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Independent Technical Support for the Frozen Soil Barrier Installation and Operation at the Fukushima Daiichi Nuclear Power Station (F1 Site)

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List of Acronyms and Symbols

A	enclosed area inside barrier (= total area – areas of buildings that penetrate water table)
A_{xs}	cross sectional area perpendicular to groundwater flow (m^2)
ALPS	Advanced Liquid Processing System (state of practice multi-nuclide water treatment)
β	projected fractional net reactor inflow $Q_{net,(0)}$ that will be realized over time compared to the baseline condition (ranges from 0 to 1)
$C_{(t)}$, C_0	blended concentration of solute from barrier and initial concentration of solute in groundwater (mass or activity / m^3)
DOE	US Department of Energy
ξ	extent or progress of barrier freezing (ranges from 0 at time = t_0 to 1 at time = t_f)
$h_{initial}$	initial water table elevation (head) in area of the barrier (m)
h_{base}	approximate base elevation of the permeable upper aquifer (m)
$h_{(t)}$	water table elevation inside barrier after barrier formation (m)
h_{min}	water level (or breach elevation) in reactor (m) – this is the elevation where net inflow to reactors = 0
infiltration	water infiltration darcy velocity (m/day)
k_f	frozen soil thermal conductivity (W/[m·°C])
$m_{b,(t)}$, $m_{f,(t)}$	solute contributed to downgradient water from ice formation in the barrier and from active flow during freezing (mass or activity)
$m_{T,(t)}$	total solute in the water that has passed through the barrier during freezing (mass or activity)
r_p	radius of freeze pipe (m)
S	freeze pipe spacing (m)
t_0 , t, t_f	freeze start time, elapsed time and end freeze time (days)
T_f T_p T_g	temperatures - freezing point of water, freeze pipe surface, and groundwater -- (°C)
TEPCO	Tokyo Electric Power Company
θ	porosity of upper aquifer zone
Q_{net}	net inflow into reactors from the groundwater (m^3/day)
$Q_{leakage}$	total leakage through ice barrier from all locations (m^3/day)
RTD	resistance-temperature device
u_c u_f	critical Darcy velocity for freeze wall closure and field Darcy velocity (m/day)
$V_{b,(t)}$, $V_{b,final}$	bulk frozen soil volume in the barrier as a function of time and final bulk frozen soil volume (m^3)
$V_{w,(t)}$, $V_{w,final}$	water volume that has left the barrier during the freeze period and final bulk water volume during freeze period (m^3)

Independent Technical Support for the Frozen Soil Barrier Installation and Operation at the Fukushima Daiichi Nuclear Power Station (F1 Site)

Synopsis

TEPCO is implementing a number of water countermeasures to limit the releases and impacts of contaminated water to the surrounding environment. The diverse countermeasures work together in an integrated manner to provide different types, and several levels, of protection. In general, the strategy represents a comprehensive example of a "defense in depth" concept that is used for nuclear facilities around the world. One of the key countermeasures is a frozen soil barrier encircling the damaged reactor facilities. The frozen barrier is intended to limit the flow of water into the area and provide TEPCO the ability to reduce the amount of contaminated water that requires treatment and storage. The National Laboratory team supports the selection of artificial ground freezing and the incorporation of the frozen soil barrier in the contaminated water countermeasures -- the technical characteristics of a frozen barrier are relatively well suited to the Fukushima-specific conditions and the need for inflow reduction. Further, our independent review generally supports the TEPCO/Kajima design, installation strategy and operation plan. We have developed a number of key points and specific technical/engineering recommendations which are summarized below.

Key Points

- The frozen barrier is being installed by a team from TEPCO and Kajima Corporation. Kajima is an engineering/design/construction corporation that provides diverse services to the nuclear, industrial, and civil infrastructure sectors. Notably, the "Soil, Foundation, and Geotechnics" Group at the Kajima Technical Research Institute has actively studied a number of soil stabilization methods, including artificial ground freezing. The frozen soil barrier at Fukushima represents one of the largest frozen soil barriers in the world, a major application for "long term" control of contaminated groundwater, and a unique use of the technology for a nuclear facility. However, artificial ground freezing was originally developed in the late 1800s and has been in use for general engineering applications since the 1950s. The technology has been applied at hundreds of construction and mining sites throughout the world – including North America, Europe and Japan. The scale of the Fukushima barrier is bounded by industry experience and the equipment and infrastructure proposed for the ground freezing is well understood. The on-site pilot test at Fukushima indicated predictable ground freezing that supported the design parameters. All of these factors increase the confidence in the TEPCO/KAJIMA frozen soil barrier project.

- Assessment of the freeze pipe spacing, refrigeration infrastructure, plans for addressing penetrations, and other design parameters indicate that the Fukushima barrier design is equivalent to the successful case-study barriers identified in our evaluation. Based on standard engineering calculations and the Fukushima soil and groundwater conditions, frozen zones around the individual freeze pipes are generally expected to adequately merge into a continuous frozen barrier in a reasonable timeframe. For areas where an isolated zone does not freeze, there are a number of relatively low-cost contingency actions.

- The final geometry of a frozen barrier reflects the local geologic conditions and the sum of the effects of various physical and chemical processes that occur at the ice water interface as the barrier is forming. Based on the expected barrier geometry, the potential “weakest” areas of the barrier can be predicted. These areas would be between the freeze pipes near the top of the barrier and in high permeability gravel layers. Targeted monitoring in these areas is recommended. If monitoring indicates a competent barrier in the predicted weakest areas, the data would provide a high degree of confidence in the overall barrier design and performance.

- Based on existing data, there are no Fukushima-specific groundwater conditions that would cause problems for the frozen soil barrier installation. Fractional freezing effects during the barrier formation (a factor that is not normally considered in construction and mining applications) have the potential to cause short term increases in concentrations measured in nearby downgradient wells. Simple scoping calculations indicate that the impacted water may have concentrations up to 1.1 to 2 times the baseline concentration. The concentrations should return to baseline levels (or below) shortly after the barrier formation is complete.

- The frozen soil barrier does not need to be 100% effective to meet TEPCO’s key objective to limit groundwater flow into the damaged reactors. The National Laboratory team recommends developing relatively simple and low cost performance monitoring techniques that provide information to assess how well the barrier meets this key objective. One of the most important monitoring strategies will be to carefully monitor the water balance and compare changes in groundwater levels to the expected behavior for a fully competent barrier. This simple hydrological approach can account for removal of water by inflow into the damaged reactors or by subdrains, infiltration of rainwater, and injection or pumping by installed wells. For the hydrologic monitoring method to be effective, all of the water flows must be measured or estimated. A scoping calculation indicates that supplemental water removal using the subdrains (or pumping wells) will significantly accelerate the objective of reducing the amount of groundwater inflow into the damaged reactor buildings. More sophisticated (and costly) monitoring methods can be employed if the baseline hydrologic monitoring indicates the barrier is underperforming.

- If the hydrologic analysis indicates significant barrier leakage and the general location of leakage, several types of supplemental targeted monitoring are potentially applicable. For this supplemental monitoring, a thermal tracer method is a reasonable option. The technique would introduce a thermal signal (using a heater for example) and look for perturbations in the temperature profiles at various points in time during heating and cooling. At Fukushima, thermal tracers appear to have more potential for application compared to chemical tracers.

- Geophysics is another important category of technologies to support supplemental monitoring of a frozen soil barrier. At Fukushima, surface interferences (buildings, roads, surface utilities, and ground capping/facing activities), subsurface infrastructure, and penetrations in the frozen barrier complicate the application of geophysics.

- Based on the information provided, the TEPCO/Kajima team appears to be planning a high quality artificial ground freezing operation that fully implements the industry standard process monitoring and controls.

- The TEPCO/Kajima strategies to freeze above and below subsurface penetrations – using added vertical freeze pipes adjacent to some penetrations or installing freeze pipes directly through other types of penetrations – are reasonable. For freezing above and below the penetrations, these strategies should be as effective as the angle drilling strategies that have been used in many previous ground freezing applications around the world. Achieving a complete freeze against the outside surfaces of penetrations may represent a more significant challenge. Previous experience at ground freezing sites indicates that a complete seal is often impeded by heat input from the penetration. Heat can be brought into the frozen soil barrier zone by transverse conduction from internal air or fluids through the penetration wall or by longitudinal conduction along the penetration wall. An unfrozen soil zone is often present around barrier penetrations. If leakage around a penetration is deemed significant, a number of engineering approaches can be used to mitigate the problem. One notable recommendation would be for penetrations having interior access and through which freeze pipes are installed. In such instances, TEPCO could insulate the freeze pipes inside the penetration as well as the interior surfaces of the penetration in the area where the penetration crosses the barrier. These actions could be implemented relatively easily and would improve the potential for effective barrier performance in those areas.

- Based on the conditions and layout at F1, the risks of frost heave and subsurface utility damage are relatively low. If sensitive surface infrastructure is located directly adjacent the frozen soil barrier (i.e., within about 5 m) then TEPCO should consider additional analysis and monitoring – particularly in areas where the barrier is forming very close to the ground surface. Subsurface water lines (water lines, sewer lines, drain lines, etc.) penetrating the barrier should be evaluated to determine if potential freezing and line blockage might occur.

- A number of engineering options are feasible to address a rising water table on the upgradient (mountain-side) of the Fukushima frozen soil barrier. If the freeze pipes above the water table are not insulated, then the freeze wall should grow upward on the mountain-side and limit the need for any additional action to address water table rise. If active mitigation is needed to address water table rise, then the following baseline engineering options: a) no action (because the amount of water entering is low and within the capacity of planned subdrain and reactor building removal rates) and b) increasing upgradient pumping from the groundwater bypass wells. Other actions that could be considered if the baseline options are not adequate include: c) adding new upgradient pumping capacity, d) installing engineered drains to move water laterally around the barrier, e) adding additional freezing capacity in areas above the original water table where spillover is observed, and f) planting a band of phreatophyte plants (to naturally extract groundwater) between the mountainside and the barrier. Extended interruption of the operations of the upgradient groundwater bypass system would increase the magnitude of groundwater rise on the mountain-side of the barrier. A focus on continued operation of this important synergistic countermeasure would reduce the risks and potential impacts of groundwater rise

- At the end of operations, the barrier will thaw and the system will develop a new hydrologic balance based on flow from the upgradient mountain-side and the modified boundary conditions provided by any continuing countermeasures. Clay and silt layers are expected to exhibit increased vertical permeability after the freeze-thaw cycle.

Introduction

TEPCO is installing a frozen ground barrier around the damaged reactors at the Fukushima Daiichi Nuclear Power Station (F1 Site). This barrier is a key component in the "contaminated water countermeasures" to minimize the future impacts associated with the nuclear reactor facilities that were damaged by the March 2011 tsunami, which was triggered by the offshore Tōhoku megathrust earthquake (Simons et al., 2011). The frozen ground barrier is designed to isolate the damaged reactors from the groundwater in the uppermost aquifer zone. Isolation of the damaged reactor facilities is intended to reduce the flow of groundwater into those facilities, allowing management of the groundwater within the barrier and preventing contamination of additional groundwater as it flows towards the harbor. Reduction of groundwater inflow to the damaged reactor facilities will facilitate the primary TEPCO goals of reducing the amount of contaminated water that requires sophisticated treatment and long term water storage, reducing secondary waste generation, and reducing site worker radiation exposure.

Installation and operation of the frozen ground barrier will provide a significant benefit and is a key component of the water management strategy to provide conditions to allow leaks into the reactors to be repaired and support decommissioning. Artificial ground freezing is a relatively standard technology used in the construction and mining industries. However, application at a nuclear site for long term control of contaminated groundwater is unique, posing challenges and providing opportunities. To help address these challenges and opportunities, TEPCO has teamed with Kajima, a high quality and well-respected engineering company with significant technical resources. TEPCO has also engaged international experts from the U.S. Department of Energy National Laboratories – the Savannah River National Laboratory and the Pacific Northwest National Laboratory – to provide independent evaluation and support.

A number of references (Powers et al., 2007; Bell, 1992; Andersland and Ladanyi, 2004; Green et al., 2014; Nicholson, 2015; Chen et al., 2010; Lietaert et al., 2010) provide good overviews of artificial ground freezing , while other references discuss artificial ground freezing in the specific contexts of construction/mining (Roworth, 2013) and hazardous waste cleanup (Dash, 1991; Sayles and Iskandar, 1995; ITRD, 2001). These references note a variety of design considerations (freeze pipe spacing [and deviation from true], coolant temperature, freezing time, strength of the frozen soil structure, water saturation, pore-water salinity, soil heave/settlement, groundwater velocity, freeze wall closure, etc.) and often point to examples of artificial ground freezing implementations (mostly in the mining and construction industries).

Objectives

The overarching objective of the National Laboratory Team technical support for TEPCO is to provide supplemental information to support a final barrier decisions and to optimize barrier design, installation, monitoring and operation. This report documents the results of the independent evaluation.

TEPCO prepared an "Examination of the measure to reduce the amount of underground water flowing into the Units 1-4 buildings with the land-side impervious wall (frozen soil method)" (July 1, 2013) that resulted in the decision to construct a land-side frozen soil barrier. The National Laboratory team concurs with the TEPCO feasibility study and has significant experience in testing in situ technologies and full-scale deployment of technologies. We have confidence in the ability of TEPCO and their support contractors (e.g., Kajima Corporation) to plan and support a frozen soil barrier feasibility study and to implement a frozen soil barrier. The topics below highlight some of the key technical challenges and opportunities specific to the implementation of the barrier for groundwater isolation in a contaminated nuclear setting. The National Laboratory Team technical support and collaboration efforts are focused on providing input to TEPCO to help maximize performance of the barrier and to identify and mitigate technical challenges that are unique to the Fukushima site and contaminated groundwater isolation. The National Laboratory Team performed technical and applied science evaluations and recommendations (as needed) on the following topics:

- Barrier Geometry
- Fukushima Site Specific Fluid and Soil Properties
- Monitoring
- Engineering Topics

Background

The Contaminated Water Treatment Measures Committee issued a "Measures for the Prevention of Groundwater Inflow" report on May 30, 2013, describing the need for a land-side barrier to reduce the amount of groundwater flowing into the Unit 1-4 reactor buildings. Reduction of groundwater inflow provides two important benefits: a) improving the conditions for decontaminating and decommissioning these buildings, and b) decreasing the volume of contaminated water produced from the buildings and the associated costly treatment and storage/disposal. Several options for reduction of groundwater inflow were considered and a scoping-level evaluation led to recommendation of an impervious barrier encircling the reactor buildings installed using artificial ground freezing. Ground freezing is a commercially available technology that is traditionally used in the construction and mining industries for short term stabilization of soil and/or for reducing water infiltration. Artificial ground freezing technology has tested in the United States at the pilot scale as a technique for controlling contaminated groundwater migration (e.g., AFI, 2000; Wagner and Yarmak, 2012), but has not been selected and implemented for long-term full-scale use. As described in the Contaminated Water Treatment Measures Committee (2013) report, the technical characteristics of a frozen barrier are relatively well suited to the F1-specific conditions and the need for inflow reduction.

In the Contaminated Water Treatment Measures Committee (2013) report, the technical information on frozen barriers was provided by Kajima Corporation, an engineering/design/construction corporation that provides diverse services to the nuclear, industrial, and civil infrastructure sectors. Notably, the "Soil, Foundation, and Geotechnics" Group at the Kajima Technical Research Institute has actively studied a number of soil stabilization methods, including artificial ground freezing. The availability of commercial geotechnical equipment and expertise in Japan increases confidence that a barrier can be emplaced in a reasonable timeframe. However, there are significant differences in the objectives for geotechnical (construction and mining) applications and the objectives for long-term groundwater isolation. Specifically, geotechnical applications are typically short term and are focused on bulk structural stabilization and the general reduction of water inflow. In these geotechnical applications, there are typically stringent timing requirements due to the costs of mobilizing construction crews and equipment but often with limited consequences associated with hydrologic underperformance of the barrier. In contrast, the performance of the Fukushima inflow reduction barrier is important in achieving specific environmental protection and water treatment cost reduction objectives. The barrier will need to be designed to be effective, implementable, robust to heterogeneous site-conditions, and conducive to performance monitoring.

Role of the Frozen Barrier in the Integrated Contaminated Water Countermeasures Underway at the F1 Site

TEPCO is implementing a number of water countermeasures to limit the releases and impacts of contaminated water to the surrounding environment. The diverse countermeasures work together in an integrated manner to provide different types and several levels of protection of protection. In general, the strategy represents a comprehensive example of a "defense in depth" concept that has been recommended for nuclear facilities by the US National Academies. Key countermeasures are depicted and categorized in Figure 1. The various countermeasures focus on the following three goals: a) removing and/or treating contaminated water, b) redirecting and controlling fresh water to avoid contamination, and c) retaining contaminated water on-site to minimize discharge to the environment. The figures and descriptions summarized in this section were adapted from information provided by TEPCO (available at http://www.tepco.co.jp/en/decommision/planaction/waterprocessing-e.html) and are intended to provide a foundation for the National Laboratory team frozen soil barrier evaluation and recommendations.

Treatment of contaminated water pumped from inside the damaged buildings is one of the most active and important countermeasures (Figures 1 and 2). This treatment is being performed using a state-of-practice multi-nuclide treatment system (ALPS). As described above, the excess treated water is being stored in tanks. Secondary wastes from the treatment are being staged for disposal. Pilot testing and research on technologies to treat contaminated harbor water is underway. These technologies focus on removal of low levels of radioactive strontium (^{90}Sr) in the presence of seawater calcium and stable Sr. Treatment of harbor water will be incorporated in the baseline countermeasures if the pilot tests confirm viability of a treatment technology.

The challenge of contaminated groundwater is being addressed through the coordinated actions of groundwater redirection/control and by retaining water. The four major systems that contribute to these goals are the groundwater bypass system, the subdrain system, the frozen soil barrier and the seaside impermeable barrier. Other activities, such as capping ("coating" or "facing" the ground surface) to reduce infiltration of rainwater, are also being performed as needed. The groundwater bypass system (Figures 1 and 3) pumps up groundwater to tanks. The water is analyzed for contaminant radionuclides. If concentrations are below World Health Organization (WHO) guidelines, the water is discharged to the ocean. The pumping wells are installed upgradient of the damaged reactors and removal of the uncontaminated upgradient groundwater reduces the amount of groundwater flowing beneath the damaged reactor area toward the ocean. Key stakeholders, such as fishermen, have concurred with the operational protocols and WHO guidelines for the release of water from the bypass system and the system is currently operating.

In addition to the groundwater bypass system, planned countermeasures also include removal of groundwater near the damaged building using a subdrain system and removal of groundwater near the seaside impermeable barrier using a trench drain (Figure 4). The proposed operation of these systems is similar to the groundwater bypass system with some additional processing steps to remove low level contamination to assure that water released meets agreed standards such as the WHO guidelines. Operation of these systems is closely tied to the final closure of the seaside impermeable barrier since closure of the barrier without providing an exit pathway for the water that is currently discharging would result in unwanted increases in water levels beneath the Fukushima Daiichi Nuclear Power Station. Operation of these systems is contingent on concurrence by key stakeholders. TEPCO is working with the fishermen and regulators to obtain such concurrence so that these countermeasures can be put into operation. As shown in the technical sections below, operation of the subdrain, groundwater drain and seaside impermeable barrier are important to the long term performance of contaminated water countermeasures. Operation of the subdrain system will be a primary factor in the performance of the frozen soil barrier. The National Laboratory team supports TEPCO's efforts to work with stakeholders to obtain concurrence to start up the subdrain and groundwater drain systems and close the seaside barrier.

As shown in Figure 5, the frozen soil barrier ("land side impermeable wall") serves a unique and important role in the contaminated water countermeasures. The barrier will isolate the groundwater surrounding the damaged facilities and provide options for control and management of the water balance in this important area. Most important will be the option to reduce groundwater levels in the upper aquifer inside the barrier and reduce the inflow of water into the buildings. This inflow reduction would result in a corresponding reduction in water treatment volumes, water storage requirements, and secondary wastes.

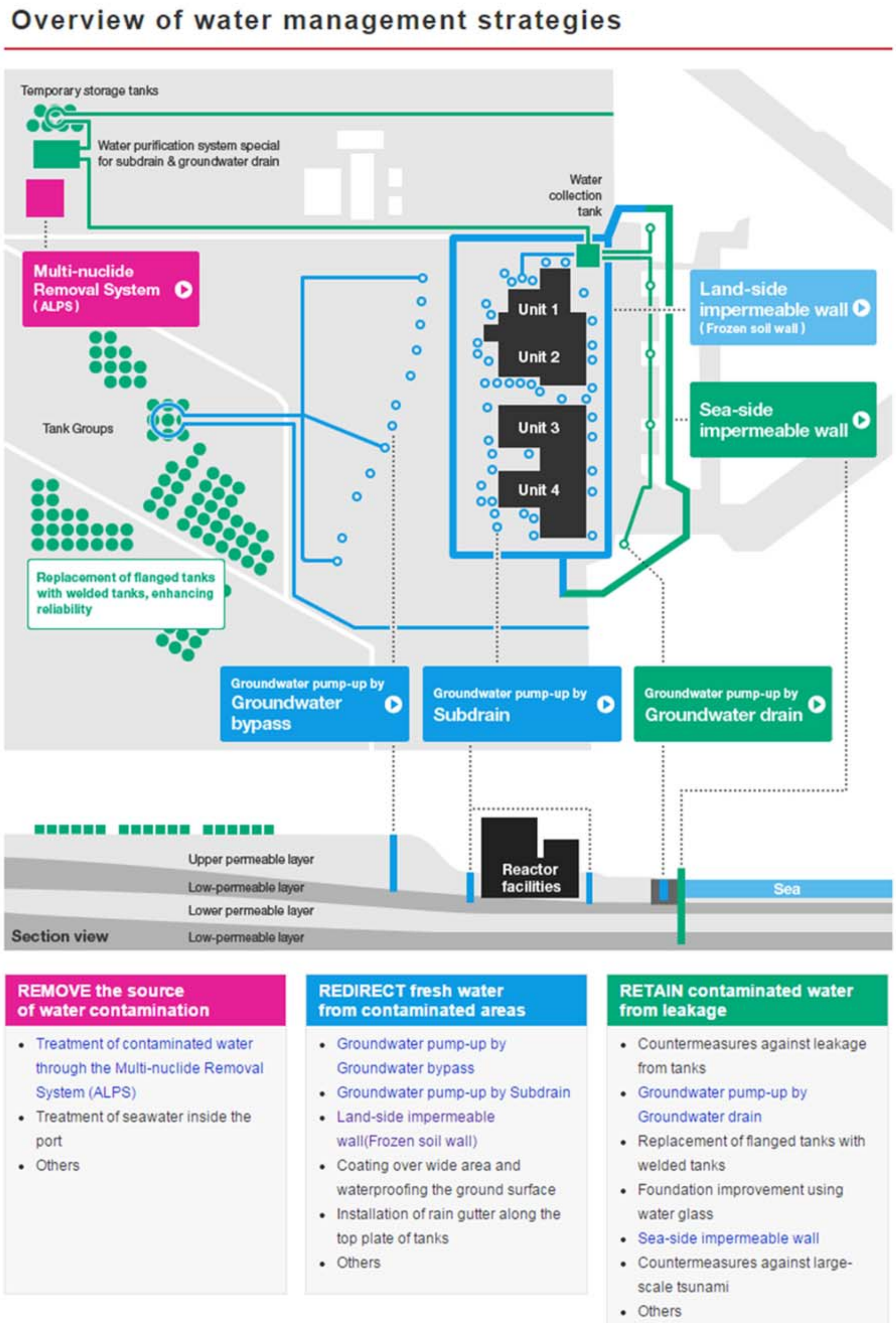


Figure 1. Summary of Contaminated Water Countermeasures being implemented by TEPCO at the F1 Site (Figures 1-5 in this section adapted from figures provided by TEPCO and available at http://www.tepco.co.jp/en/decommision/planaction/waterprocessing-e.html)

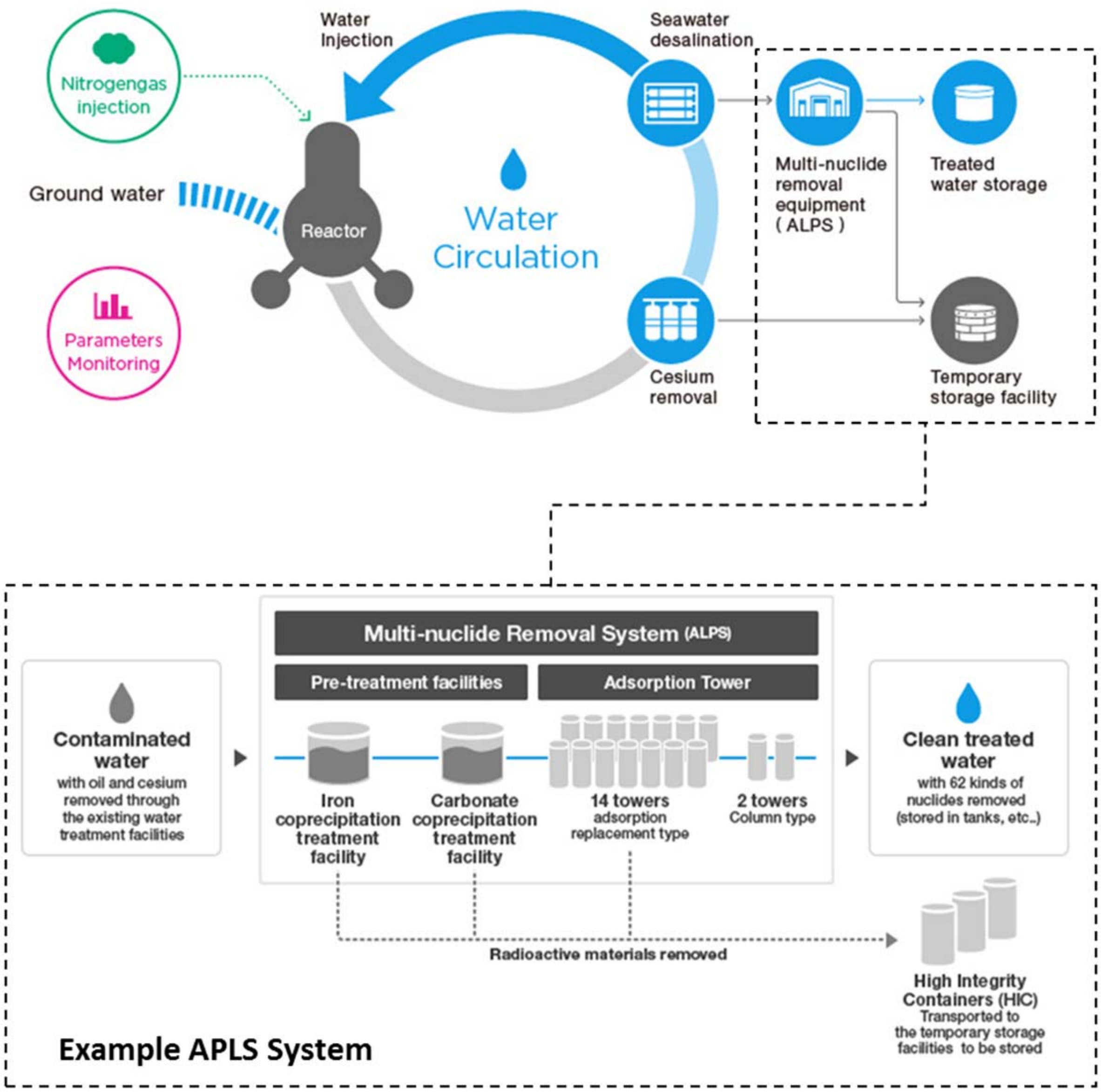
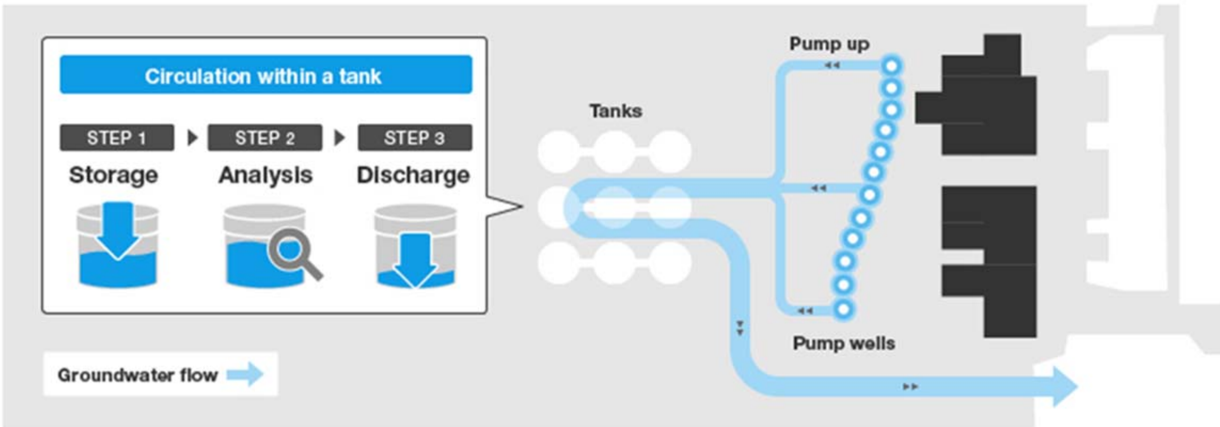


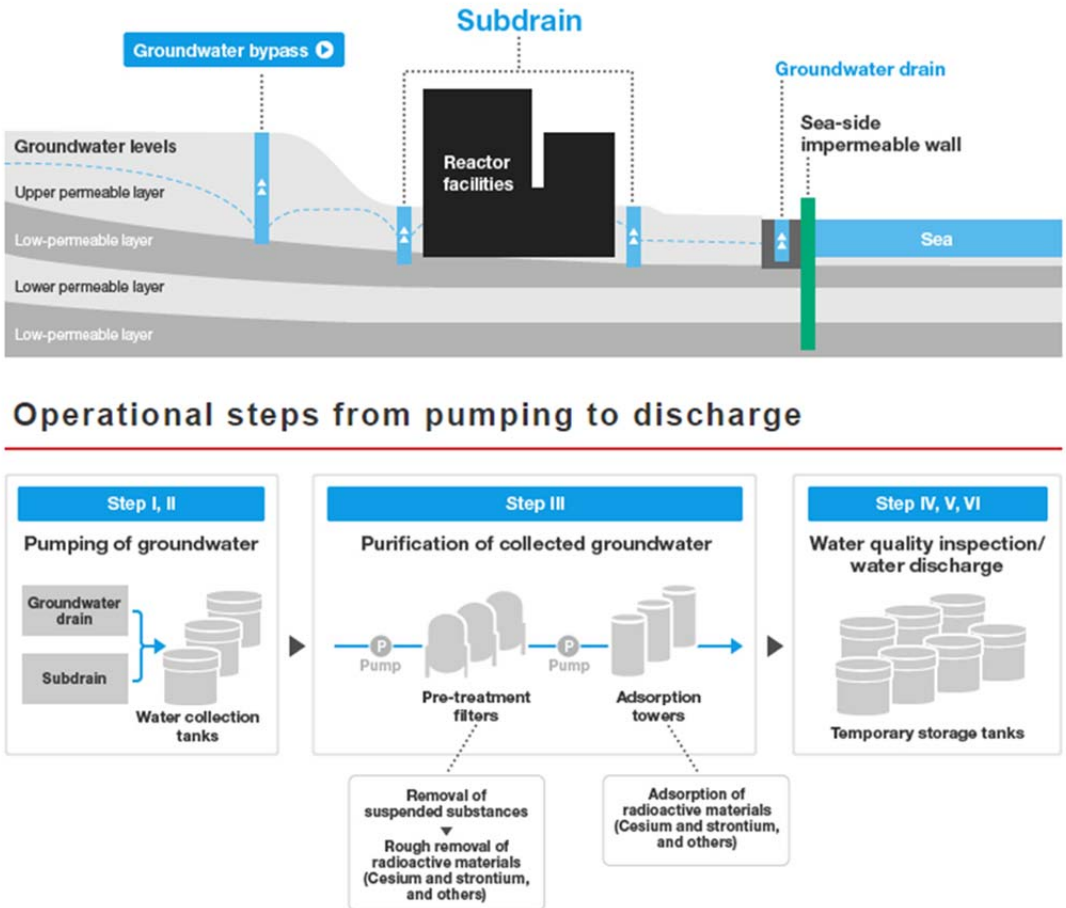
Figure 2. Key countermeasure activities related to active treatment of contaminated water

Process from Pumping up to Discharging



Process I	Pump up groundwater
Process II	Transfer the water to temporary storage tanks set in a controlled area to prevent airborne radioactive materials from entering the water.
Process III	Water quality inspection including by third parties will be conducted regularly.
Process IV	Discharge the water to the ocean after confirming that the level of contamination is below the drinking standard set by World Health Organization .

Figure 3. Groundwater bypass system



Step I	Groundwater pump-up by subdrain and groundwater drain
Step II	Water transfer to the collecting tanks
Step III	Water purification by the special system *1
Step IV	Water transfer to the temporary storage tanks
Step V	Water quality inspection *2
Step VI	Water discharge to the ocean *3

[NOTE]

*1: The special purification system has the ability to reduce the concentration of radioactive materials (except Tritium) to the extent of 1/1,000 to 1/ 10,000.

*2: The water quality will be confirmed by the third party organization to meet the regulatory notification density or the drinking water standard set by World Health Organization (WHO). The set standard is even more strict then that for Groundwater bypass.

*3: The purified water will be only discharged with the agreement of the relevant governments and local fishermen.

Figure 4. Depiction of the subdrain system, groundwater drain, and sea-side impermeable barrier with a description of the proposed plans for handling the water from these systems. The upgradient groundwater bypass system is also shown.

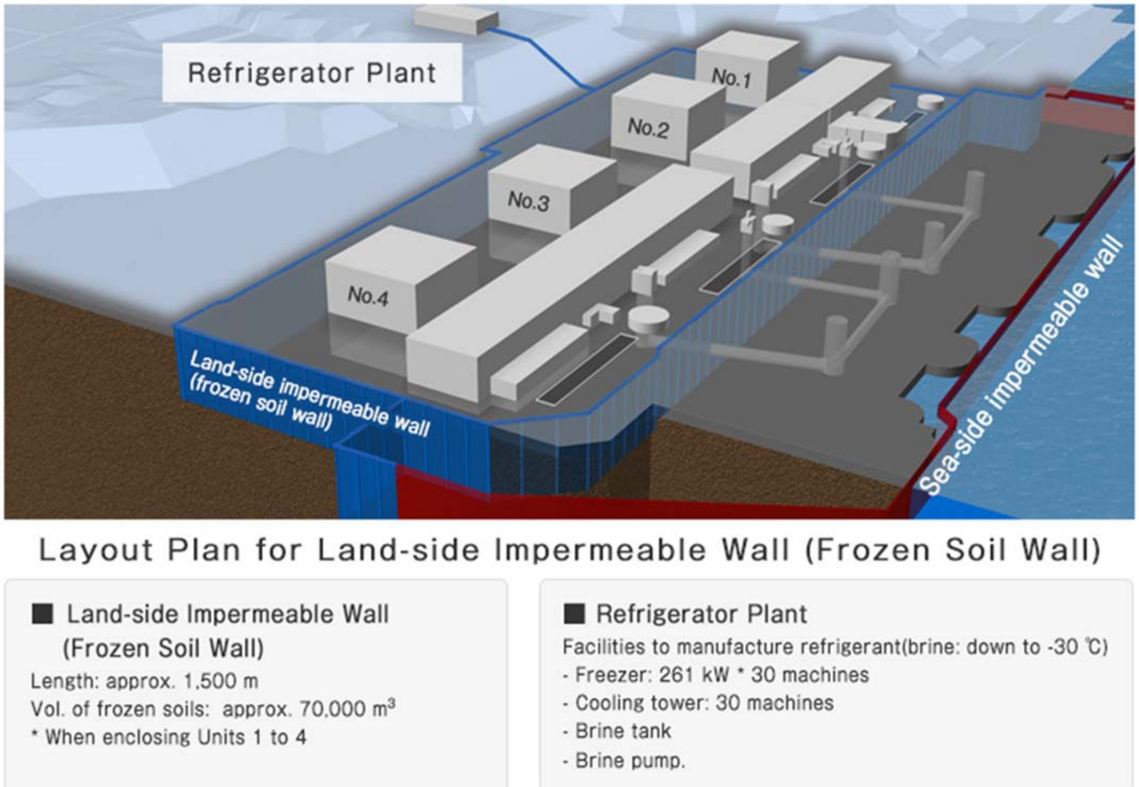


Figure 5. General diagram of frozen soil barrier

The TEPCO/Kajima team has prepared several graphics to describe the operational strategy for the frozen barrier (Figure 6). The first panel is a conceptual diagram depicting the planned steps for implementing the frozen soil barrier, a projection of the changes in groundwater levels, and key time periods that represent important stages of transition from current conditions to long term operation (baseline "existing state", after mountainside barrier closure, after seaside barrier closure, and during long term operation). Each of these periods is described sequentially in Figure 6. In each panel, the numerical groundwater modeling results (Dtransu-3D) depict a predicted water table configuration and the cross sectional sketch depicts the expected trends in water levels inside the barrier/building. These projections assume that related countermeasures, such as operation of the subdrain system are operational. If the related countermeasures are not in operation, then the projected impact and benefit of the frozen soil barrier would be reduced. This is discussed in more detail in the technical sections below.

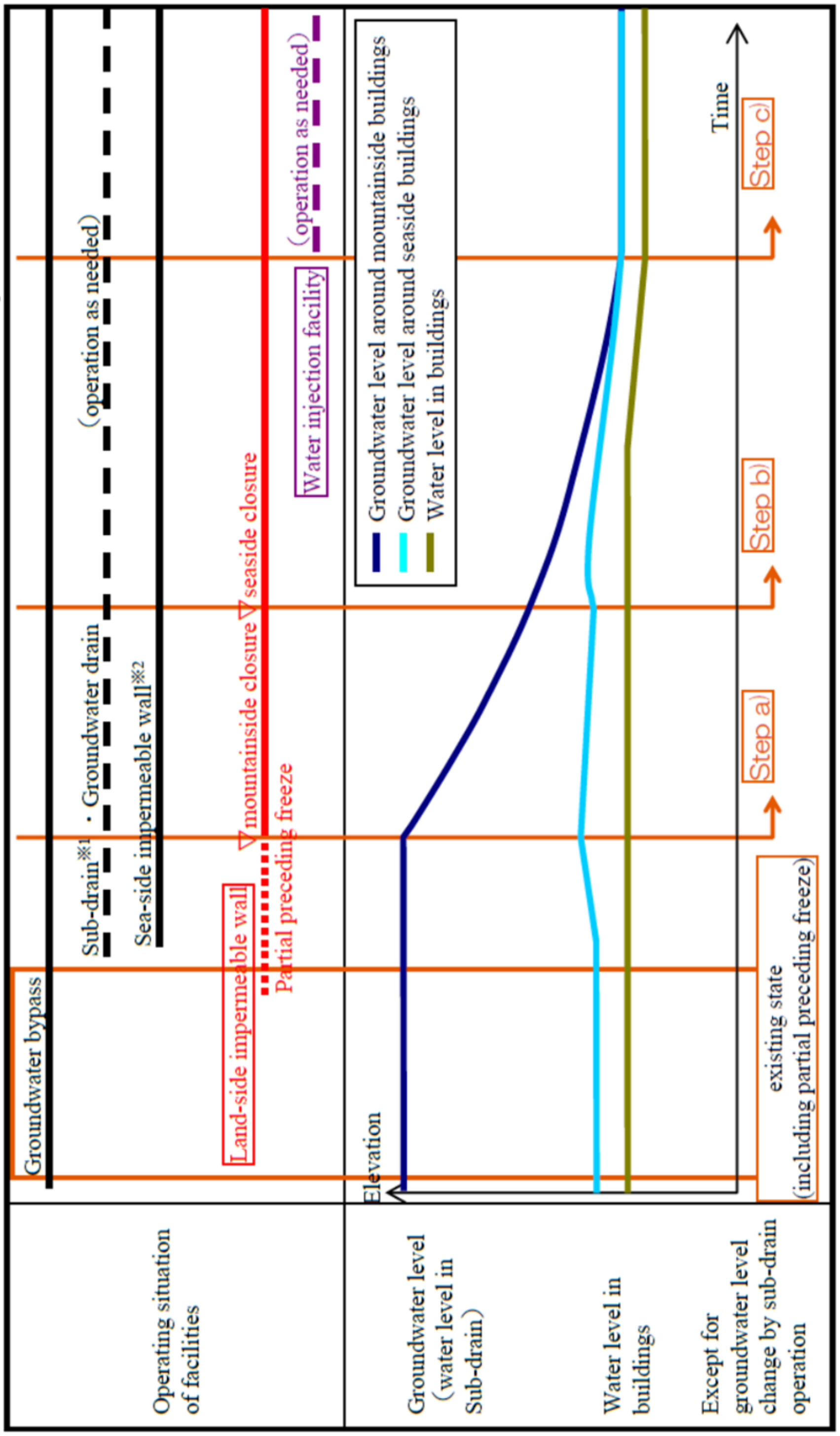
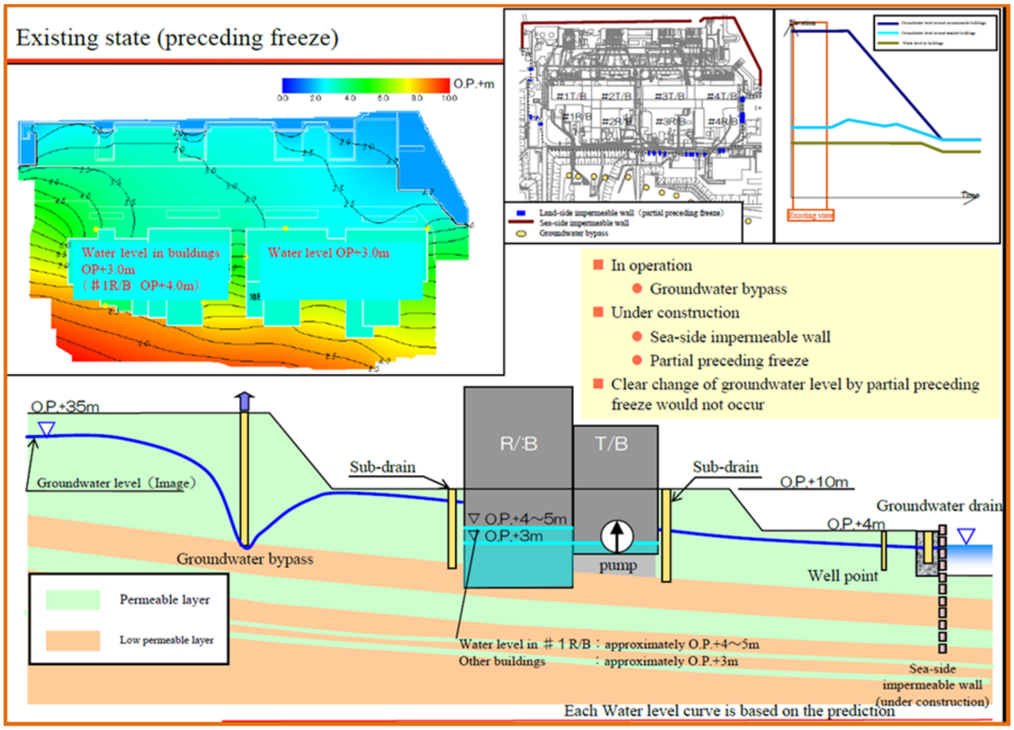


Figure 6. Detailed depiction of plan for installing the frozen soil barrier and projections of impacts on water levels in the subsurface and buildings



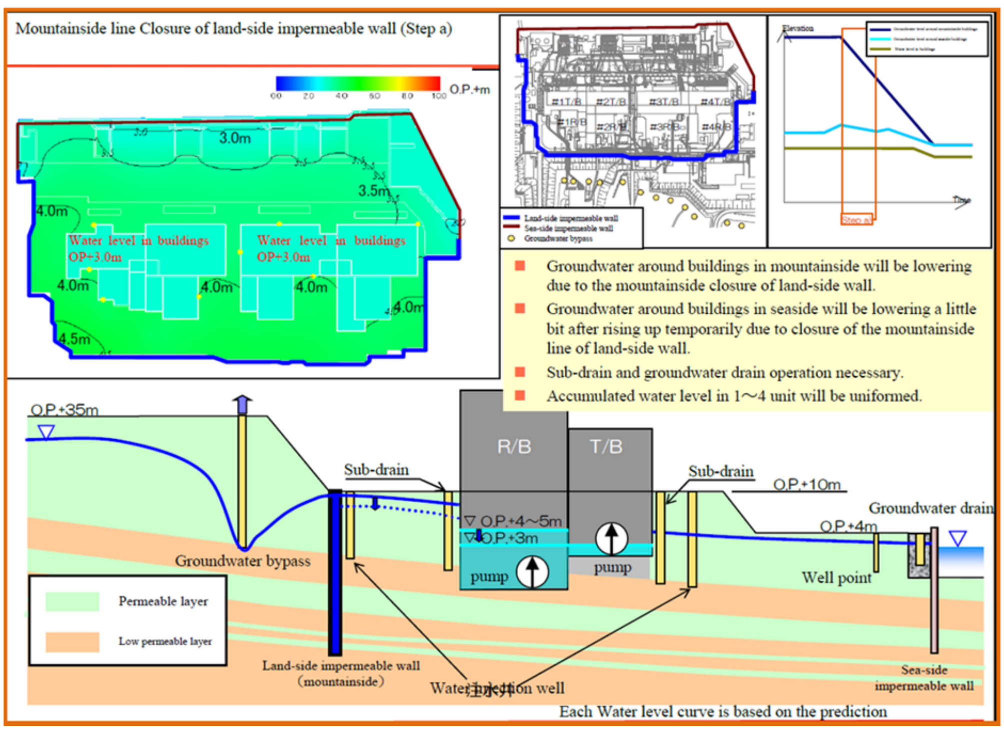
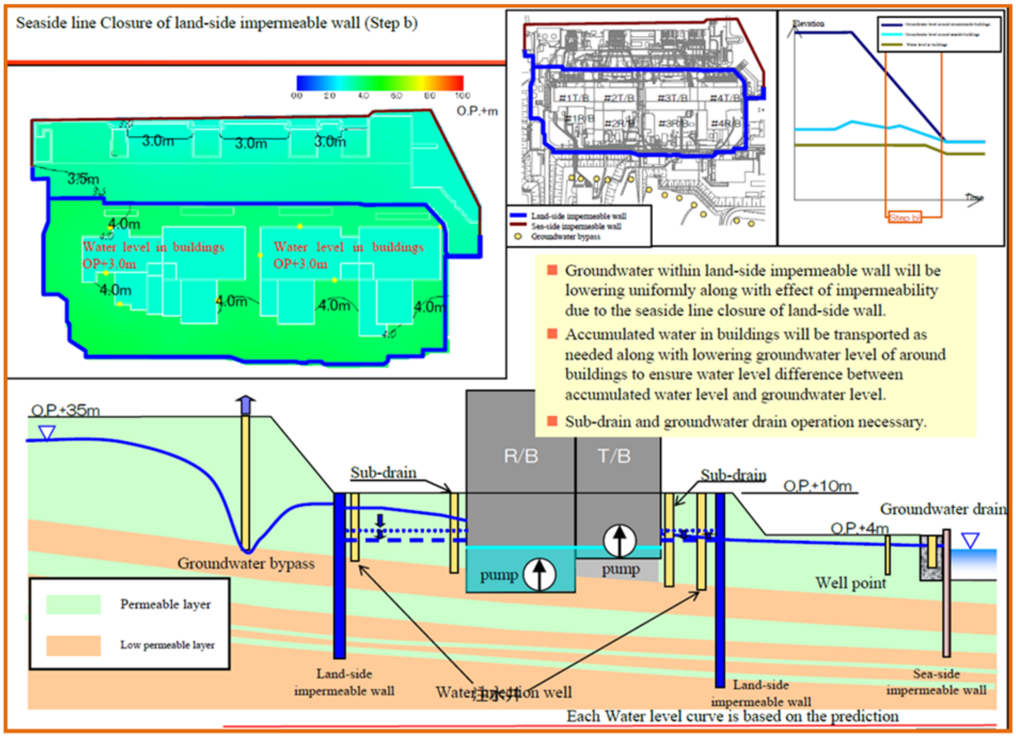


Figure 6 (continued). Detailed depiction of plan for installing the frozen soil barrier and projections of impacts on water levels in the subsurface and buildings



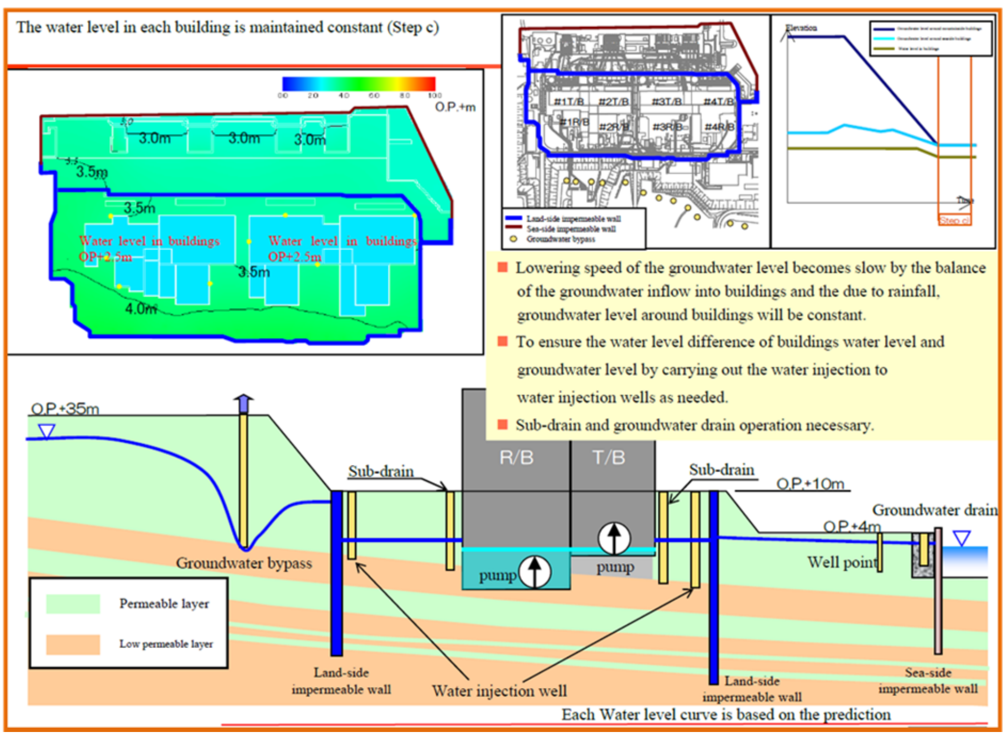


Figure 6 (continued). Detailed depiction of plan for installing the frozen soil barrier and projections of impacts on water levels in the subsurface and buildings

North American Applications of Artificial Ground Freezing in Engineering and Construction

Artificial ground freezing and frozen soil barriers have been used throughout the world to support a range of civil engineering and mining objectives. Civil engineering employs artificial ground freezing primarily for foundation stabilization and for structural support during construction, and for water control to support construction or environmental objectives. Mining engineers have employed artificial ground freezing for mine stabilization and water control. Artificial ground freezing applications rely on the basic principles of mechanical and thermal behavior of frozen soils and build on the historical literature on engineering in permafrost (Jessberger and Vyalov, 1979). In North America, frozen soil engineering has been a method of choice for tunneling and construction in urban areas, for some large mining operations in Canada, and for foundation stabilization in Alaska and Canada. A number of these projects provide relevant context for the frozen soil barrier at the Fukushima Daiichi Nuclear Power Station. In the following paragraphs, the various technologies used for artificial ground freezing are summarized, North American companies that specialize in application of artificial ground freezing are identified, and a few key case studies are summarized.

The three basic systems that have been employed for full scale artificial ground freezing are depicted in Figure 7. The most common system (Figure 7a) uses a primary refrigerant facility, a pumped secondary coolant loop, and zones of closely spaced freeze pipes in the target freeze volume. The secondary coolant is typically a concentrated calcium chloride ($CaCL_2$) solution, or brine, so these systems are often described as “brine systems”. A majority of the large scale artificial ground freezing applications use a brine system. A second type of ground freezing system uses an expendable refrigerant such as liquid nitrogen, liquid air, or solid/liquid carbon dioxide (Figure 7b). In this system, the expendable refrigerant is delivered to the freeze pipe. The refrigerant absorbs heat from the ground, evaporates (or sublimates), and the gases are vented. Because of the low boiling temperatures, expendable refrigerants are extremely effective for ground freezing. Small systems are simple to mobilize and require minimal on-site power. However, these systems are difficult to implement for large scale applications. Expendable refrigerants are often used for small short-duration projects (such as recovering a stuck tunneling machine under a river or emergency stabilization to protect a valuable structure). At the Fukushima Daiichi Nuclear Power Plant, expendable refrigerants represent a viable contingency for freezing high permeability heterogeneities (leaks) in the primary frozen soil barrier. Targeted use of expendable refrigerant systems would be a potentially cost effective alternative to bentonite injection. If granular dry ice is available on-site (for example if this material is already being used for dry ice blasting to support decontamination efforts at Fukushima) a relatively simple dry ice based expendable refrigerant system could be designed using an insulated hopper at the surface with gravity feed to a simple freeze pipe and vent. The third system that is used for commercial artificial ground freezing is the two-phase thermosiphon (Figure 7c). This system is partially filled with a liquid refrigerant (such as pressurized anhydrous ammonia, butane, carbon dioxide, or freons). The liquid boils at the bottom of the sealed themosiphon extracting heat from the ground. The vapor moves upward and, in cool climates, passively condenses in a finned section at the top of the casing (in warmer climates circulating chilled water or other fluid can be used in the surface heat exchanger to create a hybrid thermosiphon system). The primary application for thermosiphons is in cool climates to stabilize foundations; however the techniques has also been installed or proposed for large mining and environmental remediation projects in Canada. At appropriate sites, thermosihons can result in long-term energy savings.

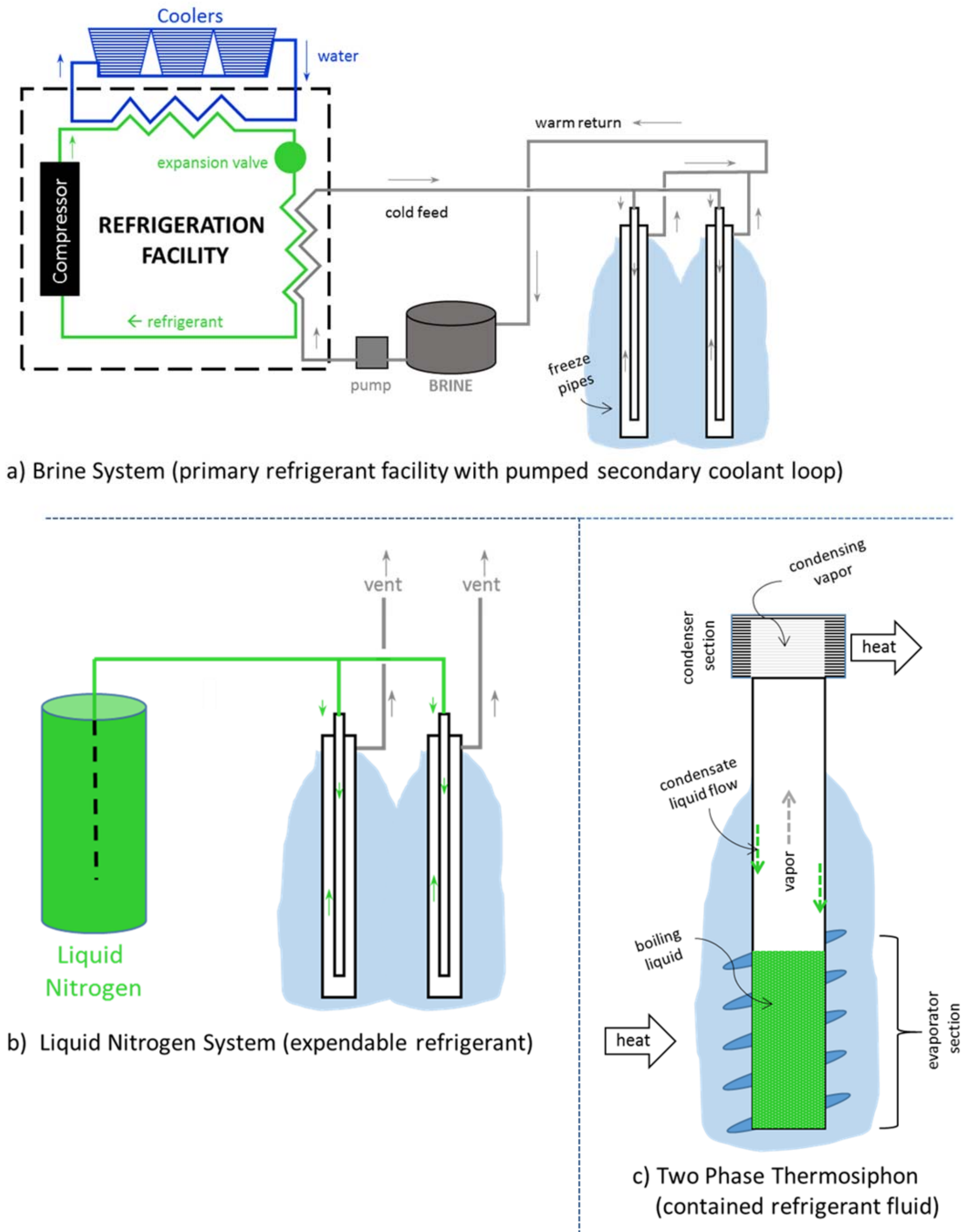


Figure 7. Three basic systems used for commercial artificial ground freezing projects

Based on the characteristics of the Fukushima Daiichi nuclear power station, the brine system that was selected by the TEPCO/Kajima team is appropriate and properly matched to the site specific conditions and engineering needs.

Figure 8 depicts additional detail related to the design of the freeze pipe assemblies and the brine circulation. Each freeze pipe assembly consists of an outer steel casing and an inner downpipe. The casing is typically constructed of steel and the downpipe can be constructed of steel or a polymer such as HDPE (supported under tension near the bottom of the downpipe). The chilled brine (≅ -30°C) feed is supplied from an insulated manifold through the downpipe. The brine then circulates up the freeze pipe – absorbing heat from the outer casing and surrounding ground. The warmer brine (≅ -25°C) exits the freeze pipe assembly into an insulated return manifold. On large scale applications, the return is sometimes installed using a "U" configuration (as shown) to help equalize flow to all of the freeze pipe assemblies within the zone (per Joe Sopko of MORETRENCH). Other manifold configurations are feasible.

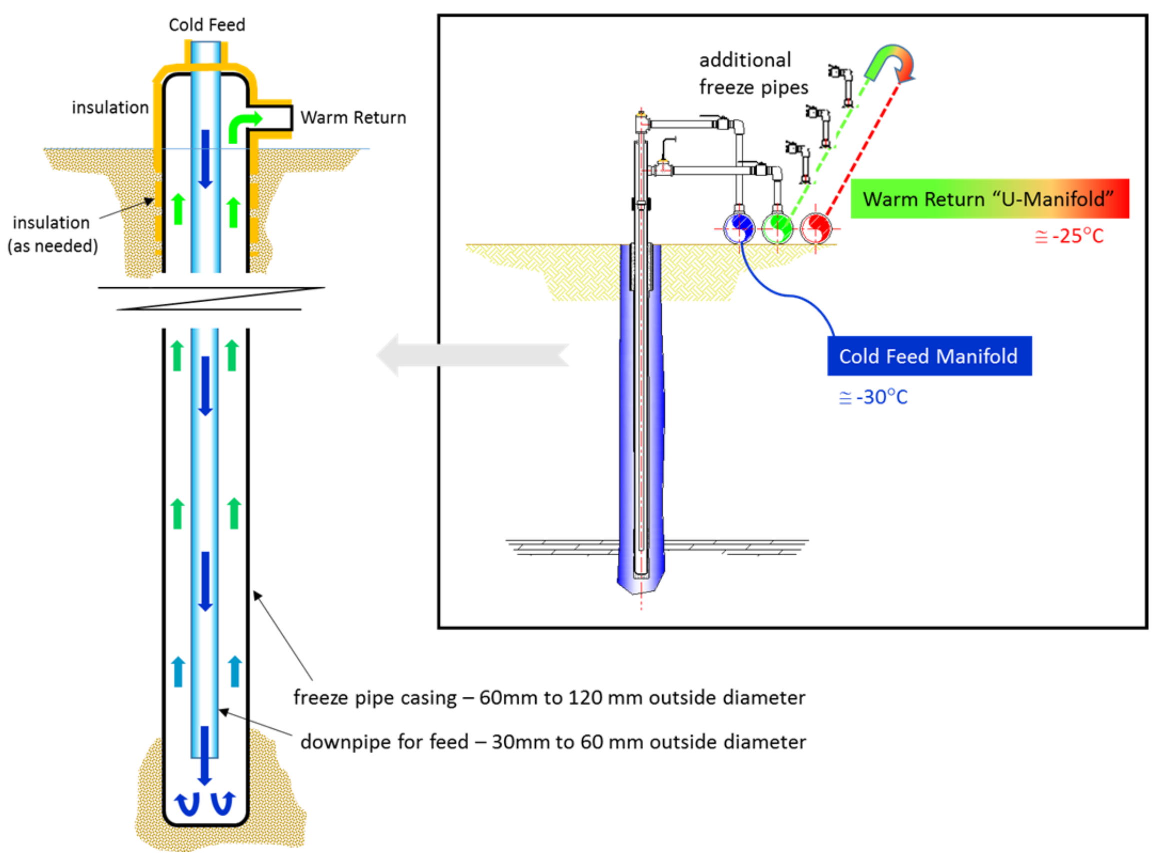


Figure 8. Typical freeze pipe deployment and configuration

Key points:

The frozen soil barrier at Fukushima represents one of the largest frozen soil barriers in the world, a major application for "long term" control of contaminated groundwater, and a unique use of the technology for a nuclear facility. Artificial ground freezing was originally developed in the late 1800s and has been in use for general engineering applications since the 1950s, however. The technology has been applied at hundreds of construction and mining sites throughout the world – including North America, Europe and Japan. The scale of the Fukushima barrier is bounded by industry experience and the equipment and infrastructure proposed for the ground freezing is well understood. The on-site pilot test at Fukushima indicated predictable ground freezing that supported the design parameters. All of these factors increase the confidence in the TEPCO/KAJIMA frozen soil barrier project.

There are three companies that currently provide the bulk of the artificial ground freezing design and installation services in North America (Table 1). The companies in the table are listed in order approximately by size (in terms of total ground freezing projects and services). Contact information for each company is provided. The third column in Table 1 is a narrative for each company that provides some information on their specialization(s). The final column lists one or two example case studies from each company that are relevant to the frozen soil barrier at Fukushima. Two of the listed companies, MORETRENCH and SoilFreeze, use brine systems for most large ground freezing projects. Based on the survey data collected, SoilFreeze uses a Freon-based refrigerant in their primary cooling loop. For improved efficiency in large projects, MORETRENCH uses ammonia-based primary refrigeration facilities. Either system should provide reasonable performance as long as the cold brine feed temperatures, system load, and warm brine feed criteria are satisfied. Arctic Foundations specializes in applications of the thermosiphon technology. Example case studies from the companies are summarized below.

MORETRENCH

The National Laboratory team selected two case studies from MORTRENCH: the Aquarius Open Pit Mine (Timmins Ontario Canada) and the No. 7 Line Subway Extension (New York NY USA), for discussion as examples relevant to Fukushima. The objective of the frozen soil barrier at the Aquarius Open Pit Mine (Figure 9) was to limit groundwater intrusion and stabilize the walls of a large open-pit mine. The mine is located in permeable water bearing sands and the frozen soil barrier technology was selected for this application because: a) water table lowering was not permitted, b) site located in a Provincial Park with several lakes, c) residential wells exist near mine site, and d) freezing determined to be acceptable to wildlife. As shown in Figure 9a, the scale of the Aquarius frozen soil barrier (4 km perimeter and 40 to 150 m depth) is similar in scale to the Fukushima barrier (though somewhat larger) and the barrier utilizes a similar brine circulation design to that being used at Fukushima.

Table 1. Major North American Companies that Provide Artificial Ground Freezing Design and Installation Services

Company	Contact	Description	Key Case Studies
MORETRENCH	Joe Sopko 100 Stickle Ave Rockaway NJ 07866 USA (973) 627-2100 or (920) 889-0190	Largest North American supplier of artificial ground freezing design and installation services. MORETRNCH deploys brine systems for most large jobs and liquid nitrogen systems for small jobs and emergencies. Ground freezing is core MORETRENCH competency that is used in combination with related geotechnical engineering activities such as slurry walls, excavation, tunneling, etc. The focus of ground freezing work is construction and mining. Most projects involve urban tunneling, water control, and stabilization of excavations during construction or mining. MORETRENCH has performed over 50 artificial ground freezing projects including many large projects relevant to the scale of the Fukushima frozen Soil Barrier. (groundfreezing.net or www.moretrench.com)	Aquarius Open Pit Mine, Timmins Ontario Canada No. 7 Line Subway Extension, New York NY USA
Arctic Foundations	Ed Yarmak 5621 Arctic Blvd, Anchorage Alaska 99518 USA (907) 562-2741	Major North American supplier of artificial ground freezing using the Thermosiphon technology. Primary company focus is foundation stabilization/protection in cold climates. Arctic Foundations has performed over 900 installation (mostly small) but has supported larger scale mining projects (relevant to Fukushima) in Alaska and through their affiliates in Canada. Arctic Foundations performed a pilot test of artificial ground freezing for the Department of Energy at the Oak Ridge Site using hybrid thermosiphons. (www.arcticfoundations.com)	Long- term management of arsenic trioxide contamination at the Giant Mine, Yellowknife Northern Territory Canada
Soil Freeze	Daniel Applegate 2825 Eastlake Ave East, Suite 230, Seattle WA 98102 USA (206) 420-2759	Major North American Supplier of ground freezing, primarily using brine systems. Primary company focus is teaming with others to provide soil freezing design and installation services for integration into construction and mining projects. SoilFreeze has performed a many projects including a large scale project (relevant to Fukushima) that currently underway in Seattle. (http://www.soilfreeze.com)	Elliott Bay Seawall Project Waterfront Refurbishment, Seattle WA USA

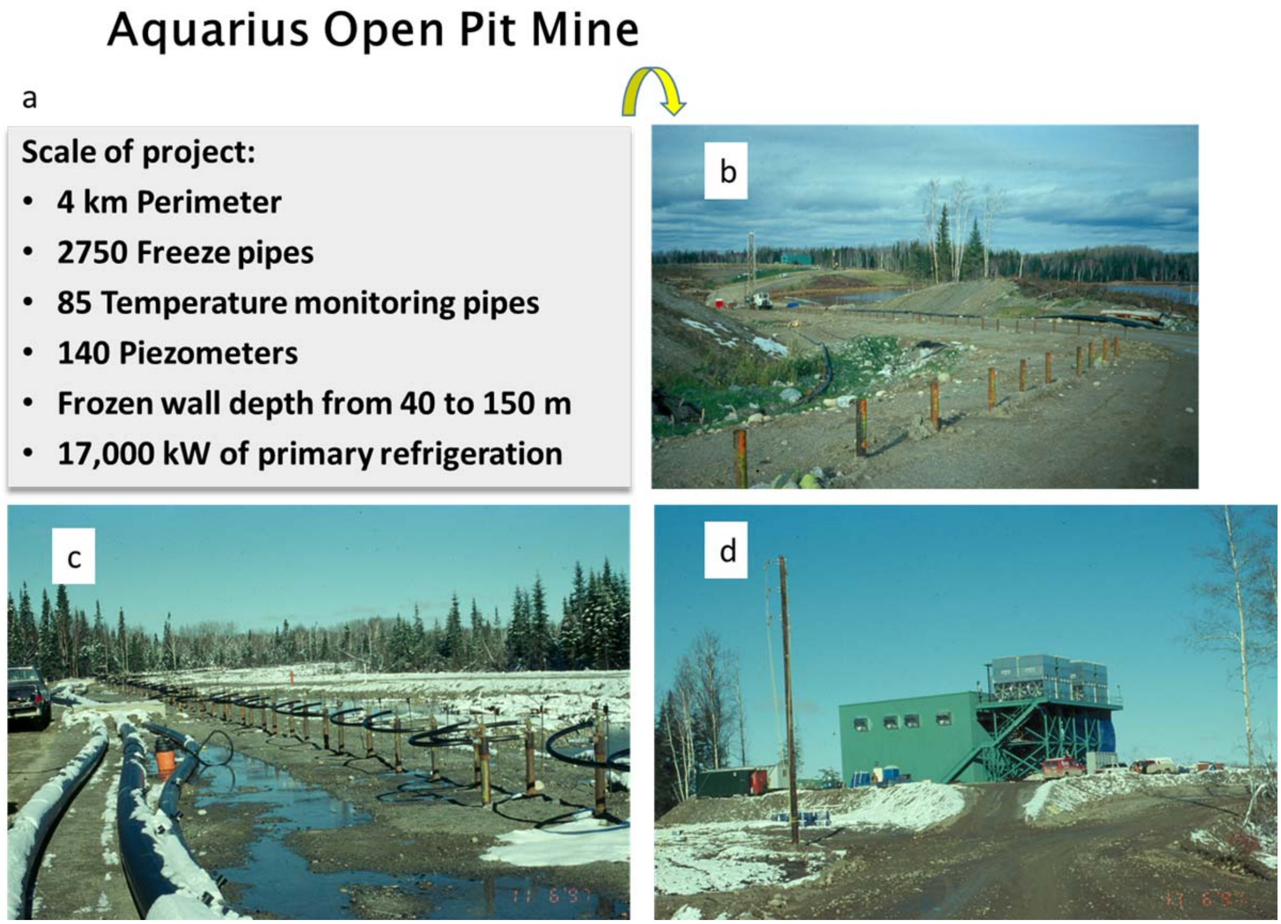


Figure 9. Example of ground freezing to support mining (open pit excavation) and protection of groundwater

Figure 9b and 9c show example photographs of the freeze pipes and brine distribution piping. Figure 9d shows the South Plant, one of the two primary refrigeration facilities. Modules that use ammonia as the refrigerant in the primary loop are used in both facilities and the total refrigeration capacity of the constructed system is approximately 17,000 kW. The system was completed and tested, but is currently in standby because the price of the target minerals collapsed on the international market and the lower price does not support mining and processing operations at Aquarius.

Aquarius is an important case study relevant to Fukushima because the system demonstrates design and construction of a similar large system. This system was constructed in a remote area, however, so a supplemental MORETRENCH case study is described below.

The second MORETRECH case study, the No. 7 Line Subway Extension (Figure 10), demonstrates the suitability of frozen barriers in crowded areas with limitations on access and the presence of underground interferences. The objective of this project was ground freezing to support boring a large underground tunnel beneath an urban area. Figure 10a shown an area being used for the ground freezing access and equipment (yellow oval) between a busy roadway and adjacent buildings and shows an angle rotosonic boring machine installing a freeze pipe. Figure 10b shows the intricacy of the required freeze pipe installation. The closely spaced boreholes are being installed at an angle to access areas under the roadway and buildings. Each borehole is carefully surveyed to assure the quality of the freezing process. Figure 10c depicts a small area with underground utilities (water, telephone, electrical and fiberoptic) and with over 100 boreholes. In the last panel, Figure 10d, area are highlighted in yellow were the freeze pipe material is transitioned to aluminum so that the large tunnel boring machine can cut through the freeze pipes during construction of the shaft. The No. 7 Line Subway Extension in one of many MORETRENCH case studies related to large ground freezing in urban or industrial settings.

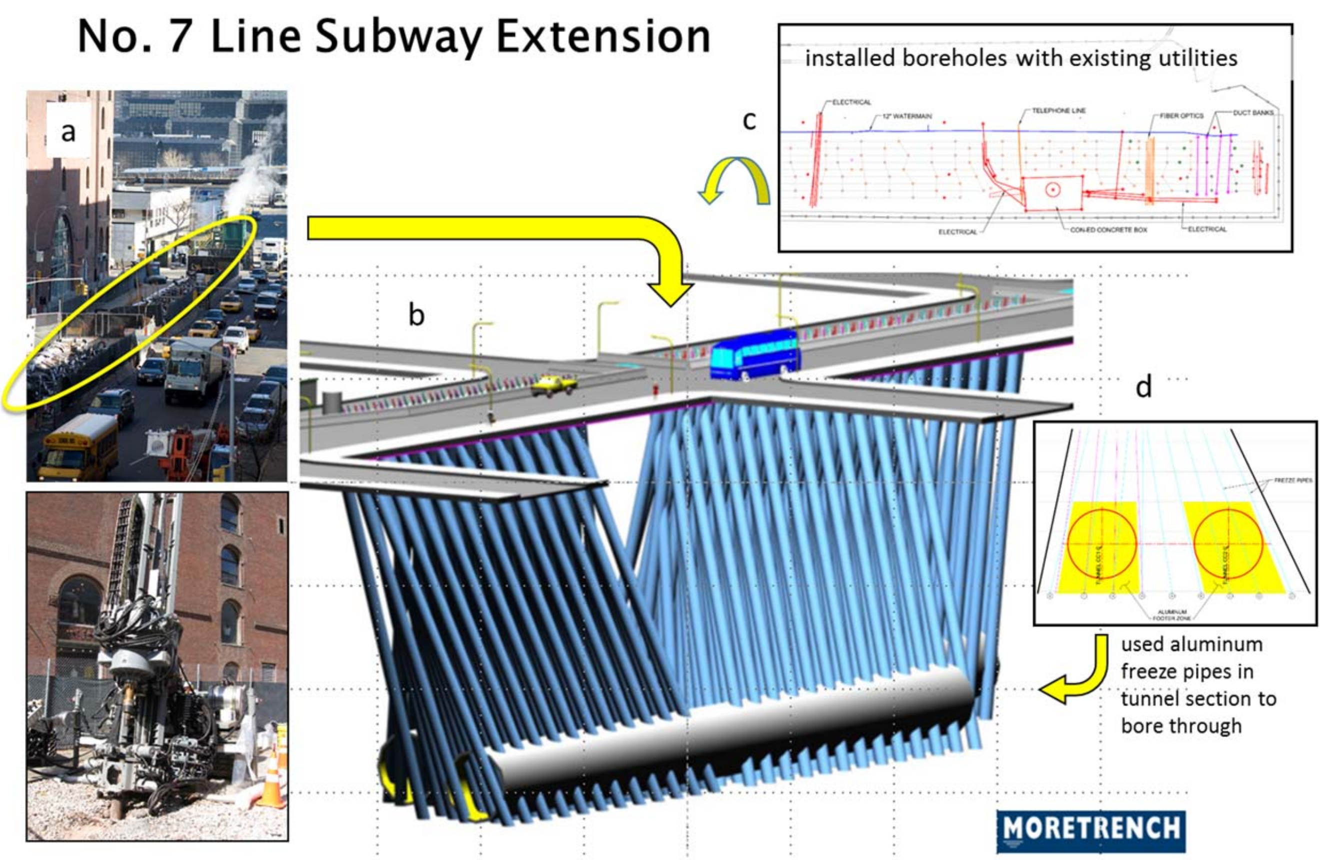


Figure 10. Example of ground freezing to support large tunnel boring operations in an urban area

Arctic Foundations

The most relevant case study for Arctic Foundations is a project for long- term management of arsenic trioxide contamination at the Giant Mine Figure 11. Gold ore at Giant Mine is associated with the mineral arsenopyrite (FeAsS) and processing the ore produced large quantities (over 100,000 metric tonnes) of arsenic trioxide dust. This fine dust was stored in vast underground chambers that failed and are releasing arsenic into the groundwater and the air. A Frozen Block Method was selected for the long-term management of the arsenic trioxide dust at Giant Mine after extensive research and peer review with industry experts, and in consultation with local residents. As shown in the panels in Figure 11, the plan is to entirely freeze the arsenic trioxide dust chambers. Freeze pipes will be installed beneath and around all of the chambers. Because of the cold climate, the thermosipon technology was selected as a baseline technology (since minimal energy will be needed to maintain the frozen blocks after thay are formed). The thermosiphons are being tested and deployed in parallel with a standard brine system. This allows a more rapid freezing and with a transition to the long term benefits of the thermosiphons. Several of the chambers will require freeze depths greater than 100m. The total cost of the freezing is projected to be between $200 million and $900 million and the project timeframe is 10 to 20 years. Based on ongoing pilot testing, the project team concluded: a) the ground is freezing faster than predicted, b) both active freezing with the brine system and the thermosiphon (hybrid freezing) system are working well, c) the data support further engineering analyses and design, and d) the freeze optimization study has demonstrated that proposed frozen block method will work.

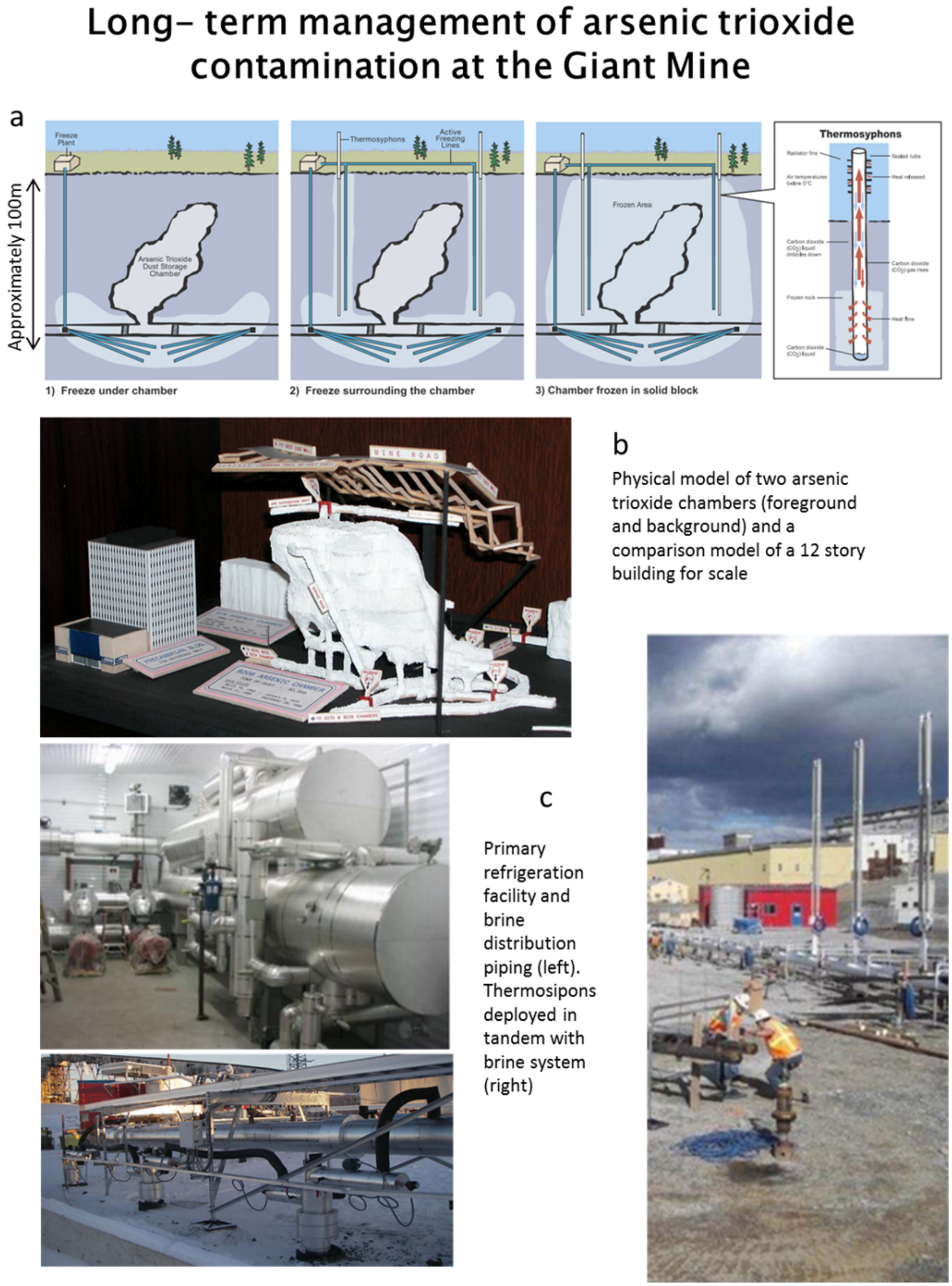


Figure 11. Example of ground freezing for control of subsurface contamination and groundwater

SoilFreeze

SoilFreeze is currently supporting the Elliott Bay Seawall Project Waterfront Refurbishment (Figure 12). The overall objective of this project is to rebuild and upgrade the existing seawall (originally constructed between 1916 and 1936). The upgraded seawall project is intended to improve protection of landside structures, provide additional pedestrian and shopping areas, allow installation of state of the art utility services (such as new fiber optic cables), and provide additional services to harbor vessels. The ground freezing was added to this project to control the infiltration of water from the seaside harbor and to stabilize the ground to avoid any possibility of damage to the important Alaska Way Viaduct (a multilevel automobile highway immediately adjacent to the construction) – Figure 12a. The frozen soil barrier total length is approximately 1 km and it is being constructed in 10 sections (Figure 12b). The sections will be frozen sequentially to support multiple construction seasons -- all of the sections do not need to be frozen at the same time. SoilFreeze is using modular Freon-based (HFC 507) units for the primary refrigeration – where possible, units will be moved and re-used for subsequent sections of the barrier. The barrier depth is approximately 10m and the surface completions for the freeze pipes include both below grade and above grade types – depending on the location and access requirements (Figure 12c). These requirements are similar to Fukushima. A number of underground interferences are anticipated and SoilFreeze has developed angle drilling strategies for a number of anticipated scenarios (Figure 12d). The Elliott Bay Seawall Project is another example of a frozen soil barrier installation in an urban or industrial setting with a similar scale to the Fukushima Barrier.

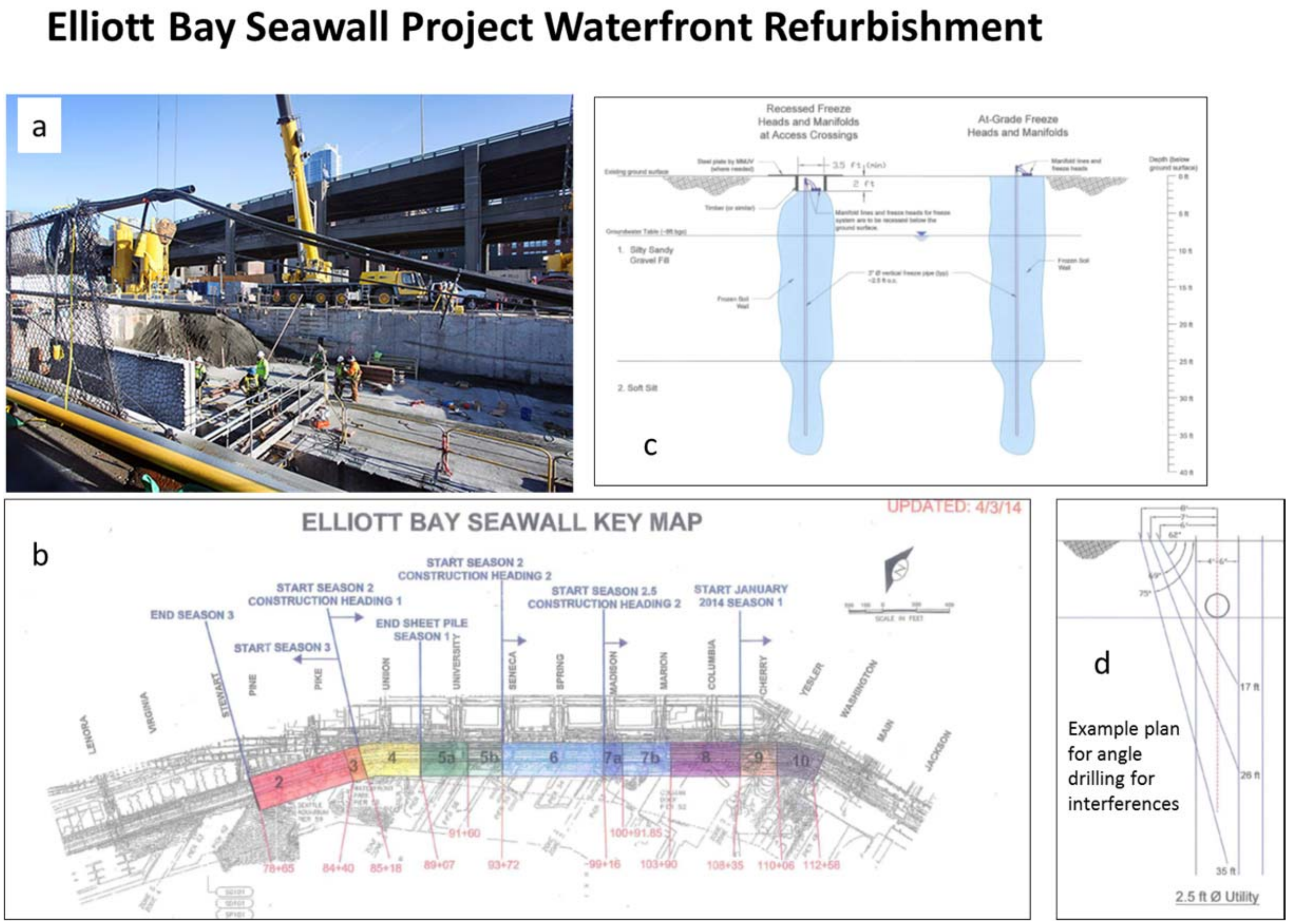


Figure 12. Example of ground freezing for control of water and soil stabilization in an urban area near a freeway

<u>Summary of North American Applications</u>

Artificial ground freezing is used in construction and mining and for various civil and environmental engineering applications. Artificial ground freezing was first documented in the late 1800s and been in engineering use since the 1950s. The technology has a long history of application and scientific support studies. Artificial ground freezing has been specifically used for foundation stabilization, water control, and to provide mechanical stability to soil to allow safe excavation or tunneling. Artificial ground freezing is relatively expensive, but the technology provides unique capabilities and advantages that can justify its use. The Fukushima frozen soil barrier is generally bounded in scale and installation complexity by some of the large past commercial applications.

Barrier Geometry

Barrier Design to Assure Freeze Wall Closure

Groundwater Movement

The velocity of the groundwater is a key factor in artificial ground freezing system design. If the groundwater flow rate is too fast, then it is difficult or infeasible to attain wall closure, wherein the frozen bodies of adjacent freeze pipes merge together to form a wall. When using a brine-based cooling system for an artificial ground freezing application, the maximum suitable groundwater velocity noted in the literature ranges from 1 to 3 m/d, with 2 m/d being the most commonly cited upper limit (Roworth, 2013; Green et al., 2014; Schmall et al., 2007; Sayles and Iskandar, 1995; Powers et al., 2007; Tsang et al., 2012; Bell, 1992). A high groundwater velocity can be dealt with by using liquid nitrogen (at least as coolant for the initial freeze wall formation), using closer freeze pipe spacing, using multiple rows of freeze pipe, reducing formation permeability/velocity (e.g., with grout injections), or by controlled upgradient pumping to alter the hydraulic gradient (Green et al., 2014; Schmall et al., 2007; Roworth, 2013; Powers et al., 2007; Bell, 1992). In addition to groundwater flow issues relevant to the initial formation of the freeze wall, a design needs to consider thermal erosion of the frozen body due to advective groundwater movement and the heat input associated with that groundwater.

Several studies have looked at the impacts of groundwater flow velocity on freeze wall closure. Ziegler et al. (2009) present a modelling investigation of freeze wall closure and the operational approaches to facilitate closure at higher groundwater velocities. Schmall et al. (2007) describe the issues with freeze-wall closure when groundwater movement is significant and use several case studies to describe situations of concern and the actions taken to deal with the groundwater movement. Pimentel et al. (2012) use numerical simulations to interpret monitoring data for three case studies and assess issues with freeze wall closure pertaining to high groundwater velocity and freeze pipe borehole deviations. Deviation of freeze pipe installations from vertical (or horizontal) by more than 1-2% of the boring length can result in zones more susceptible to failure to achieve closure (Bell, 1992; Pimentel, 2012; Powers, 2007), which would be exacerbated at higher groundwater flow velocities. GEO-Slope International provides a white paper with an example looking at groundwater flow around a freeze pipe for their TEMP/W and SEEP/W software to investigate how the groundwater flow (and associated convective heat transfer) can impact freeze wall closure.

Assessing Site-Specific Groundwater Flow

If groundwater flow is too fast, the freeze pipes will not provide sufficient cooling for the frozen ground to merge in the zone between adjacent freeze pipes. Sanger and Sayles (1979) developed a simplified approach that is useful for scoping design of frozen ground barriers. This type of analysis compares the actual groundwater flow rate (the field groundwater Darcy velocity[1] -- u_f in m/day) to a calculated critical Darcy velocity (u_c in m/day). The simplified approach is useful for confirming the design calculations

[1] In this section, the key design parameter of interest with respect to groundwater movement is the so-called Darcy "velocity." The Darcy velocity is more properly called specific discharge or groundwater flux because it represents the flow of groundwater divided by the total cross sectional area orthogonal to the direction of flow (hence the units are $m^3/[m^2 \cdot day]$). For example, a groundwater discharge of 0.5 m^3/day through a 1 m^2 area is equal to a Darcy velocity of 0.5 m/day. The Darcy velocity is relevant to the discussion of ground freezing because the volume of groundwater passing through a unit area per unit time represents a refrigeration heat load that must be addressed in the design. The use of the Darcy velocity here for heat load considerations differs from calculating solute transport in porous media, which uses the average linear velocity (also called pore velocity or seepage velocity). The average linear velocity is equal to the Darcy velocity divided by the effective porosity and has a magnitude greater than the Darcy velocity. Tracer tests provide information about the average linear velocity, which would require conversion to a flux basis for use in ground freezing design.

and numerical models used by Kajima. For an adequate design, u_f should be less than u_c. The equation for determining the critical Darcy velocity that will limit successful merging of a frozen barrier is a function of the freeze pipe spacing, diameter and temperature, the frozen soil thermal conductivity, and the ambient groundwater temperature (Sanger and Sayles, 1979; Andersland and Ladanyi, 2004):

$$u_c = \frac{k_f}{4S\ln\left(\frac{S}{4r_p}\right)} \frac{T_f - T_p}{T_g - T_f}$$

u_c = critical Darcy velocity for freeze wall closure (m/day)
k_f = frozen soil thermal conductivity (W/[m·°C])
S = freeze pipe spacing (m)
r_p = radius of freeze pipe (m)
T_f = freezing point of water (°C)
T_p = temperature of freeze pipe surface (°C)
T_g = temperature of ambient groundwater (°C)

Frozen soil thermal conductivity, k_f, for sandy materials is typically in the range of 3 to 4 W/[m·°C] (Andersland and Ladanyi, 2004). Therefore, an approximate criterion for critical groundwater Darcy velocity that would limit freeze wall closure in sandy material (assuming S = 1 m, r_p = 0.076 m, T_g = 19 °C, T_f = -1 °C, and T_p = -25 °C) is approximately: **$u_c \cong$ 0.76 to 1.0 m/day**. Note that this equation does not contain any parameters related to time and barrier closure for groundwater velocities near u_c would require an extended timeframe to achieve. Numerical modeling with software such as TEMP/W SEEP/W and practical experience (from interviews with Joe Sopko of MORETRENCH) suggest that field groundwater flowrates that are ≤ half of the calculated u_c are needed if the desired freezing time is two months or less. At groundwater flowrates approaching the theoretical u_c, the numerical models indicate that frozen soil barrier closure will take longer (e.g., three months to one year).

Available hydrologic data for Fukushima groundwater suggest that the nominal groundwater flow rates are significantly lower than the critical value calculated above. The available hydraulic conductivity (K) data for the relatively permeable upper "medium-grained sandstone" portion of the Tomioka Stratum (an unconfined aquifer) part of this formation range from 0.0021 to 0.0041 cm/sec (1.81 to 3.54 m/day), while the underlying-interbedded "muddy" portion has a measured hydraulic conductivity that is significantly lower -- approximately 10^{-6} cm/sec (0.00086 m/day). The measured horizontal hydraulic gradient (change in hydraulic head per distance along the flowpath, $\Delta h/\Delta L$) in the medium-grained sandstone aquifer is approximately 0.02 to 0.04. The nominal field derived Darcy velocity is would be calculated by multiplying the hydraulic conductivity and the hydraulic gradient: $u_f = (K)(\Delta h/\Delta L)$. For the medium grained sandstone portion of the aquifer, the field derived Darcy velocity is range would be approximately: **u_f = 0.04 to 0.14 m/day**, which is significantly below the lower bound of 0.76 m/day for the critical Darcy velocity and is in the range for barrier closure in a reasonable timeframe. Thus, the only areas of potential concern with respect to freeze wall closure would be heterogeneities, such as coarse sand and gravel lenses, which exhibit localized high groundwater flow rates. Such heterogeneities are not widely observed in the cores collected from the upper sands and muddy materials in the unconfined aquifer in the vicinity of the Fukushima Frozen Barrier.

Since $\boldsymbol{u_c} >> \boldsymbol{u_f}$, the spacing of the freeze pipes and the proposed frozen barrier design appear appropriate. This general conclusion for the upper sandstone part of the aquifer at Fukushima was demonstrated during an onsite pilot test in which the frozen soil zones around the freeze pipes successfully merged, with no indication of problematic heterogeneities. The presence of localized or unanticipated high permeability zones would be best determined though: a) evaluation of core collected from borings in the vicinity of the barrier, and b) monitoring activities – specifically, the measurement of water levels, water temperatures, and the possible application of geophysics, tracer tests, and/or hydraulic (pump) tests. If an area is identified where the barrier is not adequately closing, there are several possible contingencies. These contingencies relate to the controllable parameters in the two scoping equations – the field Darcy velocity equation [hydraulic conductivity (K) and hydraulic gradient ($\Delta h/\Delta L$)] and the frozen barrier design equation [freeze pipe spacing (S), temperature of ambient groundwater (T_g), and temperature of freeze pipe surface (T_p)]. Potential contingencies and the target parameter being modified include the following:

a. Allow additional time for the frozen soil barrier to close (allow the transient process continue to completion)
b. Inject bentonite clay, grout or colloidal silica ("water glass") in any significant highly permeable target interval (decrease K to reduce the field darcy velocity in the underperforming layer)
c. Increase pumping on upgradient bypass wells (reduce hydraulic gradient ($^{\Delta h}/_{\Delta L}$) to reduce field darcy velocity u_f)
d. Install additional freeze pipes in the underperforming portion of the barrier (reduce S to increase the critical darcy velocity u_c)
e. Install additional upgradient freeze pipes in the underperforming portion of the barrier (reduce T_g to increase the critical darcy velocity u_c)
f. Reduce the temperature of the circulating brine by increasing refrigeration capacity and/or adjusting control setpoints (reduce T_p to increase the critical darcy velocity u_c)
g. Install supplemental freeze pipes and supplemental freeze capacity in targeted location(s) using liquid nitrogen or granular dry ice. (reduce S and/or T_p)
h. Insulate or add separate cooling capacity to barrier penetrations that are causing leaks due to heat conduction

Key points:

Based on standard engineering calculations and the nominal soil and groundwater conditions, frozen soil resulting from the individual freeze pipes at Fukushima is expected to adequately merge into a continuous frozen barrier in a reasonable timeframe. In the unlikely condition where an isolated zone does not freeze, there are a number of relatively low cost contingency actions.

When considering the potential need for any of the listed contingencies a more detailed examination of site specific geology is warranted to identify the areas of highest risk and areas that warrant more focused monitoring. Figure 13 is a map showing the available boreholes. Based on examination of the borehole core descriptions and photographs:

The lithology in the upgradient (mountainside) borings is relatively consistent, with sandy material, mixed material and clayey material represented in sequence. There is minimal presence of gravel or similar high permeability strata in the unconfined upper aquifer zone along the upgradient portion of the barrier. Based on the lithology, barrier formation and merging should proceed with minimal risk along the upgradient and sidegradient legs of the Fukushima Frozen Barrier.

The lithology of the downgradient borings is more variable. Notably, strata that contain significant quantities of gravel are present in borings Fz-4 and Fz-5. Smaller amounts of gravel are also present in the other boreholes along the downgradient leg of the barrier. The silt and clay material underlying the upper aquifer zone is less prevalent in the downgradient borings compared to the upgradient borings. In terms of barrier formation and merging, the highest risk of complications would be in the area around borings Fz-4 and Fz-5 near the end of the barrier. Based on the lithology, it would be prudent to monitor the designated area during barrier installation. Note that the problematic area is on the downgradient wall of the barrier – this is a favorable scenario. The freezing of the upgradient wall of the barrier is expected to reduce the hydraulic gradient and reduce the groundwater flow (Darcy velocity) moving toward the downgradient barrier. As discussed above, reduced water flow would aid in successful merging of the downgradient barrier—even in areas where gravel strata are present. The presence of relatively thin (e.g., 1m thick) high-permeability zones would most likely manifest in the form of a discrete interval where the freeze wall thickness is reduced or deformed. As described below, these effects are documented in the literature for barriers installed in layered sediments in which high permeability lenses are present.

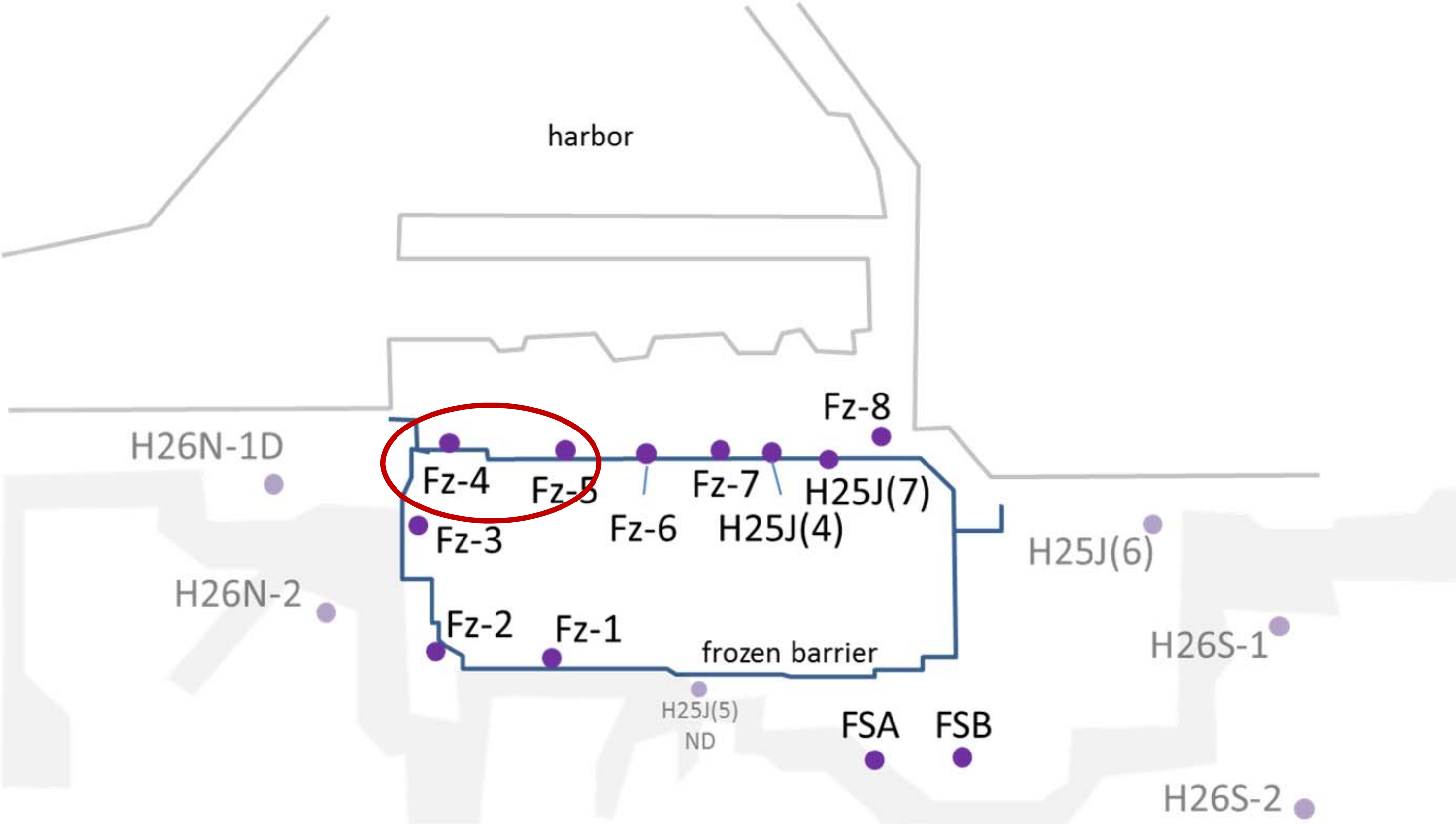


Figure 13. Boreholes in the vicinity of the Fukushima Frozen Barrier.

Barrier Geometry and Implications

The geometry of the ice formed around each freeze pipe and the resulting composite geometry of the frozen barrier are important to the conceptual model of the process and developing optimized monitoring strategies. The following evaluation is structured to document the geometry for a homogenous system and then describe the impacts of heterogeneities.

For an individual freeze pipe in a homogeneous medium-grained sand (Figure 14), the frozen soil volume will form in the shape of a modified cylinder that is distended at the base and smaller at the top. This bulb shape results from a number of physical constraints (such as the water table) and dynamic processes at the ice surface (such as heat transfer and density driven flow). A profile of the temperature of the barrier is depicted on the inset graph. The temperature increases from the freeze pipe surface (T_p) outward to the ice-water interface which is approximately at the freezing point of the groundwater (T_f). Outside the interface, the temperature increases to that of ambient groundwater (T_g). This temperature profile has important ramifications that impact interfacial processes; some of the key processes at the ice-water interface are depicted in the inset diagram. The ice interface undergoes dynamic-progressive freezing and thawing. The frozen soil zone will continue to grow until the rates of freezing and thawing equilibrate. Since the maximum density of water occurs near 4°C, a boundary layer is created that continuously moves water downward the interface. This downward movement of water is one of the reasons that the base of the cylinder is distended. After an extended period of time, the middle and upper middle portions of the barrier will widen, decreasing the degree of deformation of the cylinder. However, even after the barrier reaches steady-state, heat transfer at the water table result in a narrowing near the top of the barrier around each freeze pipe.

In a U.S. Department of Energy (DOE) sponsored demonstration project in Oak Ridge TN, a frozen barrier was installed to evaluate the technology for isolating nuclear related contamination (AFI, 2000). A cross section through the barrier that was formed (Figure 15) confirms the general processes described above. The final depth of the barrier was approximately 10m. The width of the barrier was approximately 8m at the base and 3m near the top. In this case, the aquifer was composed of relatively uniform sands/silts and the freeze pipes were spaced approximately 2m apart, so that the barrier successfully merged.

For relatively homogeneous materials, the net impact of the fundamental geometry of freezing around a freeze pipe on the composite frozen soil barrier is depicted in Figure 16. The thinnest portion of the barrier would be near the top halfway between the freeze pipes. The thickest portion of the barrier would be near the base of the barrier.

> Key points:
>
> The final geometry of a frozen barrier reflects the local geologic conditions and the sum of the effects of various physical and chemical processes that occur at the ice water interface as the barrier is forming. Based on the expected barrier geometry, the potential "weakest" areas of the barrier can be predicted. These areas would be between the freeze pipes near the top and in high permeability gravel zones. Targeted monitoring in these areas is an opportunity. If monitoring indicates a competent barrier in the predicted weakest areas, the data would provide a high degree of confidence in the overall barrier design and performance.

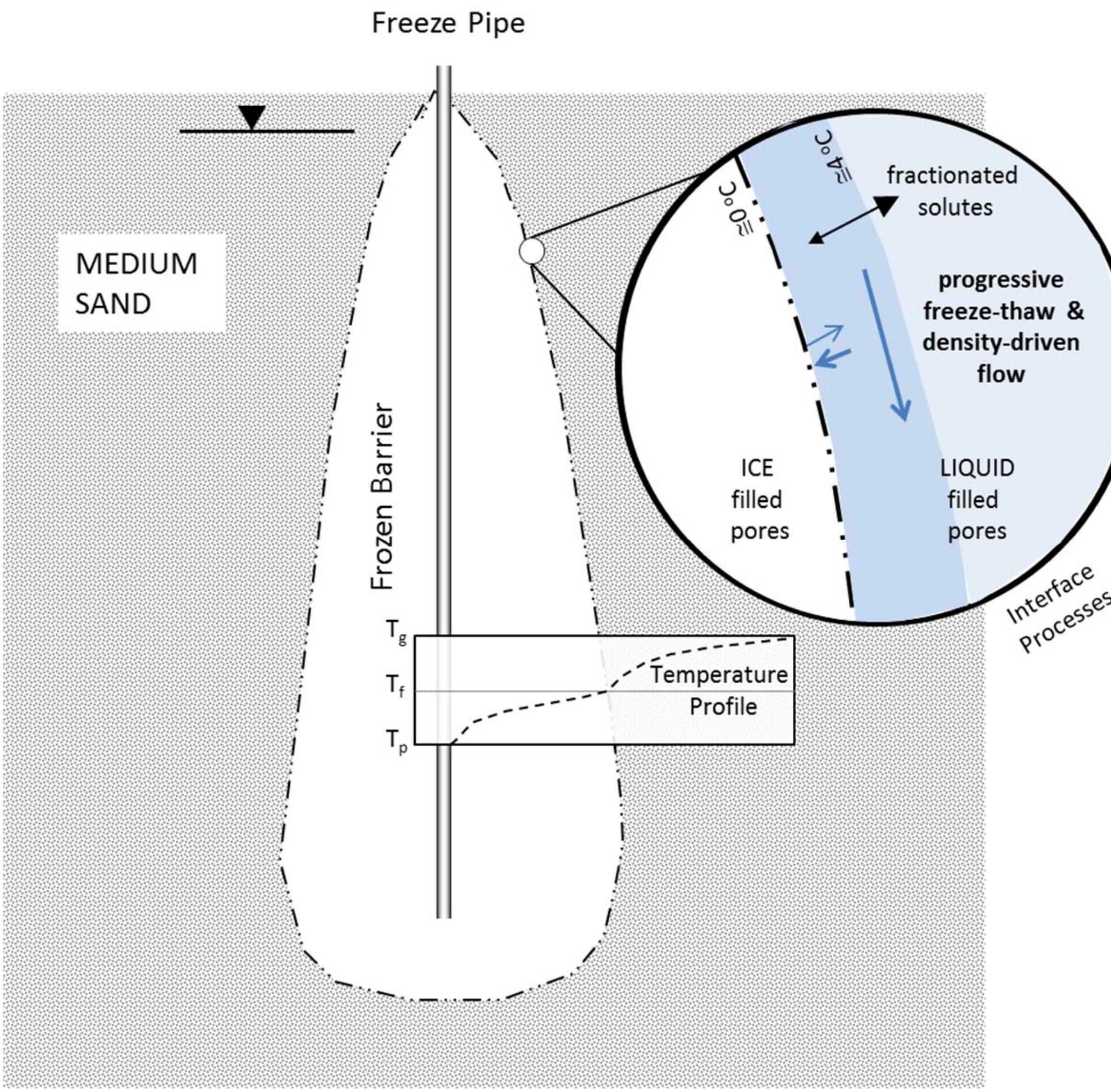


Figure 14. Frozen soil zone for an individual freeze pipe in a homogeneous medium-grained sand

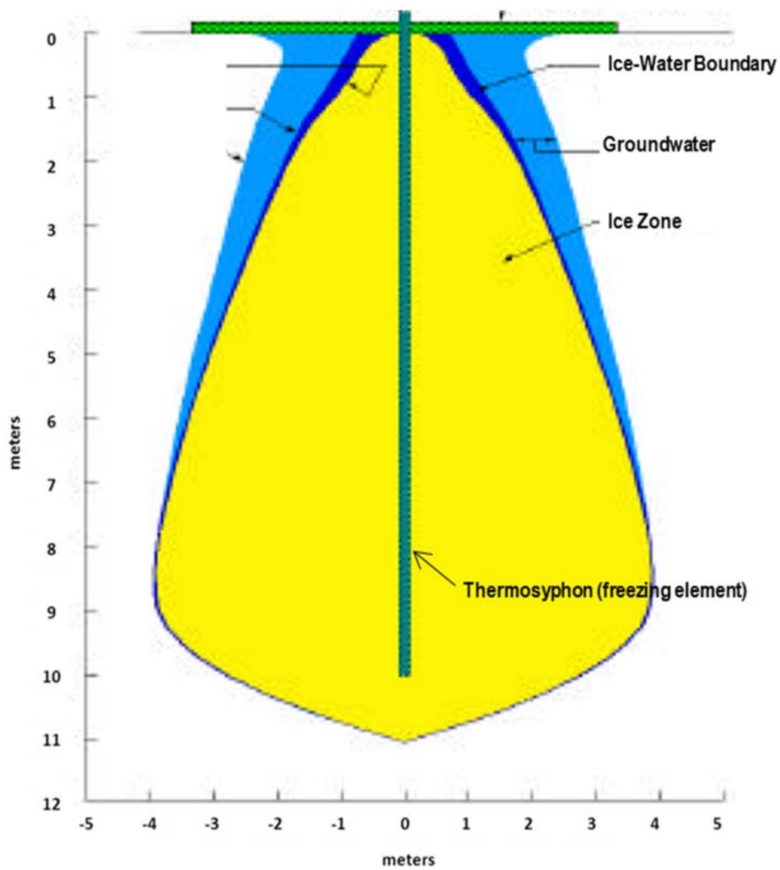


Figure 15. Cross-section of frozen soil barrier formed in the DUS Department of Energy Oak Ridge demonstration

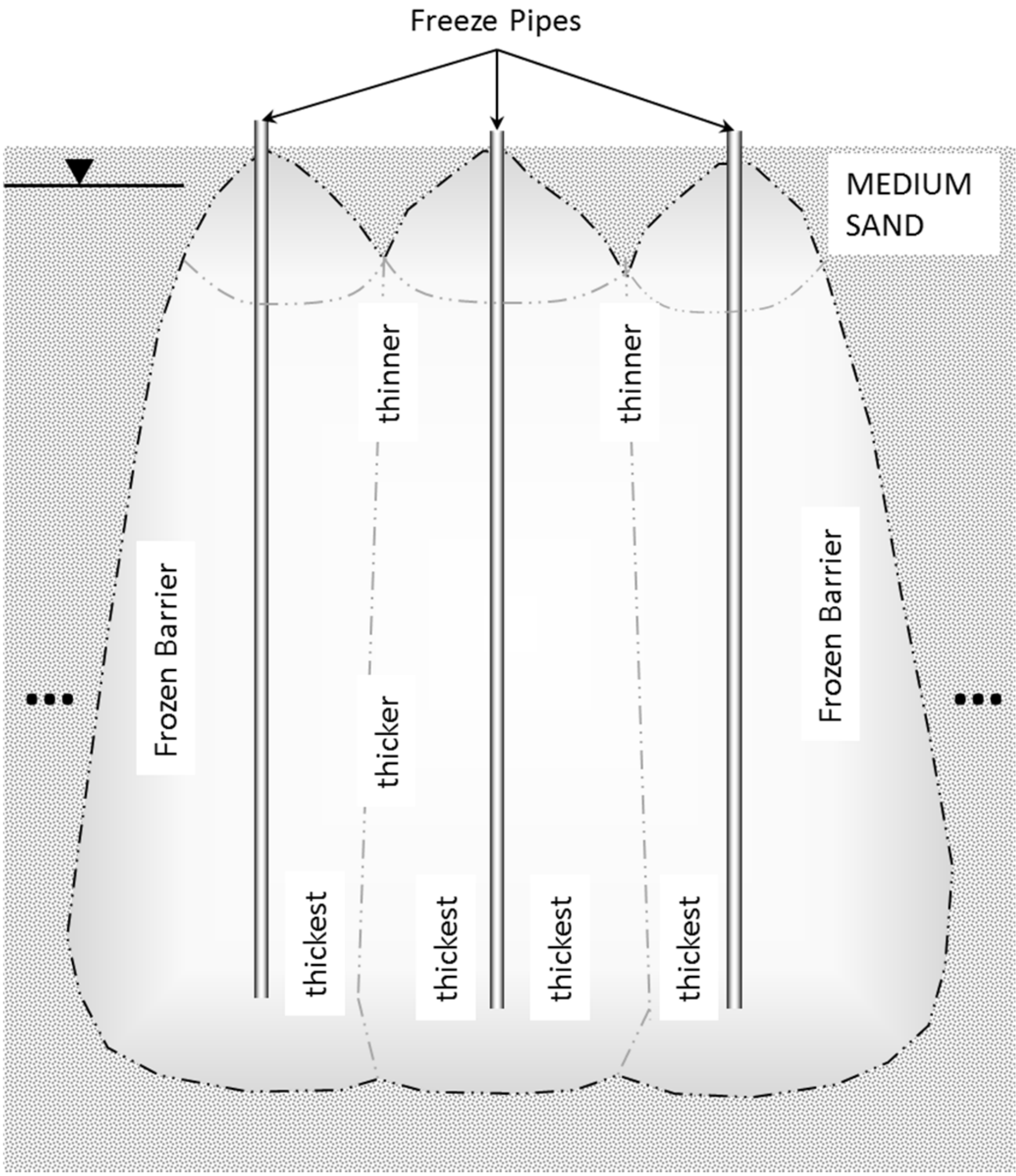


Figure 16. Expected frozen soil barrier thickness pattern in a relatively homogeneous material

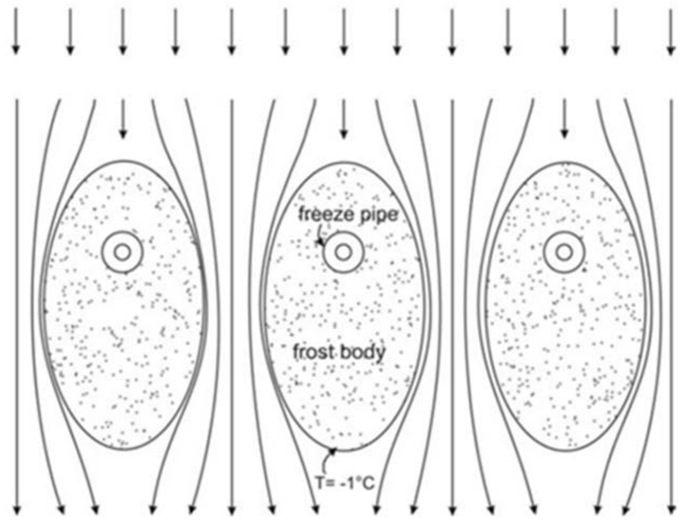


Figure 16 (continued). Expected frozen barrier thickness pattern in a relatively homogeneous material

In target areas with significant geological heterogeneity, barrier geometry can be more complex. Figure 17 depicts the barrier geometry in a complex layered system (with geologic materials that have significantly different frozen soil thermal conductivity values). In this type of application, the barrier width tends to be larger in fine sands and rocks with high frozen soil thermal conductivity. Barrier width is smaller in clays and silts with lower frozen soil thermal conductivity and is smaller and distorted in coarse sands with high groundwater flow velocity. Note that the upper aquifer zone of the Tomioka Stratum at Fukushima has a moderate heterogeneity as described above; the upgradient (mountain-side) and side-gradient legs of the barrier are relatively homogeneous and would be expected to effectively freeze. The sediments along the downgradient (harbor-side) leg of the barrier contain some higher permeability gravel strata.

In areas where the groundwater contains significant quantities of salts (or solutes), a secondary impact of the dynamic freezing and thawing process at the ice water interface (Figure 14, inset) is “freeze fractionation” in which the frozen barrier will contain water that is depleted in solutes (due to the slightly higher freezing temperature of pure water). The excluded solutes would be transferred to the surrounding groundwater flowing past the barrier as it forms. In areas where there is a relatively high salt content in the water targeted for freezing (such as areas impacted by pumped seawater), freeze fractionation has the potential to export contaminants along with salts from the barrier. These constituents have the potential to show up as a brief increase in concentration in surrounding monitoring wells.

Given the nature of the planned freeze wall implementation—a relatively long wall with significant upgradient flow—the impact of water table rise on the mountain-side freeze wall should be considered. This is discussed in more detail in the engineering section below.

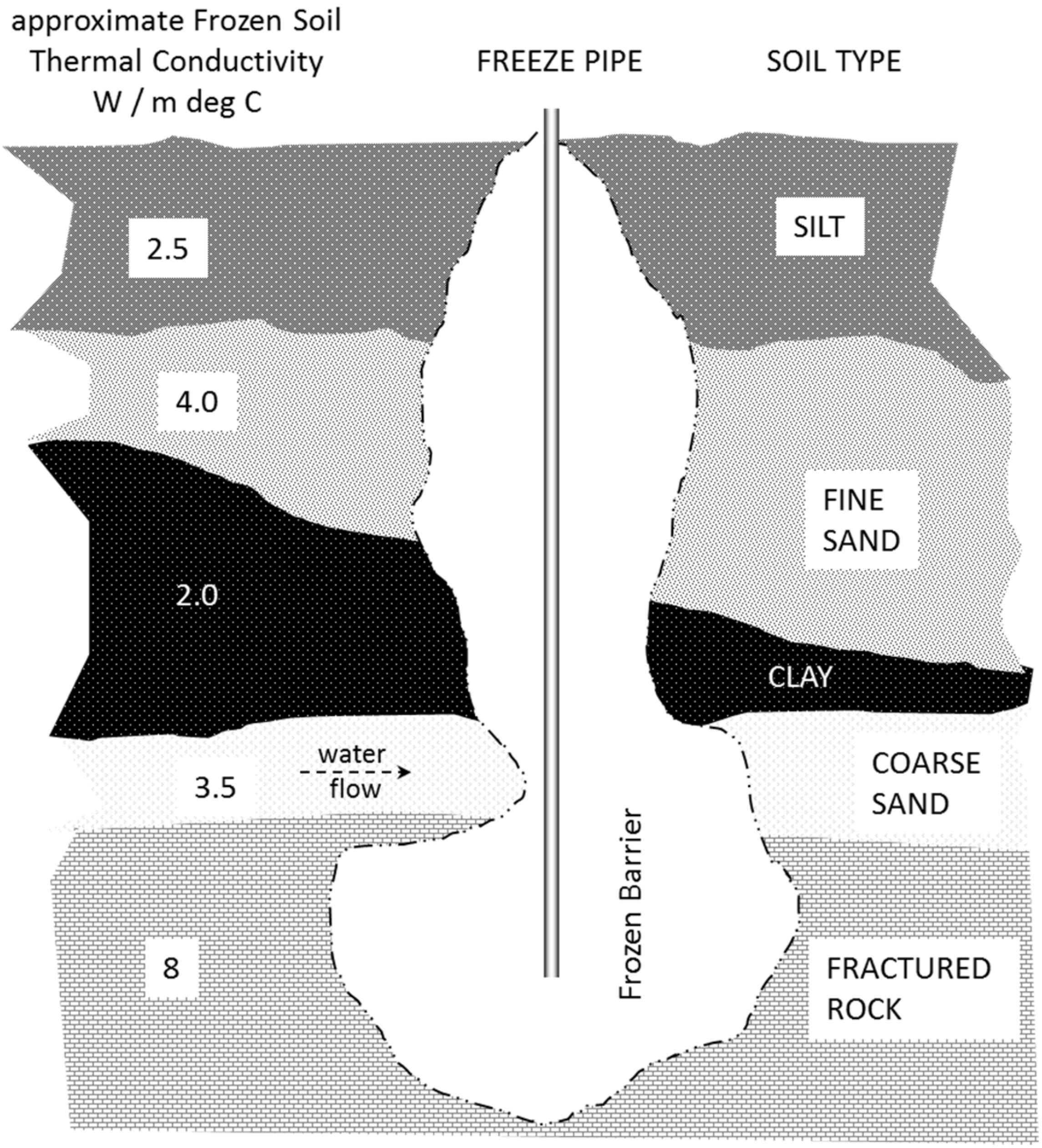


Figure 17. Barrier geometry in a highly heterogeneous setting (redrawn from Andersland, and Ladanyi. 2004)

Fukushima Site Specific Fluid and Soil Properties

One aspect in the application of a frozen barrier to the site is the presence and possible effects of dissolved solutes in the local groundwater. Dissolved solutes in the groundwater are due to 1) salt water associated with flooding following the 2011 tsunami or the or seawater used for reactor core cooling, and 2) residual contamination released to the groundwater following the damage to the reactors. In the period following the tsunami, clean water from the mountainside has continued to flow through the site. This water is being collected by the reactors or flowing toward the harbor. The groundwater flow is expected to have flushed a substantial fraction of the dissolved salts from the area around the reactors and the areas where the frozen soil barrier is being installed.

On average, seawater in the world's oceans has a salinity of about 3.5% (35 g/L, or 599 mM). The Fukushima harbor water is a blend of seawater and fresh water (from runoff and groundwater upwelling) so the salinity is less than typical seawater. The dissolved salts are predominantly sodium (Na+) and chloride (Cl−) ions. Due to the presence of these salts the freezing point of seawater is depressed from that of pure water. At ocean-water salinity of 3.5%, salt water freezes at about −2 °C (28 °F). The presence of solutes in water will lower the freezing point of water. The freezing-point depression in dilute solutions can be predicted using the Van't Hoff equation. As a general guide every mole of a dissolved solute in a kilogram of water reduces the freezing point by approximately 1.86°C.

Assuming industry standard artificial ground freezing design, the depression of the freezing point of the groundwater will have a minimal effect on the frozen soil wall. The operating temperate of the recirculating brine that will be used to develop the freeze wall (approx. -30°C) is projected to be adequate to freeze the groundwater at the site (T_f approximately -1°C). This performance was generally validated during the freeze-wall pilot-test and has been demonstrated in industrial settings where freeze walls were successfully applied in near-shore and saline water conditions.

One aspect worth considering is the effect that freezing will have on solute concentrations in the vicinity of the ice wall. Solute (salt) exclusion from the ice phase can locally increase the concentration of salts in the surrounding solution during the freezing process. As discussed below, this "freeze fractionation" process may result in relatively high concentrations in the near-field (immediately adjacent to the frozen surface) and lower magnitude concentration increases downgradient.

Near-Field Impacts of Freeze Fractionation

Figure 18 is a phase diagram for the H2O–NaCl system which is useful in illustrating changes in the adjacent solution as ice forms during the freezing process. Assuming an initial solution with a NaCl concentration of 1.00 mol per kg and an initial temperature of 0°C (Figure 18, "1"). As this solution cools below 0°C, the NaCl concentration will remain constant until the temperature reaches –3.3°C, when ice, largely a pure water phase, will begin to form, concentrating NaCl in the remaining unfrozen solution (Figure 18, "2"). In a closed system equilibrium would be maintained between the solution and ice phases during freezing and the concentration in interfacial solution would follow the ice–solution equilibrium line, increasing in concentration as temperature decreases until it reaches the eutectic composition (Figure 18, "3"), at which point the residual solution will solidify as a mixture of ice and solid salt.

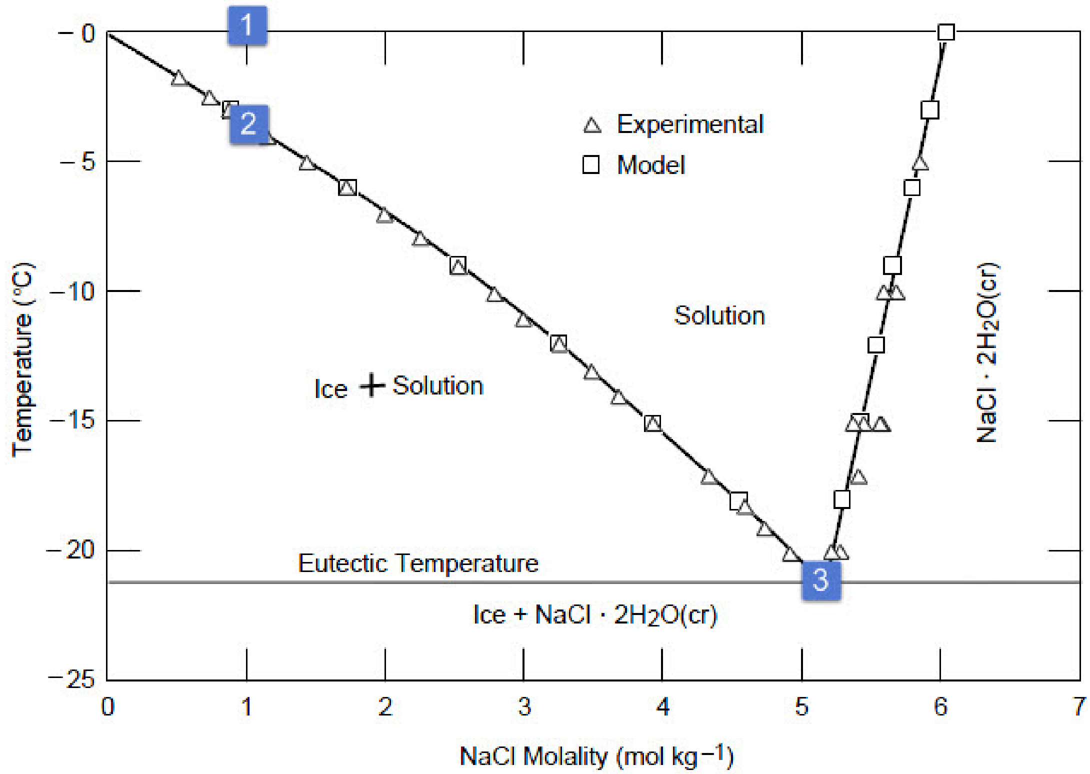


Figure 18. Example phase diagram for the H2O–NaCl system

As described with the phase diagram, when aqueous solutions freeze, solutes tend to be excluded from ice phase. This exclusion causes an increase in solute concentration with solute concentrations generally highest at the freezing front. For ground freezing applications with minimal groundwater flow, Kay and Groenevelt (1983) developed a simple equation:

$$C_f = C_i + 80\ k\ C_i$$

where C_i is the original solute concentration, C_f is the solute concentration at the freeze front and k is a solute inclusion coefficient that accounts for the fraction of salt in the frozen zone. If there is no solute inclusion in the frozen zone (k = 1), then the solute concentration immediately adjacent to the ice at the freezing front could rise to 80 times the original concentration (assuming no salt precipitation).

Sheshukova and Egorov (2002) developed a near-field numerical simulation of ice formation and localized solute behaviors in a saturated-flowing porous media system. This model used a finite-difference approximation of the coupled equations for liquid water flow, heat and solute transport and phase change. The model was used to examine a two-dimensional system in which a frozen volume develops around freeze pipes located in a horizontal field of uniform fluid flow, predicting the near-field concentrations in the immediate vicinity of the frozen volume.

The authors' simulations depict a small unfrozen wedge immediately downgradient of (and adjacent to) the freeze zone during the development of the frozen soil barrier. This occurs because solutes originally in the flowing water combine with solutes rejected from the ice and the interfacial boundary layer solution becomes more concentrated as the water moves along the edge of a frozen body toward the downgradient tip. The projected unfrozen wedge is in a flow stagnation region and the total contribution of flow from this area to the total liquid flux is relatively small. According to the numerical simulations of Sheshukova and Egorov (2002), the presence of the wedge of concentrated solutes slightly delays the downgradient growth of the frozen body. Eventually the individual frozen bodies coalesce into a continuous and effective low permeability soil barrier.

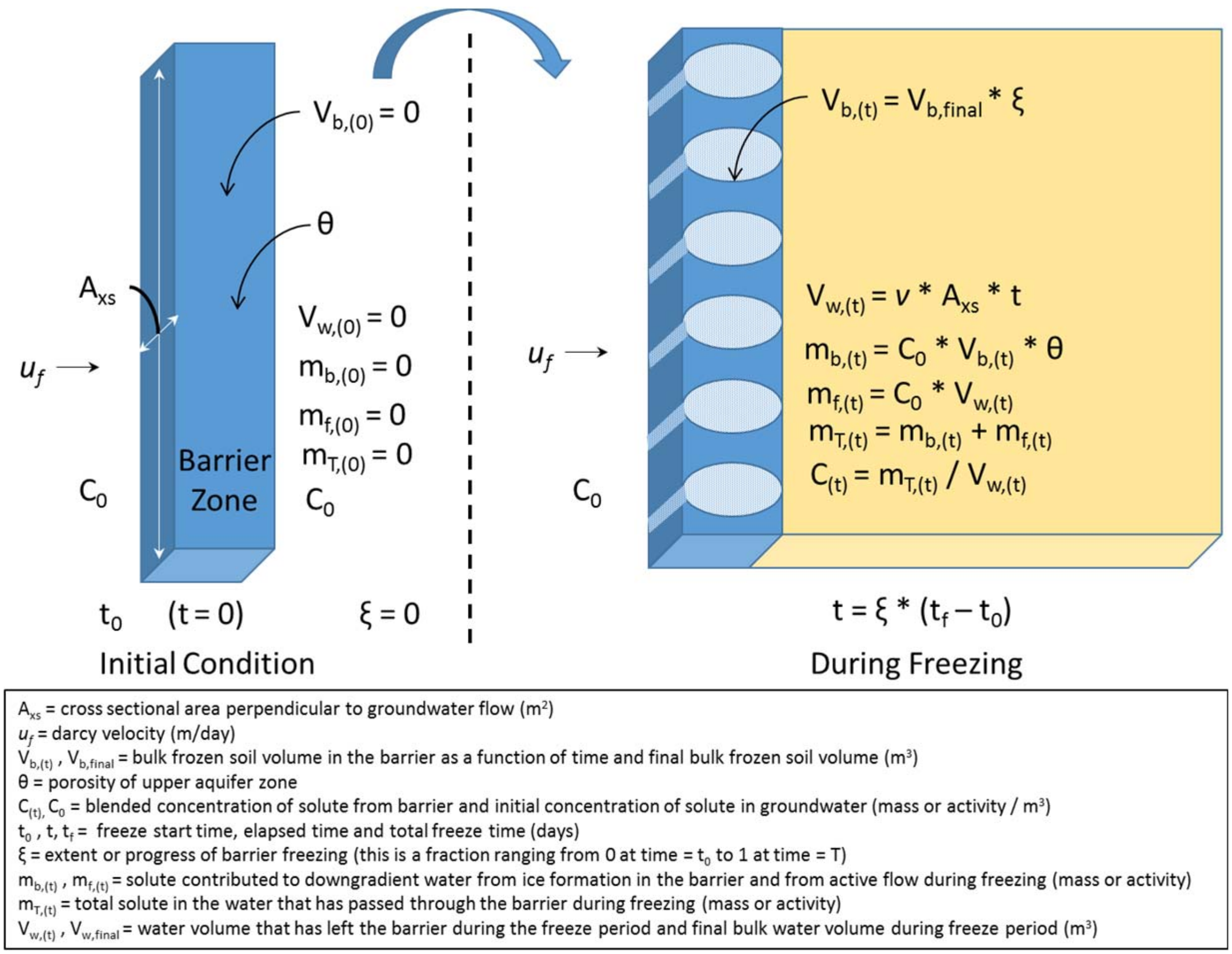
Downgradient Impacts of Freeze Fractionation

The frozen barrier application at Fukushima Daiichi has the potential for temporary increases in solute concentration due to dissolved compounds being rejected from the water phase during freezing. However, the high concentrations of solute in the near-field (immediately adjacent to the freeze boundary) do not impact all of the water flux through the barrier during its formation. As a result, the high concentration boundary layer water would not be expected to propagate to downgradient monitoring wells. Instead, we have developed an overall water balance and mass balance calculation that provides a better scoping estimate of the potential for concentration changes in nearby downgradient wells due to freeze fractionation (Figure 19). The calculation provides a scoping level estimate of the potential change in solute concentration in downgradient water that would result from solutes being rejected from the frozen barrier and added into the flowing groundwater. The calculation is based on the conservative assumption that the frozen pore water in the barrier will contain no solutes and on the following simplifications: (1) groundwater flow will continue at an approximately constant rate from the start time until the barrier closes, and (2) ice volume formation in the barrier will proceed approximately linearly from the start time until the barrier closes. Using these assumptions, a term to represent the progress, or extent, of barrier formation (ξ) can be used to derive mathematical relationships for the amount of solute released from water in the frozen soil, the amount of solute in the water that has passed through the barrier, and the volume of water that has passed through the barrier.

A narrative form of the relevant equations is as follows:

total solute in the water that has passed through the barrier during freezing ($m_{T,(t)}$) =
solute contributed by ice formation ($m_{b,(t)}$) + solute that entered from upgradient ($m_{f,(t)}$)

For any constituent, the total solute volume (mass or activity) divided by the water volume that has left the barrier ($V_{w,(t)}$) can be used to calculate a scoping concentration. The various parameters and equations needed for the calculation are depicted in Figure 19.



Figrue 19. Depiction of simplified mass balance and water balance calculation to relate fractional freezing effects to downgradient concentration changes

Using the mass balance definitions and detailed description in Figure 19, the following equation for $C_{(t)}/C_0$ can be derived:

$$\frac{C_{(t)}}{C_0} = 1 + \frac{V_{b,final}\theta}{u_f\, A_{xs}(t_f - t_0)}$$

This equation was applied to the downgradient barrier (blocks 11BLK, 12BLK and 13BLK) and the results are graphed in Figure 20 based on the following assumptions about the site: $\theta \cong 0.3$; $V_{b,final} \cong 21{,}545\ m^3$, and $A_{xs} \cong 6930\ m^2$. Figure 20 depicts the behavior of $C_{(t)}/C_0$ as function of Darcy velocity, ranging between 0.04 and 0.14 meters per day, for three different total barrier formation times (3weeks, 6 weeks and 9 weeks). As shown in this figure, downgradient concentrations are anticipated to increase relative to upgradient concentrations during the time span over which the freeze wall is developing. The magnitude of downgradient concentration increase is a function of the total time it takes for the freeze wall to develop (t_f) and the Darcy velocity (u_f). As the groundwater velocity increases, $C_{(t)}/C_0$ is projected to decrease (because there is more dilution from water flowing through the barrier). In a similar manner, the longer that it takes for the freeze wall to develop, the lower the projected downgradient concentrations (because there is less solute released into the flowing water per unit time).

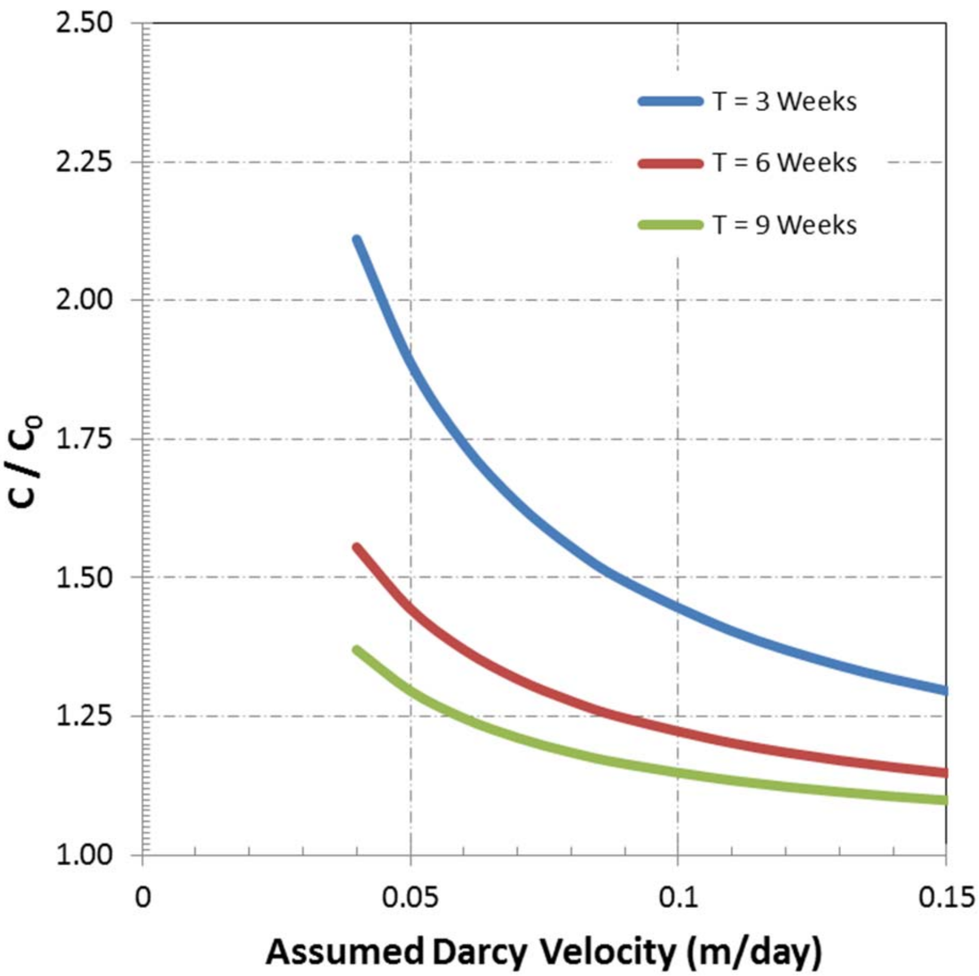


Figure 20. Scoping calculation of potential fractional freezing effects during barrier formation on downgradient solute concentration for different assumed darcy velocity (u_f) and total freeze time (t_f - t_0)

All of the projected downgradient concentration changes are relatively small (ranging from factor increases of approximately 1.1x to 2x compared to the baseline). Any increase in solute concentration that results from fractional freezing effects during formation of the frozen barrier would be transient and would dissipate after the barrier installation is complete. A hypothetical curve for the expected transient downgradient concentration behavior resulting from fractional freezing is depicted in Figure 21. Note that downgradient wells will are also subject to changes in concentration because of the changes in flow direction induced by installing the frozen soil barrier, and other countermeasures, which change flow directions in the upper aquifer.

Key points:

Based on the existing data, there are no Fukushima-specific groundwater conditions that would cause problems for the frozen soil barrier installation. Fractional freezing effects during the barrier formation (a factor that is not normally considered in construction and mining applications) have the potential to cause short term increases in concentrations measured in nearby downgradient wells. Simple scoping calculations indicate that the impacted water may have concentrations up to 1.1 to 2 times the baseline concentration. The concentrations should return to baseline levels (or below) after the barrier formation is complete.

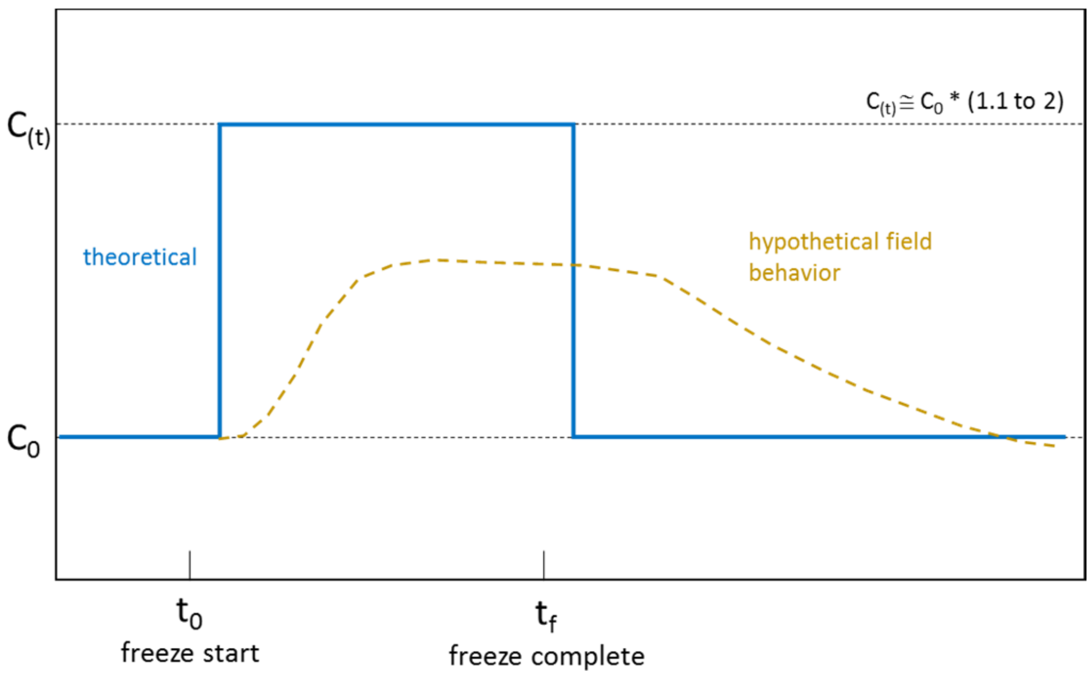


Figure 21. Simplified fractional freezing projections as a function of time for a monitoring well located a short distance downgradient of a frozen soil barrier

Monitoring

There are many technical options for monitoring of the performance of the frozen barrier, including: thermal measurements, hydrologic measurements, tracer tests, and geophysics. Some of these are discussed in more detail below. In planning for barrier monitoring, we recommend that the TEPCO/Kajima team consider the original objectives of the frozen barrier. The most important objective is reducing the amount of groundwater that is entering damaged reactor buildings. Infiltrating groundwater mixes with the water that is introduced to maintain reactor core cooling, though the infiltrating groundwater itself plays no role in reactor cooling. The collected cooling water plus the infiltrated groundwater requires costly treatment. Water is recycled for cooling purposes, but the excess treated liquid (the net flow from infiltration into the reactor, or $Q_{net,(t)}$) is accumulated in storage tanks. Thus, a prime objective of the frozen barrier is to reduce $Q_{net,(t)}$ and the associated water treatment and water storage costs. To meet this objective, the barrier does not necessarily need to be 100% effective. Monitoring that attempts to identify, isolate, and repair every location where water enters the barrier may not be necessary, may represent an unnecessary expense, may trigger contingencies with collateral impacts, and may result in unnecessary worker exposure. A monitoring strategy that is built on metrics that are consistent with the overarching frozen soil barrier objectives would provide the most effective data to support decisionmaking and project management and would provide the best information for clear communication with the public, regulators and government officials. With this in mind, the National Laboratory team supports the planned monitoring of temperatures as an initial indicator of the progress of barrier formation and recommends a longer-term monitoring strategy based primarily on hydrology – specifically monitoring of water levels inside and outside the barrier as influenced by the loss of water, $Q_{net,(t)}$, into the reactor buildings and the loss of water into the subdrain system. The other monitoring techniques discussed below, for example thermal tracer testing or geophysics, could be applied as needed if the barrier is underperforming or if supplementary information in a particular area of the barrier is warranted.

> Key points:
>
> The frozen soil barrier does not need to be 100% effective to meet TEPCO's key objective to limit groundwater flow into the damaged reactors. The National Laboratory Team recommends developing relatively simple and low cost performance monitoring techniques that provide information to assess how well the barrier meets this key objective. More sophisticated methods, such as geophysics can be employed in targeted areas if the baseline monitoring indicates the barrier is underperforming.

Hydrologic Monitoring of Barrier Performance

Once the frozen soil barrier is installed, the hydrologic situation in the vicinity of the damaged reactors will be controlled with known inputs and outputs of water. This provides an opportunity for cost effective performance monitoring of the frozen barrier. The simplest hydrologic analysis assumes that loss of water from inside the barrier is only due to leakage into the reactor – more complex models that include water injection or extraction and subdrain removal of water can be developed by simple extension. The net groundwater inflow to the damaged reactors is a parameter that is currently being measured (based on pumping rates to/from the buildings and water level changes in the buildings). Due to the net inflow, the facilities act as "pumping wells" that provide the basis for a cost effective virtual pump test that has the potential to provide robust information on the overall effectiveness of the frozen barrier.

As shown in figure 22, the barrier can be envisioned as a "bathtub" with a clayey base and frozen soil walls. Under existing conditions, net inflow into the damaged reactors ($Q_{net,(0)}$) and the baseline water table elevation (h_{inital}) are known. The leakage through the barrier ($Q_{leakage,(t)}$) represents the total of all sources of water into the barrier – through heterogeneities, around penetrations, rainfall, etc. The rest of the parameters depicted in the figure can be estimated from site lithology and hydrology data or from information on facility configuration. One key parameter is h_{min} (the water table elevation where that corresponds to no flow into the damaged reactors). This parameter may have a relatively high initial estimation uncertainty; however, as shown below the initial estimate for h_{min} may be able to be refined and improved based on the initial several months of data collected following barrier closure.

Assuming a relatively rapid barrier formation, the equations for water levels in the draining bathtub for the "no infiltration case" are simple to develop and suggest that this performance monitoring approach has the potential to be robust and informative. Importantly, this type of monitoring strategy provides estimates of parameters needed to assess how the barrier meets its primary objectives - a quantitative assessment of overall barrier performance in terms of reducing $Q_{net,(t)}$ and $Q_{leakage,(t)}$.

The simplified parametric model assumes that the groundwater flow into the reactor will be directly proportional to the difference in elevation between the water table elevation inside the barrier and the lowest breach elevation (or water level) in the reactor [$Q_{net,(t)} \propto (h_{(t)} - h_{min})$]. $Q_{net,(t)}$ will range from its baseline value ($Q_{net,(0)}$) when $h_{(t)} = h_{initial}$ down to 0 m^3/day when $h_{(t)} = h_{min}$. Similarly, the model assumes that leakage into the barrier is primarily from groundwater outside the barrier and is proportional to the difference in elevation between the water table outside the barrier ($\cong h_{initial}$) and the water level inside the barrier ($h_{(t)}$). This initial model version assumes that infiltration of rainwater is 0 m/day.

The effectiveness of the barrier in limiting this flow is quantified by the term β which is the projected fractional net reactor inflow $Q_{net,(0)}$ that will be realized over time compared to the baseline condition (the numerical value of β is assumed to stabilize over a few months as the seaside portion of the frozen soil barrier closes). The values for β range from 0 to 1. If β = 1 then the barrier is leaky and provides no benefit in terms of reduction of future inflow into the reactor. If β = 0 then the barrier is "perfect"; flow into the reactor would be expected to decline to a low rate as the bathtub drains to h_{min}. A β of 0.1 represents a long term reactor infiltration flow reduction of 90%. For example, when β = 0.1, a baseline $Q_{net,(t)}$ of 350 m^3/day would be expected to decline to 35 m^3/day (= 350*0.1). Thus, the simplified model assumes that leakage through the barrier is: $Q_{leakage,(t)} \propto \beta\,(h_{initial} - h_{(t)})$. According to the proportionalities, $Q_{net,(t)}$ will decrease as water level declines inside the barrier and $Q_{leakage,(t)}$ will increase. Over time, these two parameters will move toward a balance. In the example, the long-term flows $Q_{leakage,(\infty)} = Q_{net,(\infty)} = 35$ m^3/day.

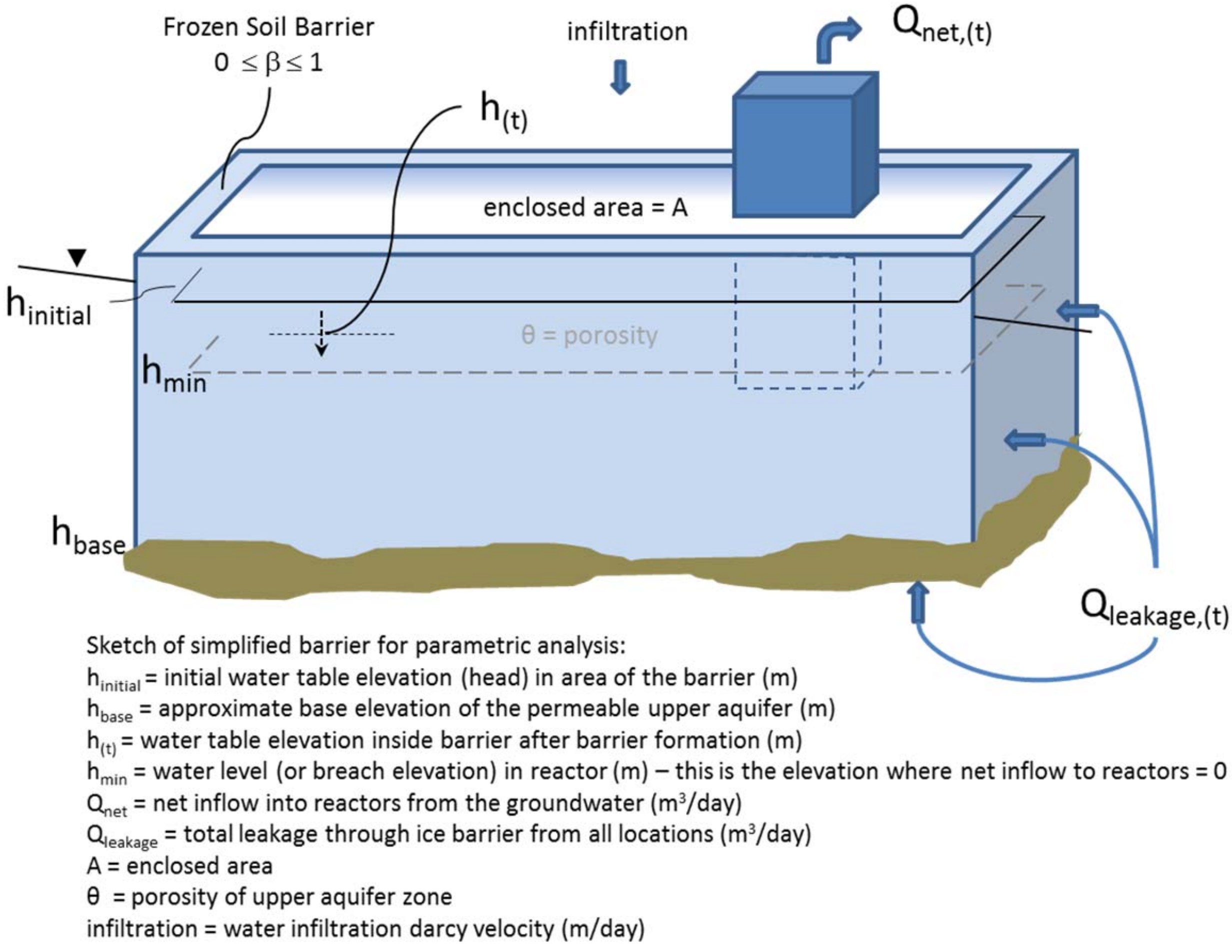


Figure 22. Diagram of simplified model for “virtual pump test” of frozen soil barrier performance

Since TEPCO intends to maintain water level in the buildings below the groundwater elevation to maintain a small flowrate into the reactor (thus avoiding a hydraulic driving force for migration of contamination out of the reactor and into the soil), a target β of 0 is not necessary. Instead, to meet TEPCO objectives we recommend setting a β consistent with the planned target volumes for groundwater inflow and treatment. Using the above example, if TEPCO plans to maintain an infiltration rate of 35 m^3/day, then a target field measured $\beta \leq 0.1$ is acceptable. Any value of β between 0 and 0.1 would meet TEPCO goals and would constitute barrier performance success. The field performance of the barrier (β) can be reasonably estimated over a timeframe of a several months using site specific spreadsheets and/or type curves as shown below.

Figure 23 is a graph of the assumed mathematical relationships between water elevation inside the barrier (h on the x-axis) and the key flow rates -- $Q_{net,(t)}$ and $Q_{leakage,(t)}$. For both flow and for water elevation, the scale is presented in normalized and parametric forms and with an example set of values. As shown, water elevation on the normalized scale ranges from 0 (=h_{min}) to 1 (=$h_{initial}$). The normalized scale for flow ranges from 0 (= no flow) to 1 (= $Q_{net,(0)}$). Water elevations below h_{min} do not participate in the model, so the precise elevation of base of the water bearing zone (h_{base}) does not impact the predictions. Consistent with the description above, $Q_{net,(t)}$ is highest ($Q_{net,(0)}$) when the water elevation inside the barrier is at its highest ($h_{initial}$) and ranges down to 0 when the water elevations declines to h_{min}. If water levels were lowered further, then water could potentially move from the building into the soil. Since the simplified model assumes that water removal from the inside of the barrier is only due to Q_{net}, it does not address water levels below h_{min}. $Q_{leakage,(0)}$ is 0 when the water elevation inside the barrier ($h_{(t)}$) is the same as the surrounding groundwater ($h_{initial}$) and increases as $h_{(t)}$ declines. After the barrier is constructed, Q_{net} and $Q_{leakage}$ would move along their respective lines from the right side of the graph toward the left. Because Q_{net} and $Q_{leakage}$ are approximately equal when the system equilibrates, the lines would intersect at a flow of $\beta * Q_{net,(0)}$. Therefore the slopes for the lines relating $Q_{leakage}$ to water level depend on β. The normalized intercept any $Q_{leakage}$ line can be determined using the formula $(\beta/(1-\beta))$ with a normalized slope of $(-\beta/(1-\beta))$.

The total water removed from the barrier over any time period is = $Q_{net,(t)} * \Delta t$. Since the area enclosed by the barrier (A) and the approximate porosity of the upper aquifer (θ) are known, this volume can be related to the change in water level inside the barrier [$\Delta h_{(t)} = (Q_{net,(t)} * \Delta t)/(A * \theta)$]. Rearranging this equation provides a useful relationship between the rate of change in water elevation inside the barrier and the net flow into the reactor → [$\Delta h_{(t)} / \Delta t = Q_{net,(t)} / (A * \theta)$]. For an example enclosed area of 60,000m^2 and nominal porosity of 0.3 the rate of change in water elevation at an initial flow ($Q_{net,(0)}$) of 350 m^3/day would be approximately 0.019 m/day. These equations can be incorporated into the simplified model to generate estimates for water elevation changes inside the barrier over time following barrier completion (Figure 24). Note that the scenario shown is based on an initial estimate of h_{min} that requires 7m of drawdown inside the barrier before inflow into the reactors declines to approximately 0.

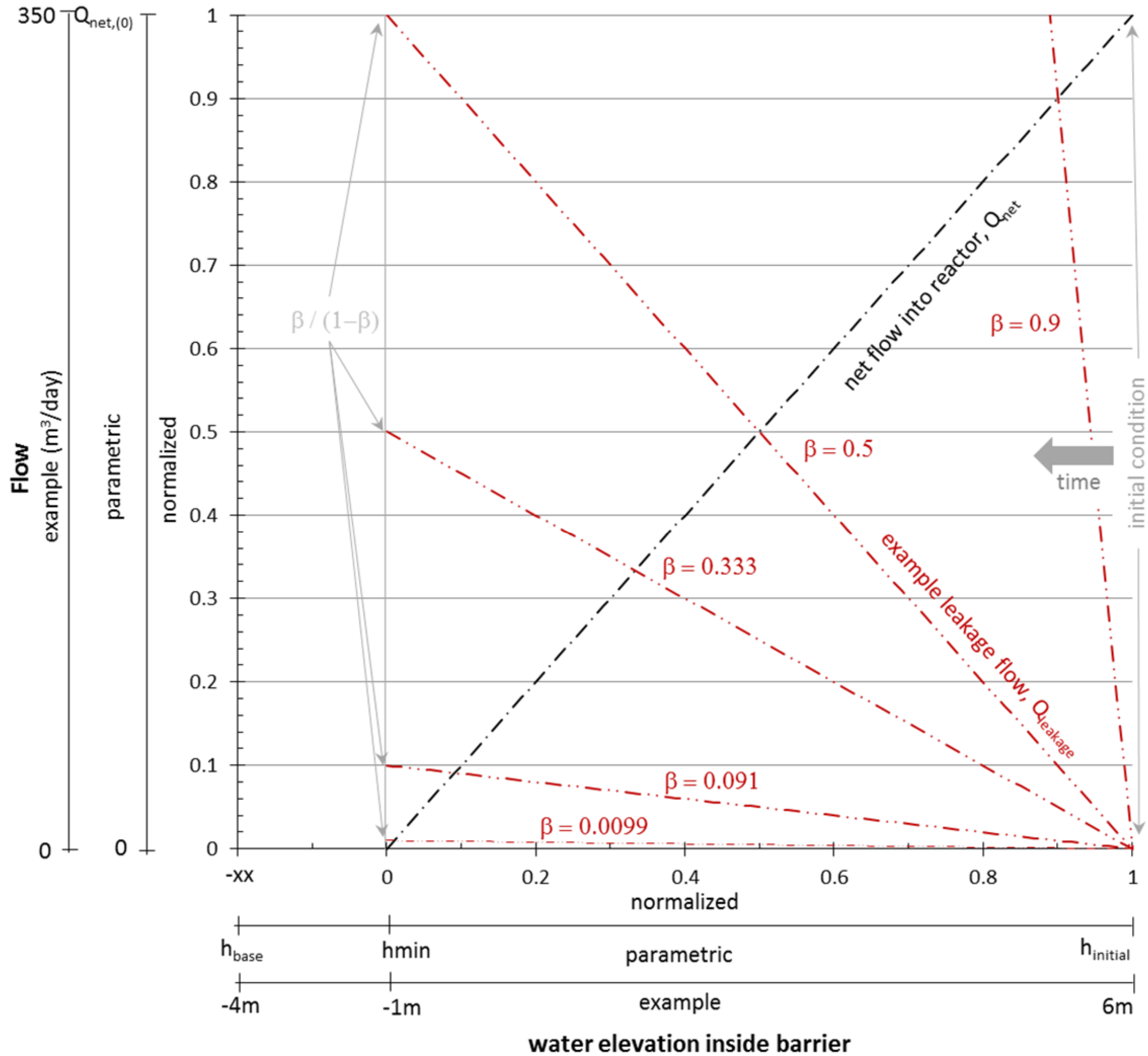


Figure 23. Mathematical relationships in the simplified parametric model (no infiltration case)

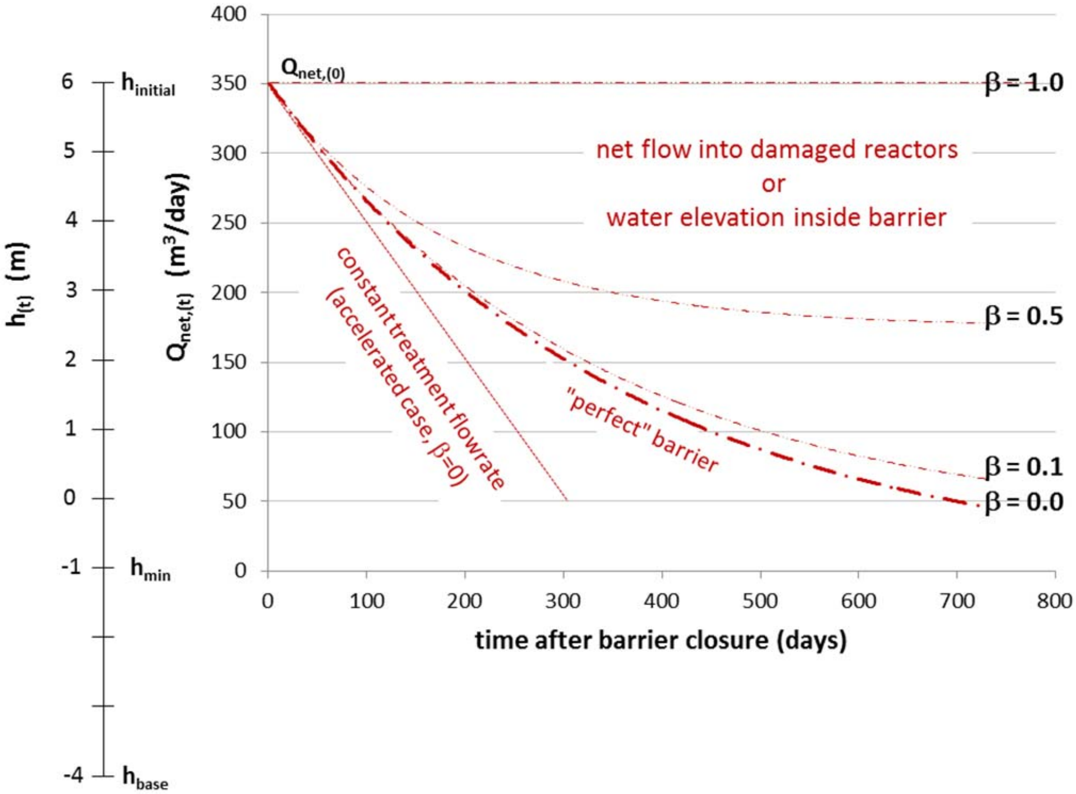


Figure 24. Example results for the simplified parametric evaluation (no infiltration case) – model parameters and assumptions provided in the text)

As shown in Figure 24, the simplified model suggests that significant leakage in the barrier will result in a measurable mathematical deviation from the "perfect" barrier in both the water elevation inside the barrier and in measured flow into buildings. If inflow into the buildings is the only water removal pathway, then an initial monitoring period of 4 months after the barrier closure would provide an assessment confirming $\beta < 0.4$, 8 months would confirm if $\beta < 0.2$, and 1 year would confirm $\beta < 0.1$. Importantly, the overall scale on the x-axis of Figure 24 (approximately 2.2 years for this scenario) suggests that the inflow rate to the reactor will decrease relatively slowly once the barrier forms.

One alternative to accelerate lowering the water level inside the barrier (thus decreasing inflow to the reactors) would be to operate the subdrain system and/or pump and treat the relatively clean water from the formation surrounding the reactor. This accelerated water removal would also accelerate knowledge on the effectiveness (β) of the barrier. While groundwater pumped from inside the barrier may still require treatment and storage, the dissolved concentration/activity of contaminants is significantly below the levels in the water being removed from the damaged reactors. Figure 24 provides an example of the acceleration that is possible by simply maintaining a constant total water removal rate (buildings + subdrain + pumping) from inside the barrier. In this example, contaminated water from the reactor building would be blended with cleaner water pumped from the upper aquifer outside the reactor / inside the barrier (the fraction of cleaner water would increase over time as groundwater flow into the reactor decreases). The line in Figure 24 is a projection of water level and Q_{net} for the accelerated constant treatment flow strategy (for $\beta = 0$). Using the accelerated strategy, if β is 0.1 or less, the time needed to limit infiltration into the damaged reactors to 50 m^3/day using the constant treatment flowrate strategy would be less than 1 year (less than half of the time needed in the baseline un-accelerated case). In the accelerated strategy, pumping and treating water from inside the barrier could be discontinued as soon as the infiltration rates in the building approach TEPCO goals. If the planned subdrain system is initiated or if relatively clean "barrier" groundwater requires low cost treatment and could be removed faster, then significant acceleration in meeting objectives is possible. The National Laboratory team recommends that the subdrain, if operated, be instrumented to monitor water removal and be equipped with control features to allow increasing or decreasing flowrates. Flow monitoring is needed to support the hydrologic monitoring of barrier performance, and the ability to control subdrain flow would provide significant water management operational control to TEPCO. For example, if water levels in the formation begin to decrease into the safety offset (e.g., 0.3m) above the water levels in the reactor building, then the subdrain flowrate could be reduced, potentially eliminating the need to inject water outside the reactors to increase water levels. The National Laboratory supports TEPCO's efforts to operate the subdrain and to work with the fishermen and other stakeholders to develop consensus about safe operational practices and discharge limits. Any supplemental water removal system would significantly accelerate progress toward meeting building inflow reduction objectives. The same general water balance model can be used for any of these scenarios by accounting for the added water removal.

> Key points:
>
> If inflow into the damaged buildings is the only water removal process, water levels are projected to decline relatively slowly inside the frozen barrier after it is completed. Operation of the subdrain system or supplemental pumping of water from inside the barrier would significantly accelerate the decline in water levels and decrease inflow into the damaged reactors. To employ the hydrology monitoring approach, water volumes being removed by all of the operating water removal systems, as well as changes in water storage in the buildings, need to be measured and tracked. In all these scenarios, a theoretical curve for draining a non-leaking barrier-formed "bathtub" can be developed. Barrier performance can be quantitatively assessed by looking for deviations from this ideal curve.

The time curves (Figure 24) are sensitive to the input parameter h_{min} (minimum water level with zero net inflow to the reactors). This parameter may be difficult to estimate prior to operation. However, a refined estimate for h_{min} can be calculated from the field measurements after data have been collected for sufficient time (approximately 3 to 6 months) using the equation:

$$field\ estimate\ of\ h_{min} at\ time\ t = \frac{h_{initial}\left[\frac{Q_{net,(t)}}{Q_{net,(0)}} - \frac{h_{(t)}}{h_{initial}}\right]}{\left[\frac{Q_{net,(t)}}{Q_{net,(0)}} - 1\right]}$$

The refinement of h_{min} over time would improve projections of water treatment volumes and overall timeframe, help inform management decisions, assist in communicating performance to regulators and stakeholders, and provide an additional check on the simplified model. If field estimates of h_{min} vary significantly over time and do not trend toward a stable range, then refinements to the underlying model should be considered. Examples of refinements that might be needed include: a) explicitly including infiltration of rainfall in the water balance, b) incorporation of a non-linear relationship of water level inside the barrier to reactor inflow based on the available area for inflow into the building as a function of elevation, and c) accounting for changing water levels inside the reactor buildings.

There have been some concerns about the potential for a rapid-uncontrolled water level decline in the vicinity of the reactors due to "closure" of the upgradient barrier before the downgradient barrier – resulting in potential for release of contamination from the reactor into the soil. TEPCO has proposed installation of wells inside the barrier to allow injection of water to maintain the water level if needed. The simple mass balance model suggests that rapid water level decline is an unlikely event and that injection of water into the wells should not be needed unless there is a significant interruption in the ability to pump water from inside the damaged reactors. Nonetheless, the National Laboratory team supports installation of the proposed wells as they provide opportunities for improved monitoring and engineering controls – for either future water injection or water extraction.

Monitoring of water levels at various locations and depths inside the barrier would provide important and useful information as water levels decline. As depicted in Figure 25, areas of significant barrier leakage or unusual lithologic conditions have the potential to alter the piezometric surface and would help identify areas where more detailed studies are warranted. In Figure 25B the red oval depicts an area where water may be leaking into the barrier through the frozen soil wall or through the clay bottom. For this case, focused geophysics or thermal tracer studies could be performed in the red oval area if the overall barrier system β is significantly underperforming relative to TEPCO objectives. If the overall β is acceptable, then this area could be put on a hydrologic watch to make sure the barrier leakage does not increase over time.

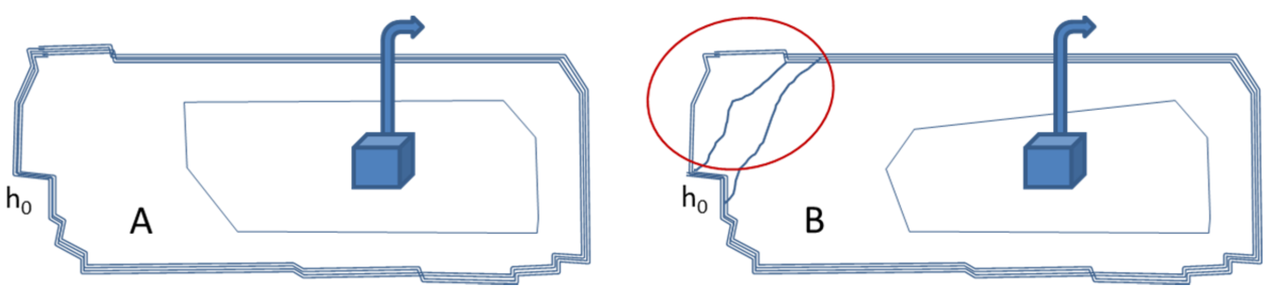


Figure 25. Sketch of hypothetical piezometric surfaces for a uniform barrier (A) and a barrier with an area of leakage (B)

The above calculations assume that there is minimal infiltration into the ground through the surface area inside the frozen barrier. If significant amounts of rainwater infiltrate inside the frozen soil barrier, then the benefits of the barrier will be reduced. Therefore, it is important to minimize infiltration into the ground. TEPCO is already planning to capping (or "facing") areas of soil to reduce infiltration. In terms of frozen soil barrier performance, infiltration reduction is an important contributor. While capping is a viable and high quality method for infiltration reduction, less extensive alternatives are available. These techniques could be considered, and implemented as appropriate, if capping requires an extended timeframe for implementation. Partial infiltration reduction does not require installing a complete cap or impermeable barrier. If a rapid infiltration reduction is needed prior to capping, TEPCO might consider installing impermeable liners in drainage channels and re-contouring the ground surface as needed to eliminate areas where water might pond or accumulate inside the frozen soil barrier. Compared with installing a large impermeable cap, these types of targeted actions would provide significant reduction in water infiltration at a relatively low cost and reduced worker exposure/risk. Impermeable channel liners are commercially available and widely used in agricultural and construction applications (Figure 26).

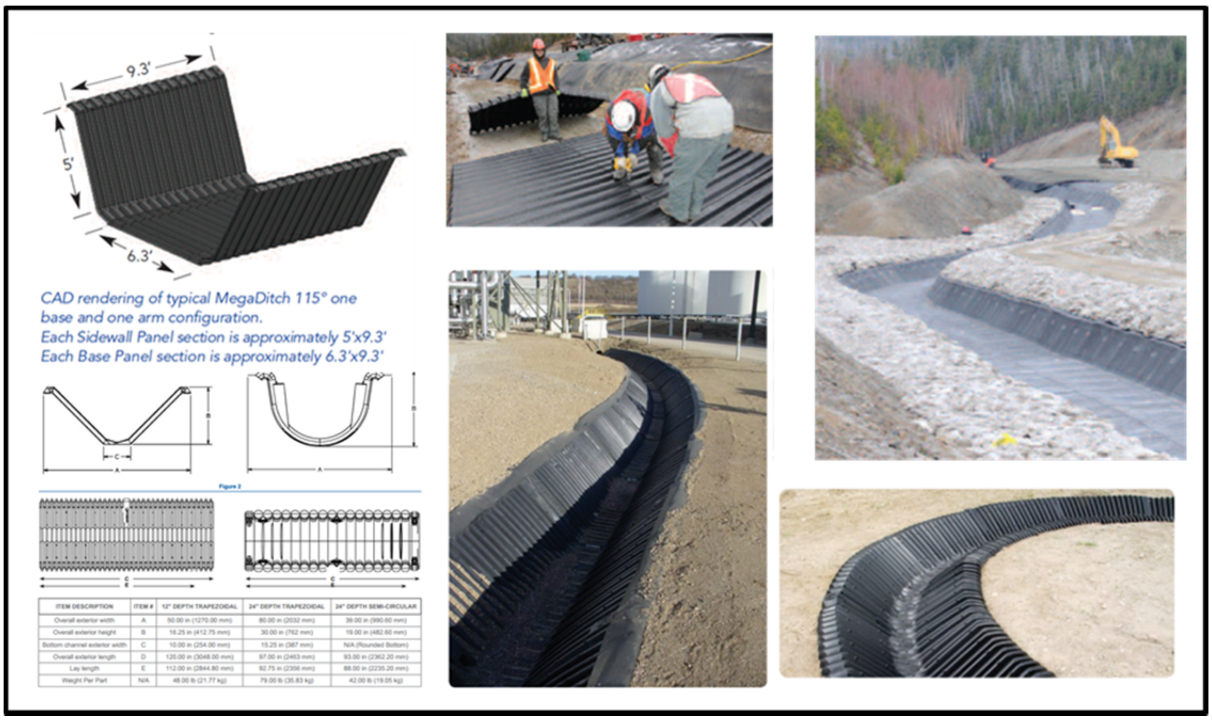


Figure 26. Examples of different size commercial channel liner products that can be used to limit infiltration (the products shown are for channel depths ranging from approximately 0.3m to 1 m and channel widths ranging from approximately 1.5m to 2.5m)

While hydrologic analysis in this section represents a simplified scenario, it captures many of the important features of the real-world challenge at Fukushima. Deviations from the assumptions in the simplified model, such as the time needed to form the frozen barrier and for β values to stabilize can be addressed by careful, steady and consistent interpretation of the initial 6 months to 1 year of data. This will allow time for the barrier to demonstrate its long-term effectiveness and for more definitive information on barrier performance to accrue. Several of the factors that normally influence the schedule urgency during installation of frozen soil barriers for construction (cost of mobilized equipment and crews for excavation or tunneling, need to reopen access to area when working in urban areas, etc.) are not factors for the Fukushima frozen barrier. The timeframe for the barrier operation is 6 to 10 years (or longer) and there is no construction urgency in terms of mobilized crews or equipment. Therefore, knowledge of barrier performance that requires 6 months to 1 year to obtain is reasonable and supports cost effective decisionmaking regarding long-term system operation and the need for contingencies.

Thermal Testing of Barrier Performance

Temperature monitoring is the baseline method for tracking the progress of barrier formation. This type of thermal testing focuses on measuring: a) the change in temperature over time in a number of representative boreholes placed between the freeze pipes and b) the delivery and return temperature of the brine solution to different zones of freeze pipes. This baseline monitoring is addressed in more detail in the engineering considerations section below.

One option for examining the integrity of a frozen soil barrier is thermal tracer testing. In a case where post-freezing leakage was observed in traditional construction (circular tunnel) application, Moretrench implemented a thermal tracer by shutting off the coolant brine, isolating each freeze pipe (or representative freeze pipes), and collecting a time-series of detailed temperature profiles in the isolated freeze pipes. Any areas of barrier leakage will result in a perturbation in the temperature profile and highlight the leak zones for targeted contingency actions (such as spot cooling with liquid nitrogen or injection of bentonite clay). This version of a thermal tracer test requires significant site access and operational flexibility (for example turning off the refrigerant brine system for several weeks and accessing a large number of freeze pipes for multiple temperature profiling events) and would not be an ideal technique for application at Fukushima. Alternative thermal tracer methods might be applicable however – particularly if applied selectively only in areas where significant barrier leakage is suspected.

Figure 27 is an example of an alternative thermal tracer strategy that would be appropriate for identifying high flow rate layers (e.g., gravel layers) and is a strategy that would not only use standard equipment but would also provide information relatively rapidly. The test uses a specially designed heater/sensor apparatus (Figure 27 center). The National Laboratory team has deployed and studied this type of long-cylindrical heater for a range of environmental cleanup applications. The heater/sensor apparatus could be deployed in boreholes several m behind the frozen soil barrier (Figure 27 left); also, if the standard temperature profiles from existing temperature monitoring boreholes within the frozen soil barrier are inconclusive, a heater element could be added to enhance the signal for the temperature profile already being collected. Areas where the barrier is competent will have minimal flow. High permeability layers where the barrier has not effectively closed will have relatively high water flow past the apparatus.

The test is run in two stages: a) by heating the central element creating a warm zone around the apparatus, and b) by turning off the heater and allowing the ground to cool. During both stages, the RTD sensor profile is monitored. Figure 27 (right section) depicts the temperature profiles for a barrier that is not leaking and a barrier where there a layered heterogeneity has interfered with barrier closure and leakage. Each of the profile lines represents a different time (a → b → c → d during heating and d → e → f → g during cooling).

The thermal tracer technique is straightforward to implement and interpret. If the placement of the apparatus is near (or within) the frozen soil barrier and is located several m from subsurface interferences, the method would be expected to be robust.

Chemical tracers would also be viable – for example by injecting a tracer outside the barrier and sampling for the tracer inside the barrier. Compared to a thermal tracer strategy, chemical tracers would require more infrastructure (an array of injection and extraction wells, chemical analysis, etc.) and more resources to implement.

Key points:

If the hydrologic analysis indicates significant barrier leakage and the general location of leakage, then supplemental targeted monitoring could be employed. For this supplemental monitoring, a thermal tracer method is a reasonable option. The technique would introduce a thermal signal (using a heater for example) and look for perturbations in the temperature profiles at various points in time. At Fukushima, thermal tracers appear to have more potential for application compared to chemical tracers.

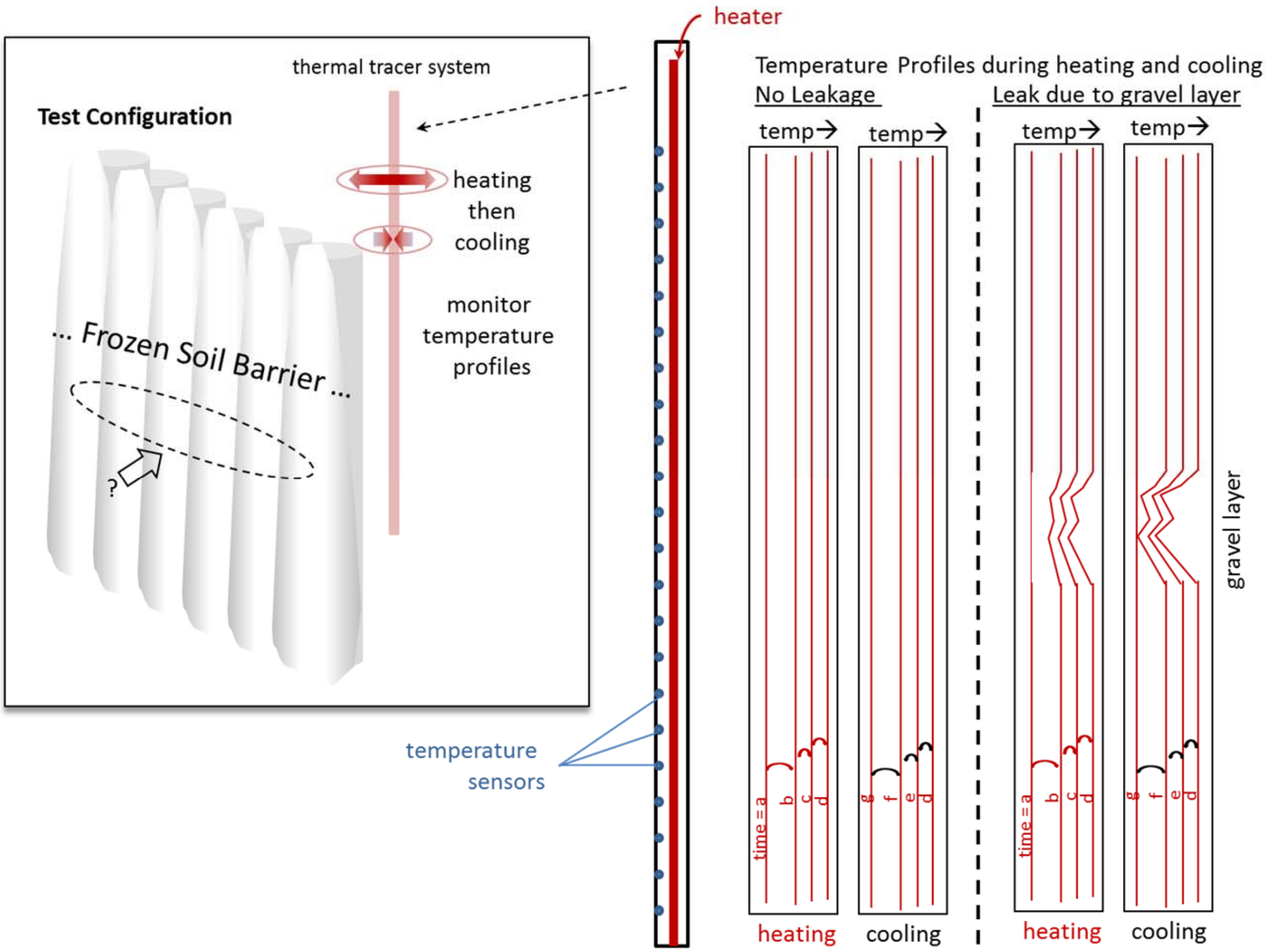


Figure 27. Example of a thermal tracer test strategy to identify barrier leaks resulting from flowing water in high permeability (gravel) layers

Geophysical Methods for Assessment of Frozen-Soil Barrier Integrity

Geophysical measurement and imaging methods provide a potential method to remotely determine subsurface physical and chemical properties. To be useful, a sufficient contrast must exist in the subsurface property to which a particular method is sensitive. There are several geophysical properties and methods that are sensitive to the contrast between frozen and unfrozen soil, making them potentially applicable for assessing the integrity of the frozen-soil barrier surrounding the Fukushima Daiichi Nuclear Power Station. However, the subsurface infrastructure (pipes and access tunnels) within the vicinity of the frozen-soil barrier will, in all cases, complicate the interpretation of geophysical data, and may render some methods useless. This section discusses seismic, ground penetrating radar, and electrical resistivity tomography techniques as potentially useful methods for remotely assessing frozen-soil barrier integrity. The section includes discussion of issues related to subsurface infrastructure that must be considered to fully assess the applicability and likely performance of a particular method.

> Key points:
>
> Geophysics is an important category of technologies to support supplemental monitoring of a frozen soil barrier. At Fukushima, surface interferences (buildings, roads, surface utilities, and ground capping/facing activities), subsurface infrastructure, and penetrations in the frozen barrier complicate the application of geophysics.

Seismic Methods

In unconsolidated sediments, the acoustic wave velocity increases significantly with a transition from unfrozen to frozen sediment. Consequently, measurements of acoustic wave velocity within the frozen-soil barrier using seismic methods can potentially be used to assess frozen-soil barrier integrity. Seismic reflection, seismic refraction, and seismic transmission are all viable methods of assessing frozen-soil barrier acoustic wave velocity. Each method is discussed below.

<u>Seismic Reflection</u>

In the seismic reflection method, a seismic source (e.g., hammer on a steel plate) is discharged on the top of the frozen-soil barrier, thereby initializing an acoustic wave within the frozen-soil barrier. The wave travels unimpeded until it reaches a contrast in density such as a pipe, access tunnel, or a zone of unfrozen soil, as shown in Figure 28 (black arrows). Changes in density induce reflected waves (white arrows) which travel back to the surface of the frozen-soil barrier where they are recorded by multiple geophones (acoustic sensors) placed along the interrogated section of the frozen-soil barrier. The seismic source and geophones are then moved along the frozen-soil barrier wall and the process is repeated. Arrival times recorded at the geophones are then analyzed to determine the position of the acoustic wave reflectors (zones of density contrast). If the position of infrastructure reflectors (e.g., pipes, access tunnels, etc.) is known, the compressional wave arrival times in a solid frozen-soil barrier would be predictable, and delayed arrival times are diagnostic of unfrozen soil. The analysis process enables the location of the unfrozen soil to be located. Access to the top of the frozen-soil barrier (e.g., through a shallow borehole) would be required to implement this method and allow placement of the seismic source and geophones atop the ice. The freeze pipes within the frozen-soil barrier need to be accounted for as part of data interpretation.

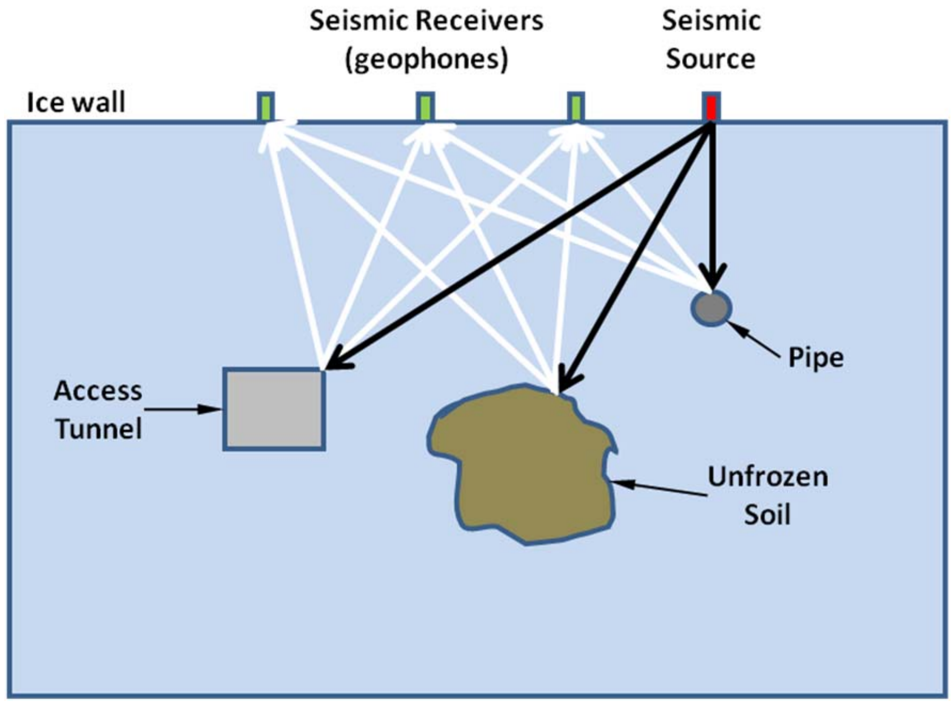


Figure 28. Section view conceptual diagram of transmitted (black arrows) and reflected (white arrows) acoustic waves within a frozen-soil barrier. Analysis of compressional wave arrival times enables detection of density contrasts such as unfrozen soil and infrastructure.

Borehole Seismic Reflection

An alternate seismic reflection approach is to place both the seismic source and acoustic receivers within a single borehole located adjacent to the frozen-soil barrier. Using this approach, an acoustic wave initiated at the source reflects off of the frozen-soil barrier, returns to the borehole, and is recorded at multiple vertical borehole receiver locations. The lack of a reflected arrival or the detection of a reflected arrival with diminished amplitude at a given depth are both diagnostic of an unfrozen zone within the frozen-soil barrier. Potential difficulties with this approach are the concurrent arrival of the direct and reflected waves, making reflected wave arrival time indeterminate, particularly if the borehole is close to the frozen-soil barrier. Conversely, if the borehole is too far from the frozen-soil barrier, unfrozen zone detection capability will be reduced. Furthermore, this approach will only analyze the portion of the frozen-soil barrier directly adjacent to the borehole
.

Borehole Seismic Refraction

Seismic refraction, in this case, relies on the measurement of acoustic wave refracted by the frozen-soil barrier between two boreholes, as shown in Figure 29, and does not require that the seismic source or the acoustic sensors be in contact with the frozen-soil barrier. The method works by initiating an acoustic wave within a source borehole, and recording the first wave arrival times in a receiving borehole some distance away. Because the frozen-soil barrier acoustic wave velocity is greater than the velocity of unfrozen soil, the acoustic wave refracts and travels along the soil/frozen-soil barrier interface at the velocity corresponding to the frozen-soil barrier properties, such that the first signal at the sensor is the refracted wave arrival. Refracted waves travelling through unfrozen portions of the frozen-soil barrier will display anomalously slow first arrival times, thereby indicating the presence of the unfrozen zone. The performance of this method will depend largely on the size of the unfrozen zone and on the location of infrastructure along the refracted wave paths. Infrastructure that penetrates the frozen-soil barrier will complicate interpretation of refraction data, making it difficult to analyze for unfrozen zone detection.

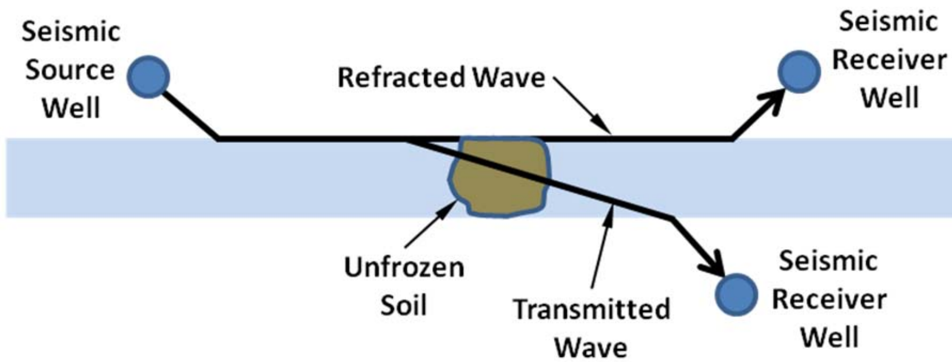


Figure 29. Plan view conceptual diagram of refracted and transmitted acoustic waves between two boreholes through and ice wall. Refracted waves travel along the wall of the frozen-soil barrier, whereas transmitted waves travel through the frozen soil barrier. Analysis of acoustic wave arrival times enables density variations such as unfrozen soil within the barrier to be located.

Borehole Seismic Transmission

Seismic transmission analysis is similar to refraction analysis, except that the transmitted wave arrival time is observed instead of the refracted wave (Figure 29). The transmitted wave amplitude is larger than the refracted wave amplitude, making first arrival times easier to determine and thereby simplifying the analysis. As with the other methods, the presence of infrastructure within the seismic wave travel paths complicates data analysis. However, the source and receiver wells, which must be on opposite sides of the wall, can be located such that transmission through infrastructure is eliminated. The tradeoff is that only a small portion of the frozen-soil barrier (i.e., the portion between wells) is analyzed. By varying the position of the source and receivers, comprehensive data sets can be collected, from which the velocity structure between boreholes may be estimated using tomographic analysis.

Ground Penetrating Radar (GPR)

Electromagnetic (EM) waves propagate through the subsurface at a velocity that is governed primarily by the relative permittivity of the materials through which the wave is propagating. The relative permittivity (dielectric constant) is the unitless ratio of the electrical permittivity of a material to the electrical permittivity of free space (vacuum). Due to the polarized nature of the water molecule, the relative permittivity of water is approximately 84 and the relative permittivity of ice is approximately 4. This large contrast in relative permittivity enables ice structures to be remotely interrogated by measuring EM wave velocities using ground penetrating radar (GPR).
In analogy to the seismic reflection method shown in Figure 28, contrasts in relative permittivity induce reflections in EM waves that can be used to locate heterogeneities in ice structures such as unfrozen zones. In this case, a radar source antenna is placed in the source position on the upper surface of the frozen-soil barrier, and the receiving antenna is placed at the receiver position. A radar pulse is propagated from the source antenna and reflections are observed at the receiving antenna location(s) (see Figure 28). Radar pulse arrival times are then

analyzed to locate anomalies within the frozen-soil barrier. Note that contrasts in relative permittivity or electrical conductivity caused by infrastructure will initiate reflections that may mask reflections from unfrozen zones. As with the seismic method, if the position and dimension of infrastructure inclusions are known, then the arrival times of reflections from those structures may be predicted and de-convolved from anomalous arrivals (i.e., from unfrozen soil or other defects) to determine the existence and location of unfrozen zones.

A related approach is where cross-hole GPR measurements are used to measure EM velocity through the frozen-soil barrier by using EM pulse generation and signal acquisition between two boreholes. Measurements where the source and receiver antennas are placed at the same elevation (i.e., zero vertical offset measurements) may be used to assess the average velocity at a given depth. More comprehensive data sets, whereby source and receiver antennas are oriented at many different vertical offsets (Figure 30), can be analyzed using tomographic imaging algorithms to provide a high resolution 2D map of EM wave velocity between the wells. Such cross-hole imaging would be well suited for use when the imaging plane (i.e., the plane between boreholes) is perpendicular to the frozen-soil barrier (Figure 30A). However, this would only allow assessment of a 1D vertical line along the frozen-soil barrier. If the imaging plane is parallel to the frozen-soil barrier, and close enough that the refracted EM wave arrival is the first arrival, then cross-hole GPR could be used to image EM velocity in a 2D section of the frozen-soil barrier (Figure 30B).

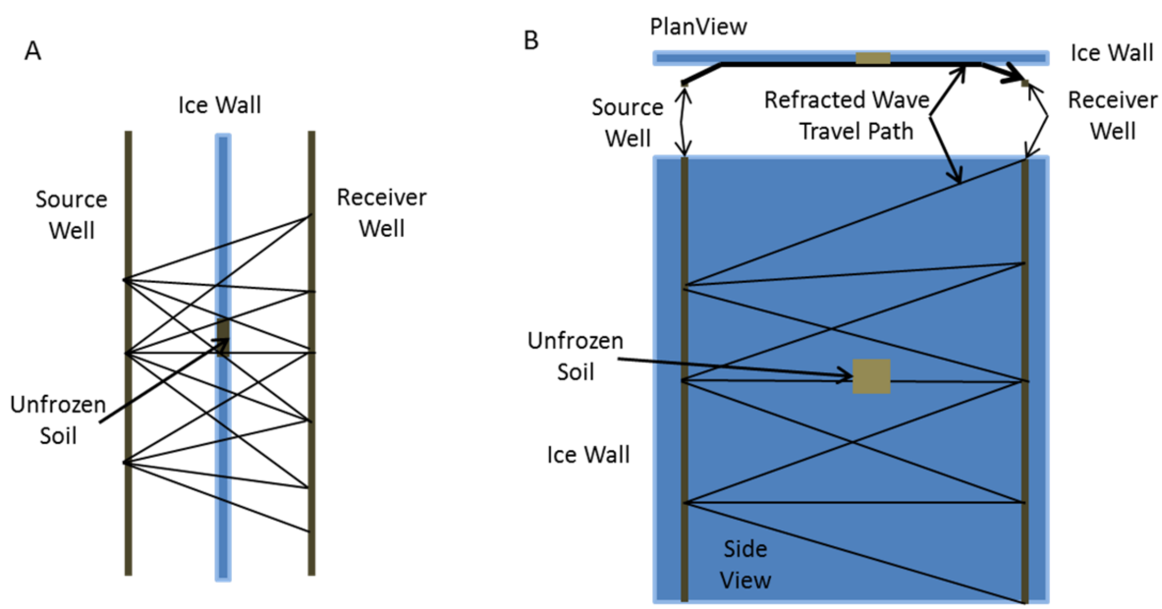


Figure 30. A) Conceptual diagram of cross-hole GPR data collection perpendicular to the frozen-soil barrier for tomographic analysis. B) Conceptual diagram of cross-hole GPR data collection parallel to the frozen-soil barrier use refracted wave arrival times for tomographic analysis.

Because EM waves are quickly attenuated in media with high electrical conductivity, the electrical conductivity of the frozen-soil barrier and soil must be considered when evaluating the likely performance of GPR for assessing frozen-soil barrier integrity. GPR transmission will be severely limited by metallic (i.e., conductive) freeze pipes or excessive metallic infrastructure within the frozen-soil barrier. GPR transmission will also be severely limited by the presence of pore water with high specific conductance. Thus, GPR will not be effective in assessing zones with seawater intrusion.

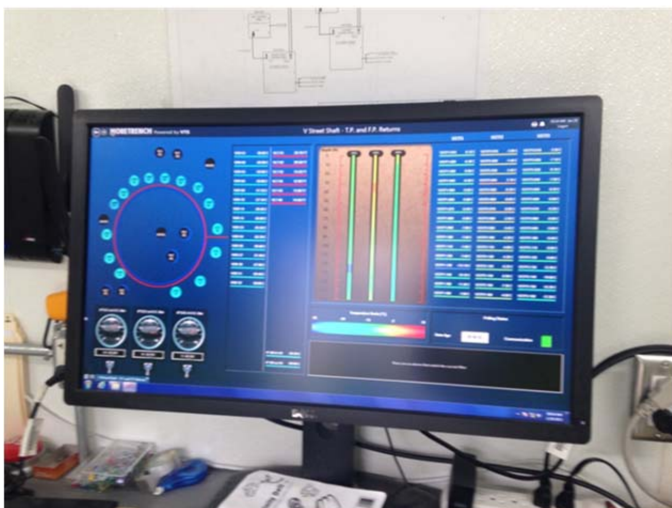
Electrical Resistivity/Conductivity Methods

Low frequency electrical currents will typically exist within unconsolidated natural sediments primarily because of ionic current flow within pore fluids. Thus, the conductivity of the pore fluids is the main factor in the direct-current electrical conductivity of sediments. Ionic current flow is highly inhibited in ice as compared to water, such that the bulk electrical conductivity of frozen sediments is much lower than the bulk electrical conductivity of unfrozen sediments. Consequently, geophysical methods that estimate bulk subsurface conductivity are, in general, attractive candidates for remotely assessing frozen-soil barrier integrity. Electrical resistivity tomography (ERT), in particular, is a well-proven and robust method for imaging subsurface electrical conductivity. However, ERT measurements are highly sensitive to the presence of metallic infrastructure (e.g., metallic pipes and wellbore casings). Although methods are available to account for such infrastructure in the ERT analysis, the presence of excessive metal can reduce imaging resolution to levels that are not useful. This is expected to be the case for larger scale ERT applications at the FPP frozen-soil barrier. However, ERT may be useful for smaller scale applications where measurements are localized. Conceptually, such measurements would be collected in a cross-hole configuration similar to that shown in Figure 30A, with the difference being that currents are transmitted between electrodes (not antennas) deployed in the boreholes. The primary advantage of ERT imaging in this configuration, in contrast to GPR imaging, is that ERT can be performed in conductive environments, whereas GPR cannot. In addition, ERT data acquisition is autonomous (i.e., it does not require field personnel), making it suitable for continuous time-lapse image applications (e.g., imaging frozen-soil barrier evolution during freezing or thawing).

Engineering Topics

Process Monitoring

Baseline process monitoring associated with ground freezing normally involves monitoring temperatures both within the coolant distribution system and within the subsurface. Temperature monitoring of the coolant equipment should follow standard industrial practices for mechanical equipment. Special considerations should be given for monitoring supply and return temperature of the brine solution in the distribution system. When properly implemented this monitoring provides insight on coolant distribution throughout the system and can be used to balance flow, identify air pockets, and ensure freeze wall formation. The temperature monitoring system should incorporate remote sensors such as thermocouples or more accurate resistance-temperature devices (RTD) that can be integrated into the overall control system. Having an integrated control system with various parameters displayed in customizable formats at a central location is preferred (Figure 31). Standard industrial process control systems provide computer interfaces that readily meet these monitoring requirements.



Artificial ground freezing process control systems monitor the primary refrigeration plant, the secondary brine coolant system (temperatures of the brine feed and return from each zone/well), and temperatures profiles in the monitoring boreholes installed between representative freeze pipes. The information is collected and organized using process control software. Different screens provide information related to the modules in the primary refrigerant facility, the brine circulation system and the temperature monitoring in each zone.

Photograph of a typical calcium chloride brine insulated feed header as it exits the primary refrigeration facility. This particular system is located in Washington DC and uses an ammonia based refrigeration system. The brine is circulated through insulated piping to soil freezing sites up to 2km away.

Figure 31. Example process control for artificial ground freezing (photographs courtesy of MORETRENCH)

As planned for Fukushima, the process monitoring scheme should focus on zones (or blocks/subblocks) of freeze pipes in operational groups. These operational groups would contain a number of freeze pipes and ideally the groups would have similar heat loads such that temperature observations between groups can be readily compared. Monitoring of brine supply and return temperature to these groups will allow calculation of the energy removal per group. During operations the difference or "split" between the supply and return temperature becomes a useful operational parameter. Brine flowrate in the system is maintained by balancing the split temperature so that a constant difference is maintained. This approach ensures that brine flows are properly adjusted so areas requiring greater energy removal are balanced with those with lower energy removal requirement. The current construction has 13 freeze blocks of varying length defined. Ideally, the control scheme would involve subdividing the 13 freeze blocks into smaller groups based upon a uniform calculated energy load.

In addition to temperature monitoring of the groups, individual freeze pipes should have supply and return temperature monitoring capability. Industry experts recommend a target return brine temperate of -25°C (or lower) as crucial in ensuring a complete freeze wall closure (Joe Sopko interview). After start-up, a differential temperature > 5°C between the supply and return can indicate air pockets within the freeze tube. Trapped air in the system needs to be systematically removed during start-up because it reduces heat transfer, limiting the effectiveness of affected freeze pipes. If an excessive amount of air is allowed to accumulate air-locks can occur and block flow to parts of the system.

Subsurface temperature monitoring is a simple technique to monitor the development of the freeze wall. Simple vertical arrays of temperature sensors can provide information on subsurface conditions and the position of the ice-front (zero-degree isotherm). Due to inherent three-dimensional nature of the freeze wall, subsurface temperatures should be measured at various depths and locations. Routine evaluation of this data will allow monitoring of the freeze wall development. The observations from the temperature sensors can be evaluated assuming a linear temperature variation which would provide a reasonable estimate of the location of the 0 to -1°C isotherm. For environmental process control applications of thermal technologies, the temperature systems installed by the National Laboratory team (and by leading ground freezing companies such as MORETRENCH) use RTDs instead of thermocouples because of the relative reliability, robustness, and design flexibility. The ability to measure a temperature profile in the monitoring boreholes will be a key factor in assessing if there are high permeability lenses that are impacting the progress of the freeze in particular depth intervals. This will be a first line of evidence regarding potential leak locations that might require contingency actions if the barrier is not achieving TEPCO objectives.

Key points:

Baseline process monitoring for artificial ground freezing focuses on the primary refrigeration facility, the brine coolant loop and measurement of representative temperature profiles from monitoring boreholes throughout the barrier. Process monitoring in the above-ground portions of the process typically include flow data, pressure data and temperature data. The information from all of the sensors in the boreholes and the above ground systems is typically collected and organized using process monitoring software that allow system control and that provides alarms for leaks and equipment malfunctions. Based on the information provided, the TEPCO/Kajima team appears to be planning a high quality artificial ground freezing operation that fully implements the industry standard process controls.

Interferences and Barrier Penetrations

One of the challenges facing the deployment of a frozen barrier are large underground obstacles such as coolant pipes and concrete duct banks that may complicate freeze pipe boring and inhibit complete freezing of the ice wall due to increased freeze pipe spacing or the presence of the obstacle. Generally obstacles would be a concern if they are larger than the standard spacing of the coolant pipes. In flowing groundwater systems, incomplete freezing above and below large obstacles would result if alternative strategies are not implemented to increase the coverage of freeze pipes. Standard practice in North America for freezing near large obstacles normally involves carefully targeted angle boring and surveying the installed borings to document proper positioning (see earlier Figures 10 and 12 for examples). The current construction approach for the Fukushima site is to adjust the placement of coolant pipes (by adding supplemental vertical freeze pipes along the edges of the obstacles) and in some circumstances by penetrating the existing obstacle and providing a watertight seal. These strategies are illustrated Figure 32. The TEPCO/Kajima strategies were designed based on thermal modeling and both strategies should provide reasonable frozen soil barrier closure in the zones above and below the various obstacles and penetrations.

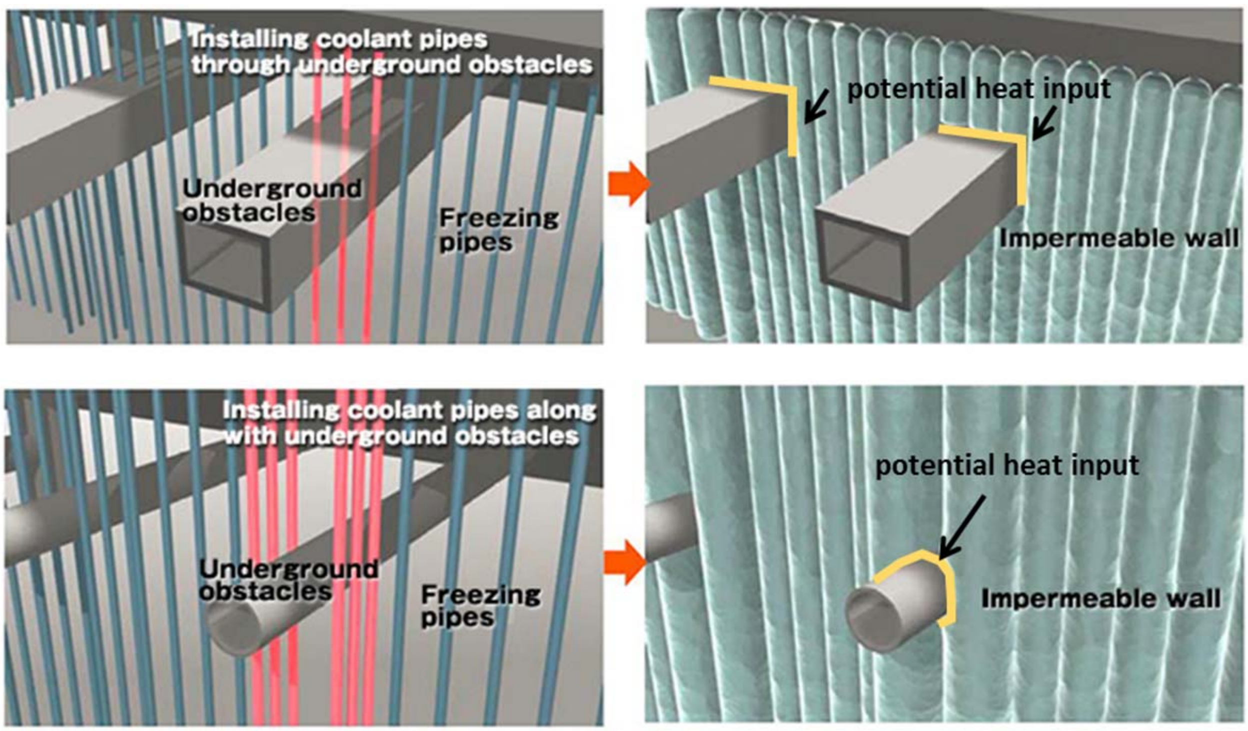


Figure 32. Strategy for managing underground obstacles and penetrations in the Fukushima frozen soil barrier graphic provided by TEPCO (http://www.tepco.co.jp/en/decommision/planaction/qa_ice_wall-e.html)

A second challenge related to subsurface obstacles and penetrations is the ability to freeze all the way to the surface of the obstruction to completely seal the frozen barrier around the structure. This is a particular challenge for large concrete structures and pipes with flowing water. These types of obstacles can serve as a heat input due their thermal conductivity, and the heat loss into flowing fluids or interior air. The largest of the penetrations at

Fukushima typically have cross-sectional areas greater than 1-square meter and a significant thermal mass and thermal conductivity such that the obstacle serves as a sink for energy being supplied by the freeze pipes.

The National Laboratory team supports the TEPCO strategy of adjusting the position and increasing the number of coolant pipes near the obstacles and the approach of penetrating obstacles and allowing the coolant pipe to pass through the obstacle. For these large types of obstacles, however, it may be necessary to further reduce energy losses. When interior access is available the coolant pipes that penetrate the obstacles should be insulated and the interior walls of the obstacle should also be insulated in the vicinity of the freeze wall (Figure 33A). Both of these actions will reduce energy losses. In North America, MORETRENCH has used this insulation strategy in past deployments and, in one case, they tapped into the freeze pipes that penetrated an obstruction and installed supplemental cooling loops along the interior surfaces to assure that the outside soil froze all the way to the exterior surface of the obstacle (Figure 33B based on interview with Joe Sopko). We do not believe that this level of contingency is needed for Fukushima, but recommend insulating the walls and the penetrating freeze pipes, where access is available. If barrier penetrations are causing barrier to leak, and the leaks are limiting TEPCO's ability to achieve barrier objectives, additional contingencies could be implemented at that time. Underground obstacles have the potential to create local uncertainties related to the integrity of the frozen barrier and some additional monitoring in these areas would be prudent.

Key points:

The TEPCO/Kajima strategies to freeze above and below subsurface penetrations – using added vertical freeze pipes adjacent to some penetrations or installing freeze pipes directly through other types of penetrations – are reasonable. For freezing above and below the penetrations, these strategies should be as effective as the angle drilling strategies that have been used in many previous ground freezing applications around the world. Achieving a complete freeze against the outside surfaces of penetrations may represent a more significant challenge. Previous experience at ground freezing sites indicates that a complete seal is often impeded by heat input from the obstruction/penetration. Heat can be brought into the frozen soil barrier zone by transverse conduction from internal air or fluids through the penetration wall or by longitudinal conduction along the penetration wall. An unfrozen soil zone is often present around penetrations. If leakage around a penetration is deemed significant, a number of engineering approaches can be used to mitigate the problem. One notable recommendation would be for penetrations having interior access and through which freeze pipes are installed. In such instances, TEPCO could insulate the freeze pipes inside the penetration as well as the interior surfaces of the penetration in the area where the penetration crosses the barrier. These actions could be implemented relatively easily and would significantly improve the potential for effective barrier performance in those areas.

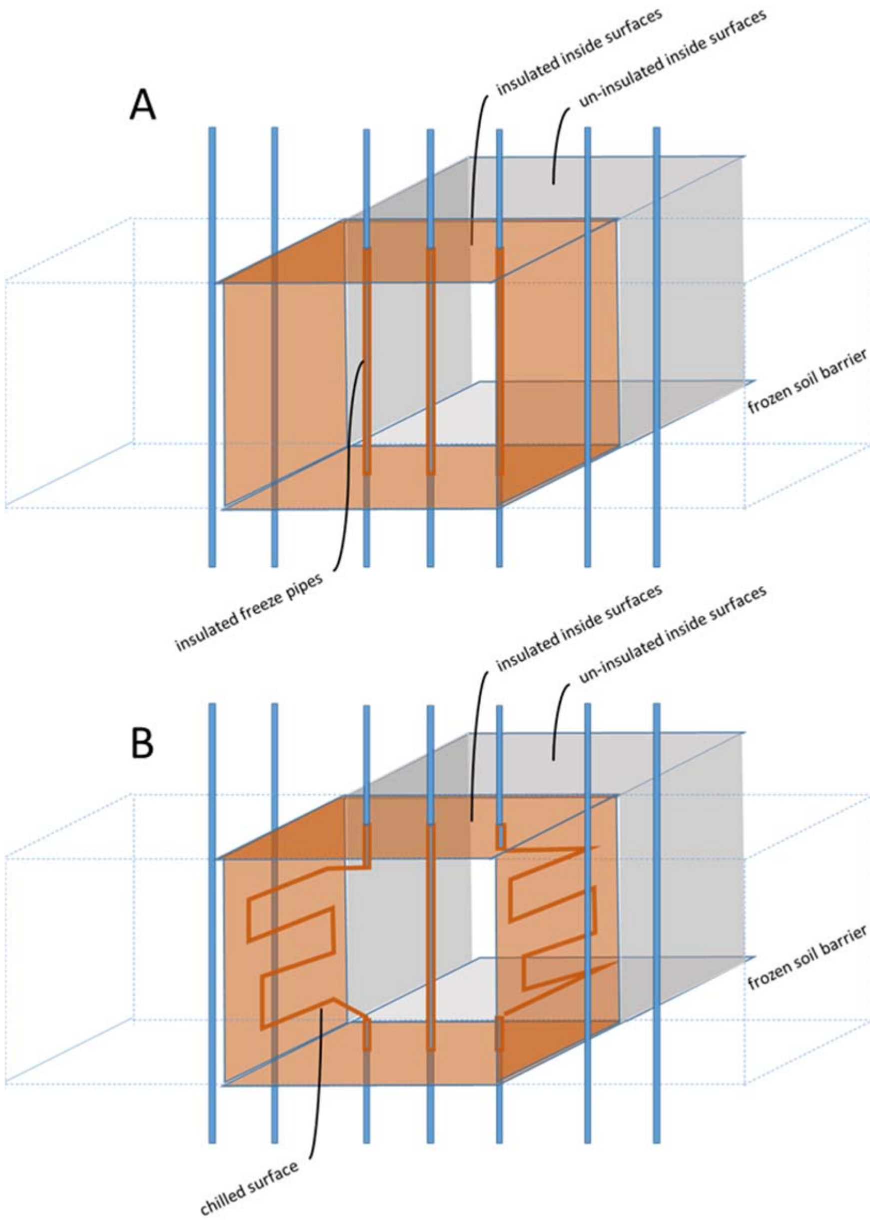


Figure 33. Example engineering solutions to the challenge of sealing large accessible penetrations with freeze pipes installed through the penetration; A) simple insulation approach (freeze pipes and interior surfaces within the frozen soil barrier insulated); B) active wall cooling concept (coils installed on all four interior surfaces, and freeze pipes and interior surfaces insulated)

Frost Heave

A number of studies have been conducted on soil heave, though most are in the context of natural ground freezing (e.g., Talamucci, 2003) and many are modelling studies (e.g., Bronfenbrener and Bronfenbrener, 2010) looking at determining a mathematical framework for representing the freeze/heave/thaw/settlement processes. However, several references discuss soil heave in the context of artificial ground freezing (Ohrai and Yamamoto, 1991; Schmall, 2014; Green et al., 2014; Yang et al., 2006; Allenby and Ropkins, 2007; Lackner et al., 2005; Roworth, 2013; Bell, 1992). Roworth (2013) identified the following points in a synopsis of heaving:

- In frost-susceptible [vadose zone] soils, water can migrate from unfrozen soil into the frozen zone due to the induced suction gradient as liquid water freezes.
- In coarse [vadose zone] soils such as sands and gravels, the pores will fill with ice and excess pore water will drain into the unfrozen areas, resulting in minimal heaving. Fine sand and silts are more susceptible to heaving.

Due to water migration in the vadose zone and the general increase in volume associated with the phase change of water from a liquid to a solid during freezing, ice formed during artificial ground freezing exerts forces in the subsurface (Powers et al., 2007). Lateral heave forces (e.g., from vertically emplaced freeze pipes such as for a freeze wall or shaft construction) are described as being "rarely an issue" because of the relatively large lateral earth pressures at typical depths below ground surface (Schmall, 2014). Near-surface applications and horizontal freeze pipe installations (which are not applicable to Fukushima) have more potential for soil heave. Soil heave from deeper horizontal freeze pipes would be attenuated by overburden pressure. In addition, field observations suggest that the ground at a distance of 3-5 times the frozen body radius (i.e., for vertical freeze pipe installation) is unaffected by artificial ground freezing (Bell, 1992). According to North American suppliers of artificial ground freezing, heaving calculations from the literature tend to overpredict the heaving observed in the field. Based on the planned location of the Fukushima frozen soil barrier (in relation to nearby buildings and structures), lateral heaving is not expected to result in collateral damage or significant pressure to the structures. It is possible that some observable heaving will occur directly above and directly adjacent to the frozen soil barrier. If the barrier passes through a sensitive area, monitoring of heaving is feasible and has been performed as part of a number of artificial ground freezing applications. Monitoring of temperatures, heave pressures, and deformations (e.g., with deflectometers, extensometers, and/or inclinometers) in these areas would provide information to assist in managing impacts from soil heave.

A variety of approaches can be applied to minimize effects of soil heave. Because evolution of the frozen zone is an important factor in controlling soil heave (Lackner et al., 2005), the freezing process itself should be conducted to control the size of the frozen soil zone (Schmall, 2014). Allenby and Ropkins (2007) describe how "careful monitoring of both ground and return brine temperatures and the use of valves to adjust the brine flows enabled the frozen zone to be developed and maintained with the minimum of ground heave." The proximity of freeze pipes relative to structures of concern is important and can be controlled by the location of the freeze pipe. Routine maintenance of certain structures (e.g., roads or railway tracks) can correct for minor impacts from soil heave (Allenby and Ropkins, 2007; Green et al., 2014). The freezing pipes themselves should be designed, installed, and monitored to avoid pipe damage (and associated brine coolant leakage) due to soil heave.

Freeze Damage to Subsurface Utilities

Artificial ground freezing is generally viewed as amenable for freezing around buried utilities (ITRD, 2001; Chen et al., 2010). Ground freezing does not generally damage the following buried utilities: power lines, phone or fiber optic cables, most gas transmission lines, and large sewer lines and storm drains. The most vulnerable types of utilities are small sewer and drain lines and buried pressurized water pipe that traverses the vertical frozen soil barrier. If water in the pipe is flowing on a regular basis, then freezing/damage is unlikely. If the water in the line is stagnant (or seldom flows) then freezing of the water must be prevented to avoid blockage and potential line breaks. One effective method for preventing water in a line from freezing is to pre-excavate the soil in the area of the frozen barrier (extending about 1m on either side of the wall centerline), insulate (or heat trace) the line, and expose this section of insulated water line to air rather than leaving it buried in the frozen barrier. Leaving air around the sides and top of insulated water lines has been used on a number of ground freezing projects in North America. Many of these were relatively short-term construction-focused projects with shallow water lines, however, and such a method may not be appropriate at Fukushima with a longer projected operating life and deeper penetrations. Other engineering strategies that would protect buried water lines include: excavation-heat tracing-reburial, maintaining flow through the lines, or rerouting lines (e.g., to the surface) in the vicinity of the frozen barrier.

> Key points:
>
> Based on the conditions and layout at Fukushima, the risks of frost heave and subsurface utility damage are relatively low. If sensitive surface infrastructure is located directly adjacent the frozen soil barrier (i.e., within about 5 m) then TEPCO should consider additional analysis and monitoring – particularly in areas where the barrier is forming very close to the ground surface. Subsurface water lines penetrating the barrier should be evaluated to determine if potential freezing and line blockage might occur.

Water Table Issues

Given the nature of the planned freeze wall implementation—a relatively long wall with significant upgradient flow from the mountainside, the impact of water table rise on the freeze wall should be considered. No significant discussion or literature information was found relative to artificial ground freezing applications involving an increase in the water table elevation or groundwater "spillover" at the top of a freeze wall. The only mention of water table fluctuations with respect to artificial ground freezing that was found (Bell, 1992) was relatively brief and simply pointed out such fluctuations could impact the mechanical properties of the frozen body due to variations in water content. At Fukushima, the general purpose of the frozen soil barrier is to prevent water from entering the enclosed zone. However, some fraction of the groundwater flux entering the zone may be manageable through the subdrain system or pumping and the water flux from a rising water table may be within the performance margin for water inflow.

The impact of a rising water table will depend on how artificial ground freezing is implemented. One scenario is where the freeze pipes are un-insulated above the current water table. In this case, as the mountain-side water table rises, water flowing over the top of the freeze wall would itself undergo freezing. The extent of the freezing of this "spill over" water will depend on the stage of artificial ground freezing (initial wall development or wall maintenance) and the groundwater velocity. The second scenario is where the freeze pipes are insulated from the ground surface down to the water table. This type of insulation would limit frozen body formation near infrastructure and to improve the system efficiency. In this insulated case, groundwater that rises above the top of the freezing zone would be expected to “spill over” the top of the freeze wall. This could cause issues with thermal erosion at the top of the freeze wall, particularly during outages of the brine circulation system.

Key points:

A number of engineering options are feasible to address a rising water table on the upgradient (mountain-side) of the Fukushima frozen soil barrier. For example, if mitigation is needed to meet overall barrier performance objectives, additional upgradient pumping using the groundwater bypass system could be implemented. If the freeze pipes above the water table are not insulated, then the freeze wall should grow upward on the mountain-side and limit the need for any additional action to address water table rise.

Reasonable water management and engineering contingencies are viable for either scenario. These contingency options could be implemented as needed. The most reasonable baseline options are: a) no action (because the amount of water entering is low and within the capacity of planned subdrain and reactor building removal rates) and b) increasing upgradient pumping from the groundwater bypass wells. Other actions that could be considered if the baseline options are not adequate include: c) adding new upgradient pumping capacity, d) installing engineered drains to move water laterally around the barrier, e) adding additional freezing capacity in areas above the original water table where spillover is observed, and f) planting a band of phreatophyte plants (to naturally extract groundwater) between the mountainside and the barrier. Extended interruption of the operations of the upgradient groundwater bypass system would increase the magnitude of groundwater rise on the mountain-side of the barrier and should be avoided if possible. A focus on continued operation of this important synergistic countermeasure would reduce the risks and potential impacts of groundwater rise.

Post-Operational Issues

The plan for the Fukushima Frozen Soil Barrier is to discontinue brine circulation after the major leaks into the damager reactor buildings have been repaired. At that time, the water control provided by the barrier would no longer be required. After shut-down of the primary refrigerant facility and brine circulation, the barrier would slowly thaw. This would release the water currently held in the barrier ice (the barrier water should be relatively clean, as discussed earler). The thawing of the barrier would also allow water from the mountainside to flow into and through the area and establish a new steady state based on the modified boundary conditions provided by any continuing countermeasures such as the groundwater bypass system, the seaside barrier, and groundwater drain. If the groundwater beneath the site is sufficiently clean, then some of these other countermeasures might be candidates for modifying or discontinuing.

The most significant post-operational issue would be changes induced in the permeability of silts and clays of the upper Tomioka Stratum. Several researchers have observed that freezing and thawing affects the permeability of soils and sediments. For fine grain (silty and clayey) materials, most studies indicate that freezing and thawing increases permeability (Chamberlain and Gow, 1979; Smith, 1972; Porkhaev, 1961; Chamberlain and Blouin, 1977; and Czeratzki and Frese, 1958). Several of these studies (Chamberlain and Gow, 1979; Chamberlain and Blouin, 1977; and Czeratzki and Frese, 1958) indicate that the increase in permeability after freezing and thawing results from aggregation of particles and crack formation. Chamberlain and Gow (1979) examined the effect of freezing and thawing on the vertical permeability of clays. They tested samples under applied stress to represent real-world conditions. They found that permeability after freezing and thawing was higher in all four samples tested and that the ratio of permeability (thawed sample / original sample) was in the range of 10x to 100x.

Based on the literature, it is likely that vertical permeability of the clay and silt layers that are within the Fukushima frozen soil barrier will be higher than the original baseline levels after the barrier thaws. The change in vertical permeability is likely to be in the range observed in the literature (10x to 100x) in those layers. This has the potential to allow increased vertical interaction and movement of water within the upper 10 to 20 m of the subsurface. While this increase is not likely to result in any significant negative impact, the National Laboratory team recommends considering this expected change during the planning for shut-down of the frozen soil barrier operations.

Key points:

At the end of operations, the barrier will thaw and the system will develop a new hydrologic balance based on flow from the upgradient mountain-side and the modified boundary conditions provided by any continuing countermeasures. Clay and silt layers are expected to exhibit increased vertical permeability after the freeze-thaw cycle.

Software

The following is a list of some software discussed in the context of artificial ground freezing. Most software uses the finite element method (FEM) to simulate temperature (and in some cases strength and/or fluid flow) to determine the appropriate design (freeze pipe placement, coolant temperature, etc.) for the application. Several vendors use a combination of TEMP/W and SEEP/W to simulate ground freezing for systems with active groundwater flow.

TEMP/W	FROSTB	GWFREEZE
SEEP/W	HYDRUS-1D	SHEMAT
FREEZE		

Summary of Potential Failure Modes & Mitigation Strategies

The frozen barrier being installed is intended to limit the migration of uncontaminated groundwater into those portions of the site that contain radioactive contaminants in the subsurface and to prevent the future migration of these contaminants towards the sea. The following discussion identifies possible failure modes associated with the frozen barrier. This information is an extended summary of the discussions within the National Laboratory Team and a meeting between the National Laboratory team and Joe Sopko of MORETRENCH.

Excessive Groundwater Velocities

The critical groundwater velocity required for freezing is a design parameter that is established once the radius and spacing of the freeze pipes are selected. Subsurface variations in soil permeability and flow transients during frozen barrier development may cause local groundwater velocities to exceed the critical groundwater velocity. Because groundwater flow introduces additional heat this may cause incomplete freezing in some areas. As described above, potential mitigation options include: no action (if the overall barrier is meeting the water control objectives), allowing more time for barrier closure, increased freezing capacity (upgradient or targeted freeze pipes), decreased flow (by injection of bentonite or grout), or reduced groundwater gradient (by increasing upgradient water removal. Past artificial ground freezing operations have traditionally used either an added row of freeze pipes or injection of bentonite. However, any of the listed options should be effective for Fukushima in the event of excessive groundwater velocity.

Barrier Deterioration

Barrier deterioration, i.e. thawing of the frozen soil barrier, involves ice erosion by warming, or by contact with liquids that have a freezing point depression lower than the frozen soil temperature. Once formed, the frozen soil barrier must be capable of resisting deterioration due to warming or by contact with various liquid contaminants (brines) that may occur in the soil. Warming is prevented by continued operation of the cooling system at rates sufficient to maintain the integrity of the frozen barrier. If the cooling system were temporarily shut down heat flow from adjacent unfrozen soils would slowly warm and then thaw the barrier. Once completed the frozen barrier is designed to withstand long-term interruptions of power, maintaining effectiveness for approximately two months.

Ice erosion may also occur when local groundwater has a reduced freezing point due to increased concentration of solutes. A credible source of dissolved solutes that would impact the effectiveness of the frozen barrier is associated with coolant (brine) leaks and spills. The formation of the frozen barrier involves above-ground and below-ground piping and circulation of a brine solution to promote cooling and freezing of the soil and groundwater. The brine is generally a 25-30% solution of a highly soluble salt, such as calcium chloride, with a concentration that is maintained near the eutectic point to reduce the freezing point of the brine. Should spilled brine come in contact with the frozen barrier, the freezing temperature of the resulting groundwater would be significantly lowered. The presence of brine will cause thawing of the barrier. During operations brine volumes should be routinely monitored and leaks and spills promptly identified and mitigated.

Underground Obstacles

The inability of the frozen barrier to close due to the presence of abandoned underground obstacles is a credible scenario at the Fukushima Daiichi site. The underground obstacles have the potential to create localized non-uniform heat loads that could affect the development and integrity of the frozen barrier. The strategy of adjusting and increasing the coolant pipes near the obstacles and the approach of penetrating the obstacle and allowing the coolant pipe to pass through the obstacle are appropriate. As discussed above, large obstacles may require insulation or the removal of heat from the interior of the obstacle using local cooling coils.

Other Considerations

In addition to the above items, the following are topics that may impact the long-term operation of the frozen barrier. These items are less credible than those identified above and generally relate to extreme events or other alterations to proposed operations at the Fukushima Daiichi site.

- Near surface thawing of the frozen barrier due to infiltration of warm air. The temperature of the frozen barrier is maintained by freeze pipes that circulate a brine solution below -25°C. The heat extraction capacity of these freeze pipes is generally on the order of 90 watts per meter of length. While warm air does not have a large heat capacity any minimal effects can readily be eliminated by providing surface insulation along the path of the frozen barrier.
- Flooding of area being contained by the frozen barrier. If a future flooding event occurs (e.g., due to a Tsunami) then the water added to the barrier would need to be removed using the available control systems (such as the subdrains) to restore the water balance objectives. We recommend that TEPCO develop a contingency plan for this type of system recovery and have the plan available for use following barrier startup.

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