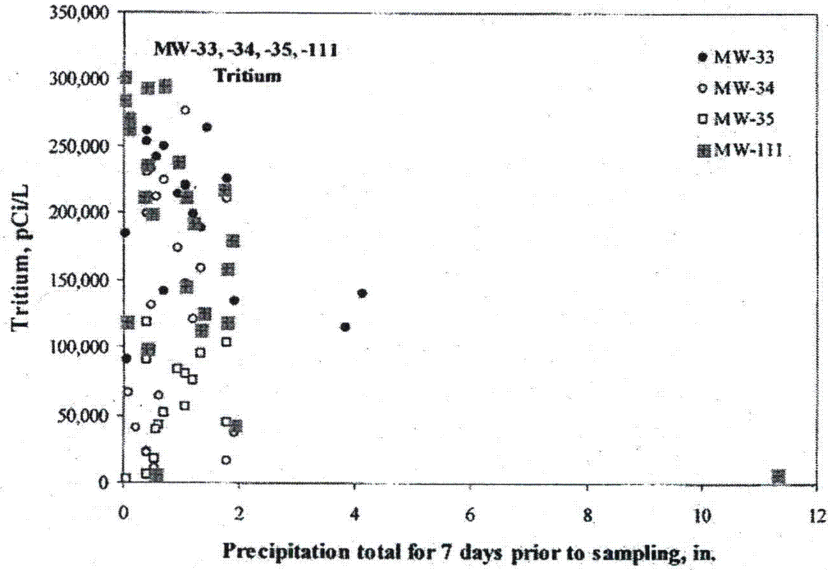
TRITIUM CONCENTRATIONS AND PRECIPITATION VS TIME FOR MW-30

Similar temporal variations in Tritium concentrations are observed in data generated by testing of samples downgradient of IP2-SFP at MW-33-34-35 and -111; see the following figure:



TRITIUM CONCENTRATIONS VS TIME FOR MW-33, -34, -35 AND -111

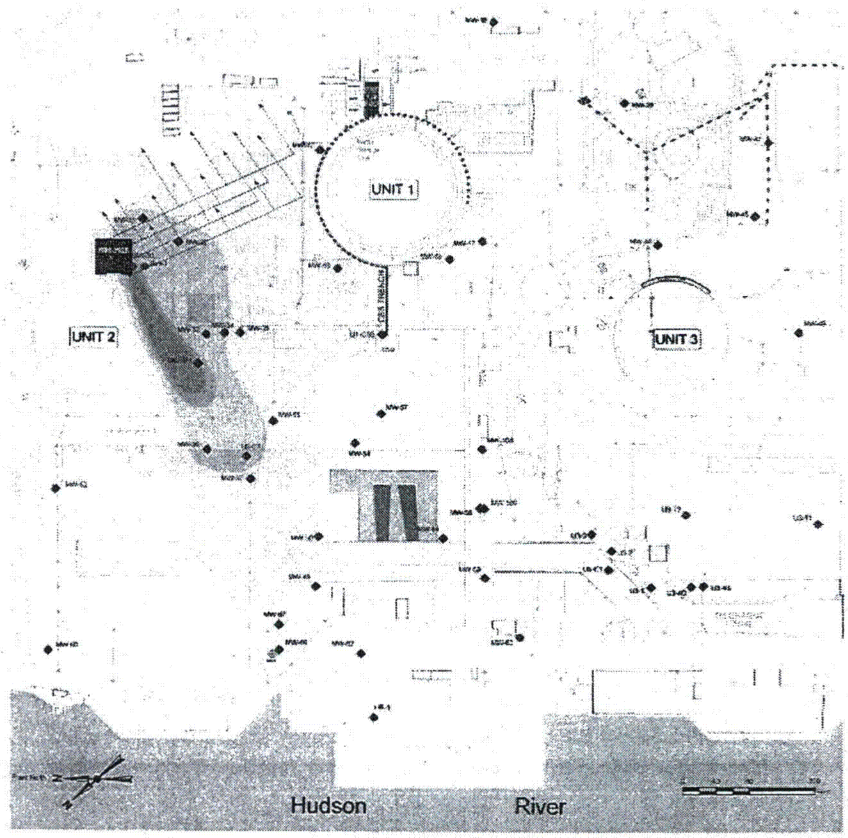
MW-111 is a shallow overburden well completed to a depth of 19 feet below ground surface (bgs). This well is located in a soil-filled bowl-shaped depression within the Transformer yard (see **Figure 1.3**). Consequently, the concentrations of Tritium in samples collected from MW-111 are more sensitive to precipitation (and the likely associated exfiltration from the proximate storm drain) than samples collected from other wells in this area (see above). In particular, note the substantial decrease in Tritium concentration as shown on the following graph, in samples collected after significant precipitation events in October 2005 and May 2006.



TRITIUM CONCENTRATIONS VS PRECIPTIATION

9.3.2 Long Term Variations in Tritium Concentrations

Recognizing the limitations posed by short term fluctuations, we constructed **Figure 9.3**, which shows the lateral extent of Tritium contamination in the late summer of 2007 ("current conditions").



CURRENT UNIT 2 PLUME

Our review of this figure, in conjunction with **Figure 8.1**[120] and **Table 5.1,** reveals the following:

- Despite interdictions, the lateral extent of the two plumes (i.e., the Tritium plume vs. the bounding isopleths) is similar. This indicates storage in the unsaturated zone remains important, and that previous releases did not generate significant groundwater mounding.
- The highest concentrations remain in the area of IP2-SFP. This is consistent with the observed relatively high (4 to 9 feet per day) groundwater transport velocities and an ongoing but smaller release from the unsaturated zone.
- Interdictions made at the IP2-SFP appear to have resulted in measurable reductions in Tritium groundwater concentrations over the entire Unit 2 plume length[121]. The larger reductions in Tritium concentrations are most evident in the source area, closer to the IP2-SFP (see table below).

ANALYSIS OF TRITIUM CONCENTRATIONS OVER TIME

Max. Observe (1) Tritium Concentrations (pCi/L)	Monitoring Well	Current (2) Tritium Concentrations (pCi/L)	Elapsed Time between Max. and Current Concentrations (days)	Current Conc. As Percent of Maximum
601,000	MW-30	92,000	657	15
302,000	MW-111	98,800	629	33
107,000*	RW-1	30,600	3	48
40,600	MW-31	37,700	39	93
44,400	MW-32	14,200	406	32
264,000	MW-33	23,000	390	9
276,000	MW-34	22,200	476	8
119,000	MW-35	5,950	510	5
55,200	MW-36	12,500	494	23
44,800	MW-37	6,680	400	72
3,980	MW-42	1,600	490	40
13,200	MW-53	8,050	346	61
13,100	MW-55	9,910	263	76
10,800	MW-50	4,500	427	42
9,100	MW-66**	9,100	0	100
4,860	MW-67**	4,860	0	100

* Sample obtained during Pumping Test.
** Only one sample analyzed.
(1) Any depth, any date at the indicated location.
(2) Maximum concentration, at any depth, reported during the last project sampling event at the indicated locations.

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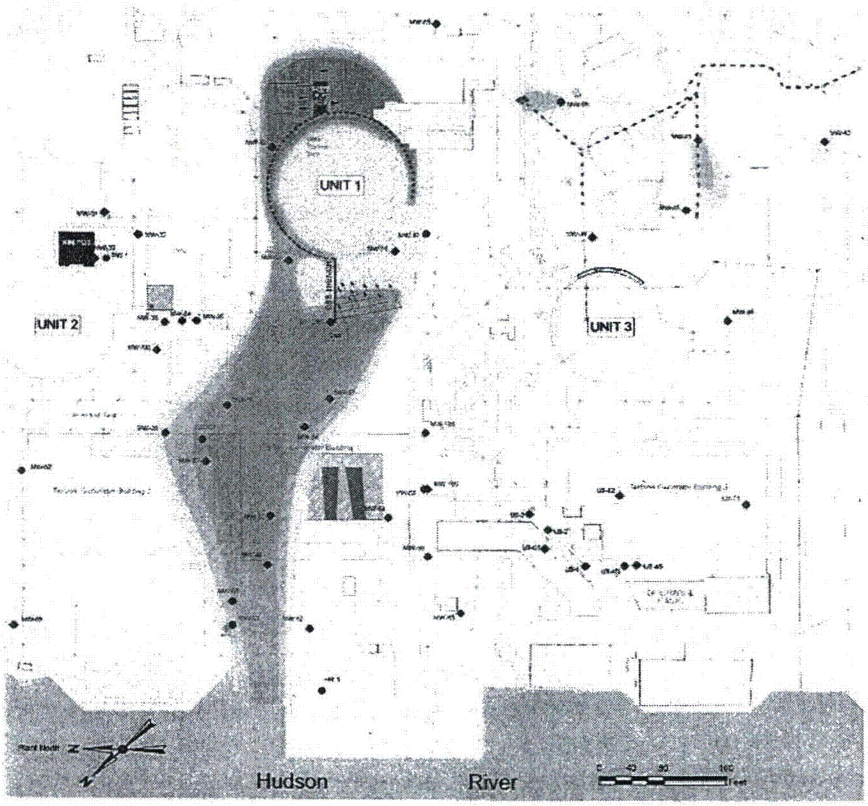
120 When comparing the Unit 2 (Tritium) plume shown on **Figure 9.3** with the bounding isopleths presented on **Figure 8.1**, the analyses/methods used to develop the bounding isopleths need to be fully considered – please refer to **Section 8.0**.

121 As based on monitoring well data over the plume length down to and across the Discharge Canal to MW-37, as well as the apparent migration velocity of Tritium in the groundwater observed on-Site. Data from monitoring wells downgradient of MW-37 have not been sampled over a sufficiently long period of time to confirm this conclusion. Further analysis of the plume behavior will be conducted as the Long Term Monitoring Plan data is developed over time.

9.4 UNIT 1 STRONTIUM PLUME BEHAVIOR

Figures 8.2 and **9.4** illustrate the migration paths for Strontium. These flow paths represent Strontium originating from an ongoing legacy leak(s) in the IP1-FHB (see **Section 8.0**). This leak explains the Strontium levels detected in MW-42. This well is located in close proximity to the NCD[122], with the upper screen spanning the elevation of the drain (elevation 33 feet) and the lower screen located approximately 35 feet below the drain elevation. This well exhibits upward vertical gradients from the bedrock into the overburden and the NCD. Therefore, a release through a crack in the Water Storage Pool wall (also forms the wall of the FHB), for example, would flow down through the backfill and into the drain where it would enter groundwater near monitoring well MW-42. However, as described in **Section 8.0**, the NCD is not 100% effective in hydraulically containing leaks from the IP1-SFPs. Contaminated pool water collected along the eastern portion of the NCD is released from the NCD via exfiltration as the groundwater elevations drop below elevation 33 feet towards the West; this is one source mechanism responsible for the Unit 1 Plume.



BOUNDING UNIT 1 ACTIVITY ISOPLETHS

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[122] It is noted that MW-42 is screened in the bedrock slightly North of the drain. As such, it is located hydraulically upgradient of the drain. The drain should therefore form a sink between the potential leaks and the well, thus capturing contaminants from the FHB further South, with the well only encountering groundwater flowing from the North to the South towards the drain (i.e., the well should not sample groundwater in communication with IP1-FHB leaks). However, during rain events, it appears that the groundwater elevations at the drain can increase to a point where the groundwater flow direction is temporarily reversed (flows from the NCD northward past MW-42) due to the high inflows associated with storm drain leaks (storm drains being repaired, and/or taken out of service). This flow reversal can deposit Strontium on fracture surfaces around MW-42, which later enters the well during purging.

The easternmost portion of the overall Unit 1 plume is shown to exist below the entire IP1-SFPs. GZA termed this the eastern Unit 1 CB Flow Path. Strontium-contaminated groundwater in this area will migrate either to the NCD or the CSB drain, depending on where the specific release point is located relative to these drains.

As discussed in **Section 8.0**, the overall Unit 1 plume also extends to the West towards MW-47 and MW-56. GZA termed this the southwestern Unit 1 CB Flow Path. Once the contaminated water enters the groundwater on the South side of Unit 1, it flows either East to the CSB footing drain or to the Northwest towards Hudson River, depending on the hydraulic gradient at the location where the release reaches the water table.

In addition, we believe the bedrock trench that contained the Unit 1 Annulus-to-CSS drain creates a preferential pathway (through the backfill within the bedrock trench), further aiding the transport of Strontium-contaminated groundwater to the West. GZA termed this the Unit 1 CSS Trench Flow Path. Once leakage enters the trench, it should flow along the sloped bottom until it finds bedrock fractures through which it will exfiltrate. This leakage will then flow through the unsaturated zone along the strike/dip of the fractures until it encounters the saturated zone, and thereafter will follow groundwater flow. This pattern is illustrated on **Figure 9.4** by dashed arrows to the West of Unit 1. It results in a spreading of Strontium-contaminated groundwater, which then flows with groundwater to the Hudson River.

Figures 8.2 and **9.4** also show the Strontium contamination related to releases from legacy piping. These historic releases from the drain pipes are currently manifested as sporadic, low level detections of Strontium in groundwater wells (MW-39, -41 and -43) along the legacy piping. Note, as shown, this spatial distribution of contamination is not a result of groundwater contaminant transport to the South; rather it is a result of multiple release points along the piping. In summary, this contamination represents residual contamination which has attenuated and decayed over time, and will not result in further significant migration.

Once outside the drain capture zone, the Strontium migrates West towards the lower groundwater elevations measured in the IP2-TY and along the walls of the Discharge Canal along the southern end of the IP2-TB (MW-36, -55, -37, -49, -50 and -67) (see **Figures 8.2** and **9.4**). A more southerly track is not anticipated because: 1) the higher groundwater elevations measured in MW-58 and -59 just to the South of the IP1 TGB; and 2) the likely existence of low conductivity concrete backfill along the inside of the IP1-TB walls, its subbasement, discharge piping and eastern Discharge Canal wall (as contrasted with the much higher conductivity blast-rock backfill likely used in the IP2-TY and along the outside of the IP1-TGB walls as well as adjacent to the upgradient IP1 structures).

In addition, as discussed in **Section 6.0** and shown on **Figure 6.2**, there are North-South trending faults in the vicinity of MW-49, MW-61, and MW-66, which are characterized by clay-rich fault gouge[123]. In GZA's opinion (see **Section 6.4.5**), these zones of low hydraulic conductivity limit the southerly extent of contaminated groundwater. In addition, this area is characterized by the two discrete plumes (Tritium and Strontium) commingling and following the same flow path West towards the Hudson River. We attribute this flow pattern to a zone of higher transmissivity located between Units 1 and 2. Also note this area of higher flow is accounted for in our groundwater flux calculations.

The Unit 1 plume in the Transformer yard area is shown as widening due to Strontium concentrations detected in MW-111 and MW-36. This widening may reflect the increased thickness of the saturated zone soil deposits around MW-111, or the presence of high conductivity backfill around the Discharge Canal. This conclusion is supported by the hydraulic heads that indicate groundwater flow to the North along the canal as discussed above pursuant to the Unit 2 plume and the tracer test. West of the Discharge Canal, the Strontium pathways correspond to those described for the Unit 2 plume in **Section 9.3**.

9.4.1 Short Term Strontium Concentrations

As observed with Tritium, it appears that Strontium groundwater concentrations fluctuate, over short durations, more than can be reasonably explained[124] (see **Table 5.1**)by a continuous release at generally constant concentration. We attribute these fluctuations to variations in flows in the IP1-NCD, which are directly influenced by precipitation events (see **Section 8.2**). That is, we postulate that as flows in the drain vary, so do the concentrations and/or volumes of Strontium contaminated water being released.

9.4.2 Long Term Variations in Strontium Groundwater Variations

We used the results of the last sampling event to construct the current Unit 1 plume (see **Figure 9.4** and **Table 5.1**). In reviewing that figure (see below), note the overall configuration is similar to that of the bounded Unit 1 plume (see **Figure 8.2**[125]). The major difference between these plumes is the decrease in concentrations shown in the immediate vicinity of the IP1-SFP[126]. We attribute this decrease in Strontium concentrations to the increased rate of demineralization of the IP1-SFPs water (overall source of the plume).

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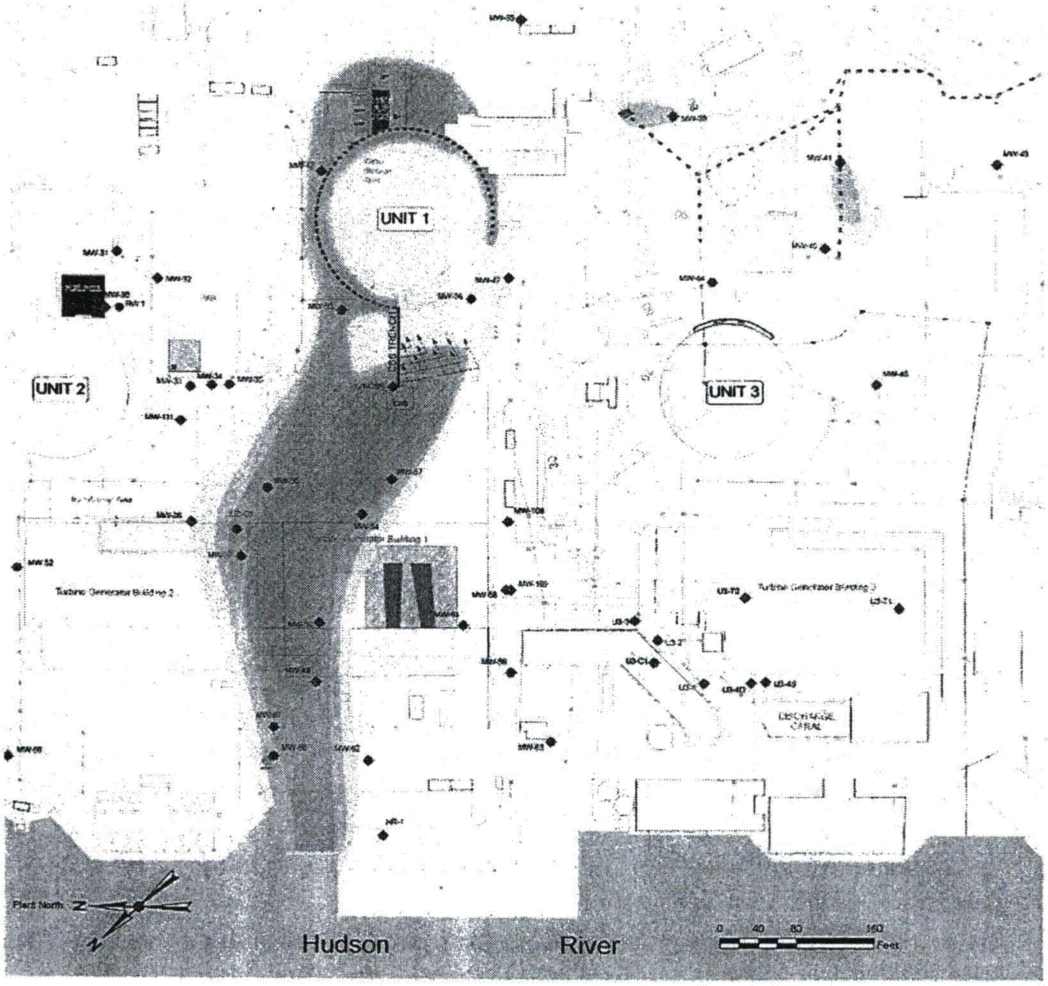
[123] This conclusion has been verified in the areas where the gouge was confirmed with split spoon sampling. See individual boring logs in **Appendix B** for further, more detailed, information.

[124] For example, our review of sampling procedures and laboratory methods did not explain the variations observed in samples collected from monitoring well MW-42.

[125] When comparing the Unit 1 (Strontium) plume shown on **Figure 9.4** with the bounding isopleths presented on **Figure 8.2**, the analyses/methods used to develop the bounding isopleths need to be fully considered – please refer to **Section 8.0**.

[126] It should be noted that the latest data just recently received (well after the report data-cut-off-date of August 31, 2007) for MW-42 shows an increase to 46 pCi/L. This increase, however, still remains within levels consistent with an overall reduction in concentrations in this area, as attributed to accelerated demineralization of the IP1-SFPs.



CURRENT UNIT 1 PLUME

However, because of the timing of the interdictions and, we believe, the slower groundwater transport rates for Strontium, overall the Unit 1 plume has not decayed to the extent the Unit 2 plume has decayed (see **Section 9.4.1**). In fact, due to what we attribute to short term Strontium fluctuations, at six of the well locations within the Unit 1 plume, the highest Strontium groundwater concentrations were observed during the last project sampling event (see the following table for additional detail). In reviewing both figures, note that they show what we believe are conservative estimates of the lateral distribution of the higher (25 pCi/L) Strontium groundwater concentrations.

ANALYSIS OF STRONTIUM CONCENTRATIONS OVER TIME

Max. Observed [1] Strontium Concentration (pCi/L)	Monitoring Well	Current [2] Strontium Concentration (pCi/L)	Elapsed Time between Max. and Current Concentrations (days)	Current Conc. As Percent of Maximum
110	MW-42	20.1	490	18 [3]
37	MW-53*	37	0	100
3.6	MW-47*	3.6	0	100
2.7	MW-56	2.4	332	89
26.8	UI-CSS*	26.8	0	100
21.9	MW-54	19.2	88	88
40.4	MW-55	34.0	263	84
45.5	MW-57	37.9	44	83
5.0	MW-36	2.3	483	46
29.8	MW-37	23.3	40	78
31	MW-50*	31	0	100
25.6	MW-49*	25.6	0	100
19.1	MW-67**	19.1	0	100**
6.2	MW-66**	6.2	0	100

* Current concentration is the maximum concentration of samples analyzed at this monitoring well.
** Only one sample analyzed.
(1) Any depth, any event, at the indicated location.
(2) Any depth, on the date of the last project sampling event, at the indicated location
(3) It should be noted that the latest data just recently received (well after the report data-cut-off-date of August 31, 2007) for MW-42 shows an increase to 46 pCi/L.

10.0 FINDINGS AND CONCLUSIONS

At no time have analyses of existing Site conditions yielded any indication of potential adverse environmental or health risk, as assessed by Entergy as well as the principal regulatory authorities. In fact, radiological assessments have consistently shown that the releases to the environment are a small percentage of regulatory limits, and no threat to public health or safety. In this regard, it is also important to note that the groundwater is not used as a source of drinking water on or near the Site.

Consistent with the purpose of the investigations, we have developed six major supporting conclusions which are described in the following subsections. Based on our findings and conclusions, we are recommending completion of source interdiction measures with Monitored Natural Attenuation as the preferred remedial measure. Refer to **Section 11.0** for more information, including our reasons for making this recommendation.

10.1 NATURE AND EXTENT OF CONTAMINANT MIGRATION

The primary groundwater radiological contaminants of interest are Tritium and Strontium. Other contaminants (Cesium-137, Nickel-63 and Cobalt-60) have been detected, but are limited to areas that have groundwater pathways dominated by Tritium and/or Strontium, and are accounted for in Entergy's dose calculations.

Groundwater contamination is limited to Indian Point's property and is not migrating off-property to the North, East or South. The contamination migrates with the Site groundwater from areas of higher heads to areas of lower heads along paths of least resistance, and ultimately discharges to the Hudson River to the West. This is supported by the bedrock geology, multi-level groundwater elevation data and the radiological results from analytical testing. The nearest drinking water reservoirs are located at distances and elevations which preclude impacts from contaminated groundwater from the Site and there is no nearby use of groundwater.

a. The Site is located over a portion of the aquifer basin where Site-wide ambient groundwater flow patterns, both shallow and deep, have been defined. These flows are towards the Site from higher elevations to the North, East and South. Groundwater flow on Site enters the Hudson River through: footing drains (which discharge to the Discharge Canal); the Discharge Canal; the storm drain system; or direct discharge. The results of over two years of investigations demonstrate that the off-Site groundwater migration to the South, as originally hypothesized by others prior to these investigations, is not occurring.
b. Surface water samples collected from the Algonquin Creek, the Trap Rock Quarry and from the drinking water reservoirs do not exhibit impacts from the Site.
c. The Hudson River is the regional groundwater sink for the area. We found no Site data, published information, or other reasons suggesting that groundwater would migrate beneath the river. To the contrary, based on the area's hydrogeologic setting and all available information, we are confident that groundwater beneath the Site discharges to the river.

d. Because of the hydraulic properties of the bedrock, the bedrock aquifer on-Site will not support large yields, or accept input of large volumes of water.
e. There are no identified off-Site uses of groundwater (extraction or injection) proximate to the Site that influence groundwater flow patterns on the Site. Furthermore, we have no reason to believe that potable or irrigation wells will be installed on or near the Site in the reasonably foreseeable future, in part because municipal water is available in the area.
f. Groundwater flow at the Site occurs in two distinct hydraulic regimes that are vertically connected, bedrock and overburden soils. Most of the groundwater flow and contaminants are found in the bedrock fractures. No evidence of large scale solution features exist in the rock cores obtained from any of the bedrock borings advanced at the Site; i.e., no open voids such as tunnels, caverns, caves, etc., sometimes referred to as "underground rivers," were found. Our on-Site investigatory findings are consistent with that expected for the Inwood Marble. Therefore, this work eliminates from concern solution feature flow associated with karst systems. The second regime is groundwater flow in the unconsolidated soil deposits. This includes groundwater found in native glacial and alluvial deposits, as well as groundwater flow in anthropogenic structures such as blast rock fill and utility trenches. These flow paths, while potentially complicating migration patterns, all terminate at the Hudson River.
g. While groundwater movement in the bedrock is controlled by fracture patterns, the high degree of fracturing allows groundwater flow to be effectively represented and modeled on a Site-wide scale using the well developed techniques derived for porous media[127].

10.2 SOURCES OF CONTAMINATION

The investigations identified two sources of radiological contamination. The IP1-SFPs and the IP2-SFP/Transfer Canal. The IP1-SFPs are the primary source of Strontium groundwater contamination, while the IP2-SFP is the primary source of Tritium groundwater contamination. No evidence of releases from Unit 3 have been identified during this investigation.

During the course of GZA's and Entergy's investigations, we have identified the sources of leakage associated with the IP2-SFP and Transfer Canal. These sources have been eliminated and/or controlled by Entergy. Specifically, Entergy has: 1) confirmed that the damage to the liner associated with the 1992 release was repaired by the prior owner and is no longer leaking; 2) installed a containment system (collection box) at the site of the leakage discovered in 2005, which precludes further release to the groundwater; and 3) identified a weld imperfection in the Transfer Canal liner that, once identified, was prevented from leaking further by draining the Transfer Canal. This weld imperfection was then subsequently repaired by Entergy (completed in mid December 07). Therefore, all identified leaks have been addressed. Water likely remains between the IP2-SFP stainless

[127] While fracture-specific numerical models exist, they are less well developed and less flexible than porous media-based models. The use of a porous media representation requires some level of approximation, particularly on small scales of tens of feet. However, the fracture flow models also require substantial approximations based on fracture statistics and are thus, more problematic at this Site than a porous model.

steel liner and the concrete walls, and thus additional active leaks can not be completely ruled out. However, if they exist at all, the data[128] indicate they must be very small and of little impact to the groundwater.

Our investigations also identified the source of all the Strontium contamination detected in groundwater beneath the Site as coming from the Unit 1 Fuel Pool Complex (IP1-SFPs). The IP1-SFPs were identified by the prior owner as leaking in the mid-1990's. All of the pools have been drained by Entergy except the West Pool, which currently contains the last 160 Unit 1 fuel assemblies remaining from prior plant operations. This plant was retired from service in 1974. Following detection of radionuclides associated with IP1-SFPs in the groundwater, Entergy, as part of their already planned fuel rod removal and complete pool drainage program, accelerated efforts to further reduce activity in the IP1-SFPs through demineralization..

The on-Site tracer test demonstrated that aqueous releases in the vicinity of IP2-SFP are stored *above the water table* in either: 1) unsaturated zone dead-end fractures; and/or 2) anthropogenic foundation details such as blast-rock backfill over a mud-mat (see **Section 8.1.2**). This impacted unsaturated zone water is then periodically released to the groundwater over time as driven, for example, by infiltration of precipitation. Consequently, subsequent releases *to the groundwater* can continue for significant durations after the initial leak has been terminated. In addition, the tracer studies further demonstrate that the migration rates for the Tritium plume *in the groundwater* can be slowed down as compared to the groundwater itself. This reduction in Tritium plume migration velocity occurs when impacted groundwater encounters, and becomes "entrapped" by dead-end fractures, both naturally occurring fractures and those created by excavation blasting during Site construction[129].

The radionuclides identified in the Unit 3 area are related to historic legacy leakage from IP1, and reflect what remains of the plume that has been naturally attenuating since approximately 1994. The pathway to the Unit 3 area was via the IP1-SFDS and then to the storm drain system which transverses along the southeastern portion of the Site; not via groundwater flow to the South (see **Section 8.2**). Exfiltration from this storm drain system had, in turn, resulted in contamination of the groundwater along the storm drain piping. The Sphere Foundation Drain Sump no longer discharges to the storm drain system and this legacy release pathway had therefore been terminated because the associated piping was capped in 1994.

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[128] These data include: monitored water levels in the SFP, with variations accounted for based on refilling and evaporation volumes; the mass of Tritium migrating with groundwater is small; and the age of the water in the interstitial space.

[129] Once contaminants enter dead-end fractures, they no longer migrate with the groundwater flow. However, this "entrapped contamination" does re-enter the flow regime over time due to turbulent flow mixing at the fracture opening as well as diffusion.

10.3 GROUNDWATER CONTAMINANT TRANSPORT

Based on our assessment of the bedrock's hydraulic properties, the area's hydrogeologic setting, the properties of the contaminants, the age of the releases, interdictions made to eliminate or reduce release rates, and the distances between the source areas and the Hudson River, we believe the groundwater contaminant plumes have expanded to their maximum extent and are now decreasing in size. In this regard, the Unit 2 Tritium plume is decreasing faster than the Unit 1 Strontium plume, as anticipated. These conclusions are based on the data available which, given the aggressiveness with which Entergy implemented the investigations, is compressed in duration[130]. Therefore, ultimate confirmation of these conclusions will require monitoring over a number of years to allow ranges in seasonal variation to be adequately reflected in the monitoring data. During long term monitoring, GZA further anticipates that contaminant concentrations in individual monitoring wells will fluctuate over time (increasing at times as well as decreasing, as potentially related to precipitation events), and that a future short term increase in concentrations does *not*, in and of itself, indicate a new leak. In addition, it is also expected that some areas within the plumes will exhibit faster decay rates than others. Both behaviors are commonly observed throughout the industry with groundwater contamination sampling and analyses, and therefore, conclusions pursuant to plume behavior must be evaluated in the context of all of the Site-wide monitoring data. Overall, however, GZA believes that the continuing monitoring will demonstrate decreasing long term trends in groundwater contaminant concentrations over time given the source interdictions completed by Entergy. It is also further emphasized that even the *upper bound* Tritium and Strontium groundwater concentration isopleths presented on **Figures 8.1** and **8.2** result in releases to the river which are only a small percentage of the regulatory limits, which are of no threat to public health.

a. The major groundwater transport mechanism is advection. Sorption retards the migration of radiological contaminants other than Tritium relative to groundwater advection rates, while Tritium, within hydraulically interconnected fractures, can migrate at rates that approach the groundwater seepage velocity.
b. The Unit 2 contaminant plume is characterized by Tritium in the groundwater. Over the last two years, the highest Tritium concentrations in the Unit 2 plume have decreased (see **Table 5.1** and **Figures 8.1** and **9.3**). However, the center of mass of the Unit 2 plume is not rapidly migrating downgradient, and remains in proximity to the IP2-SFP. While a small active leak can not be ruled out completely, this behavior is also consistent with the identified role of unsaturated zone (above the water table) storage of historic releases, with precipitation-induced infusion of this entrapped water into the groundwater regime over time.
c. The Unit 1 contaminant plume is primarily characterized by Strontium concentrations in the groundwater, though near the physical pool area other isotopes are present as expected due to proximity. Over the last two years, the highest Strontium concentrations in the Unit 1 plume have decreased **(Table 5.1)**. These decreases in concentration are consistent with a reduction in Strontium

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130 It is noted that a number of key monitoring installations have only recently been completed. and monitoring rounds spanning multiple seasons are not yet available.

concentrations in the Unit 1 West Fuel Pool via pool water recirculation through demineralization beds. While the physical leak(s) in this fuel pool still exist, the source term to the groundwater has been reduced through reduction in the contaminant concentrations in the leak water. It is noted, however, the Unit 1 Strontium decreases are more modest and are generally more limited to the immediate source area than that observed for Tritium at Unit 2. The slower rate of plume decay is not unanticipated give the adsorption properties of Strontium. Further planned interdictions include removal of the fuel rods and draining of the pool water, which will permanently eliminate the West Fuel Pool as well as the entire IP1-SFP complex as a source of contamination to the groundwater. With elimination of this source, natural attenuation will reduce Strontium concentrations in the Unit 1 plume over time.

10.4 GROUNDWATER MASS FLUX CALCULATIONS

During the project (over the past two years), as testing progressed and more information became available, we refined methods to calculate the groundwater flux and associated radiological activity to the Hudson River. As described below, we have developed a procedure which is scientifically sound, relatively straight-forward, and appropriately conservative. Groundwater flow rates are provided to Entergy, who computes the radiological dose impact.

a. Migration of radionuclides to the river is computed based on groundwater flow rates, in combination with contaminant concentrations within the flow regime. This information is then used in surface water models to compute radiological contaminant concentrations in the river and thus potential dose to receptors.
b. To assess the validity of the precipitation mass balance method used to date for computing groundwater flux across the Site, GZA also performed groundwater flux computations using an independent method based on Darcy's Law. Thus, the results from two widely accepted groundwater flow calculation methods were compared against each other. The first, the precipitation mass balance method, is a "top-down" procedure based on precipitation-driven water balance analyses. The second, based on Darcy's Law, is a "bottom-up" method using hydraulic conductivity and flow gradient measurements. These two methods resulted in estimated groundwater flow values which were in agreement, providing a high degree of confidence in the values obtained relative to their impact on subsequent dose computations and risk analyses.
c. The original groundwater flux computations were developed for two separate areas of the Site. The northernmost area included both the Unit 2 and Unit 1 plumes. The southernmost area encompassed Unit 3. This bifurcation of the Site was established given: 1) the co-location of the Unit 2 plume and the Unit 1 plume near the western boundary of the Site just upgradient of the river; 2) the much lower contaminant concentrations in the Unit 3 area; and 3) the amount of data available at that time. Current data, derived from a greater number of groundwater elevation and sampling points than reflected in earlier data, show the Site can be divided into six separate areas. The computations were further separated into shallow and deep flow regimes given: 1) the generally higher hydraulic conductivity in the shallow

portion of the bedrock, and 2) the generally more elevated contaminant concentrations in the shallow flow regime.

d. The groundwater contaminant concentrations used for the radiological dose computations were obtained primarily from the analysis of samples taken from the recently completed multi-level wells specifically installed for this purpose. These wells are located downgradient of the Unit 2 and Unit 1 infrastructure[131] and are positioned within the plumes and just upgradient of where the groundwater discharges to the river and Discharge Canal. The multi-level nature of these wells allows the groundwater to be sampled over at least five separate elevations in the bedrock, in addition to the overburden layer above. Sampling zones specifically targeted the most pervious depths within the bedrock boreholes. As such, the groundwater samples encompass the full depth of the contaminant plume, from the upper soil zones to depths where the contaminant concentrations have fallen off to insignificant levels. The high number of samples over the depth of the plume provides a higher degree of confidence that the significant flow zones are accounted for. The high number of vertical sampling zones also provides a higher level of redundancy relative to the longevity and efficacy of the monitoring network over time.

10.5 GROUNDWATER MONITORING

The current groundwater well and footing drain monitoring network is consistent with the objectives of the NEI Groundwater Protection Initiative[132]. Wells have been installed and are currently being monitored to both detect and characterize current and potential future groundwater contaminant migration to the river, as well as, in concert with specific footing drain monitoring, provide earlier detection of potential future leaks associated with the existing infrastructure.

a. The network of 59 monitoring well locations and over 140 sampling intervals/locations, has allowed us to identify groundwater flow patterns. A subset of this network will provide an adequate long term monitoring system.
b. Existing and potential sources have been identified, and monitoring is in place to both evaluate current conditions and identify future releases, should they occur.
c. The nature and extent of contamination is known and reporting requirements are in place.

10.6 COMPLETENESS

Investigations at the Site have been broad, comprehensive, and rigorous. Major components of the field studies include: detailed acquisition of geologic information; automated long duration collection of piezometric data; vigorous source area

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[131] The multi-level sampling network is concentrated in the Unit 2 and Unit 1 areas given that this is where contaminant concentrations are by far the highest. The individual monitoring wells located downgradient of Unit 3 are judged sufficient for computations in this area given the low contaminant concentrations measured, even in the typically more contaminated shallow flow regime.

[132] NEI developed a set of procedures/goals for nuclear plants to assess the potential for releases of radionuclides to potentially migrate off-Site.

identification; comprehensive aquifer property testing, including performance of a full scale Pumping Test; and large-scale confirmatory contaminant transport testing, in the form of an extensive tracer test. The results of this systematic testing program are in agreement with conditions anticipated by our Conceptual Site Model. Based on our review of findings, we have concluded that the field studies conducted at the Site have addressed the study objectives.

a. There is no need to monitor groundwater at off-Site locations. The density and spacing of on-Site monitoring wells is adequate to: 1) demonstrate that contaminated groundwater is migrating to the Hudson River to the West, and not migrating off of the property to the North, East or South; 2) monitor the anticipated attenuation of contaminant concentrations; 3) identify future releases, should they occur; and 4) provide the data required to compute radiological dose impact.
b. Hydraulic conductivity is the most important aquifer property. We have completed more than 245 hydraulic conductivity tests, including a full-scale Pumping Test. Therefore, we believe no future aquifer testing is required. In addition, the contaminant plumes have reached their maximum spatial extent. Therefore, there is no need for contaminant transport modeling.
c. The sources of releases to the groundwater have been identified. In addition to monitoring, actions have been taken to reduce or eliminate these releases. Therefore, we believe no future source characterization is required.
d. All information indicates Monitored Natural Attenuation is the appropriate remedial response and is GZA's recommended approach (see **Section 11.0**). The existing monitoring network will serve this remedial approach. Therefore, no design phase studies are required.