# A Frozen Soil Barrier to Control Groundwater Inflow into Damaged Reactors at the Fukushima Daiichi Nuclear Power Station – 16613

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## ABSTRACT

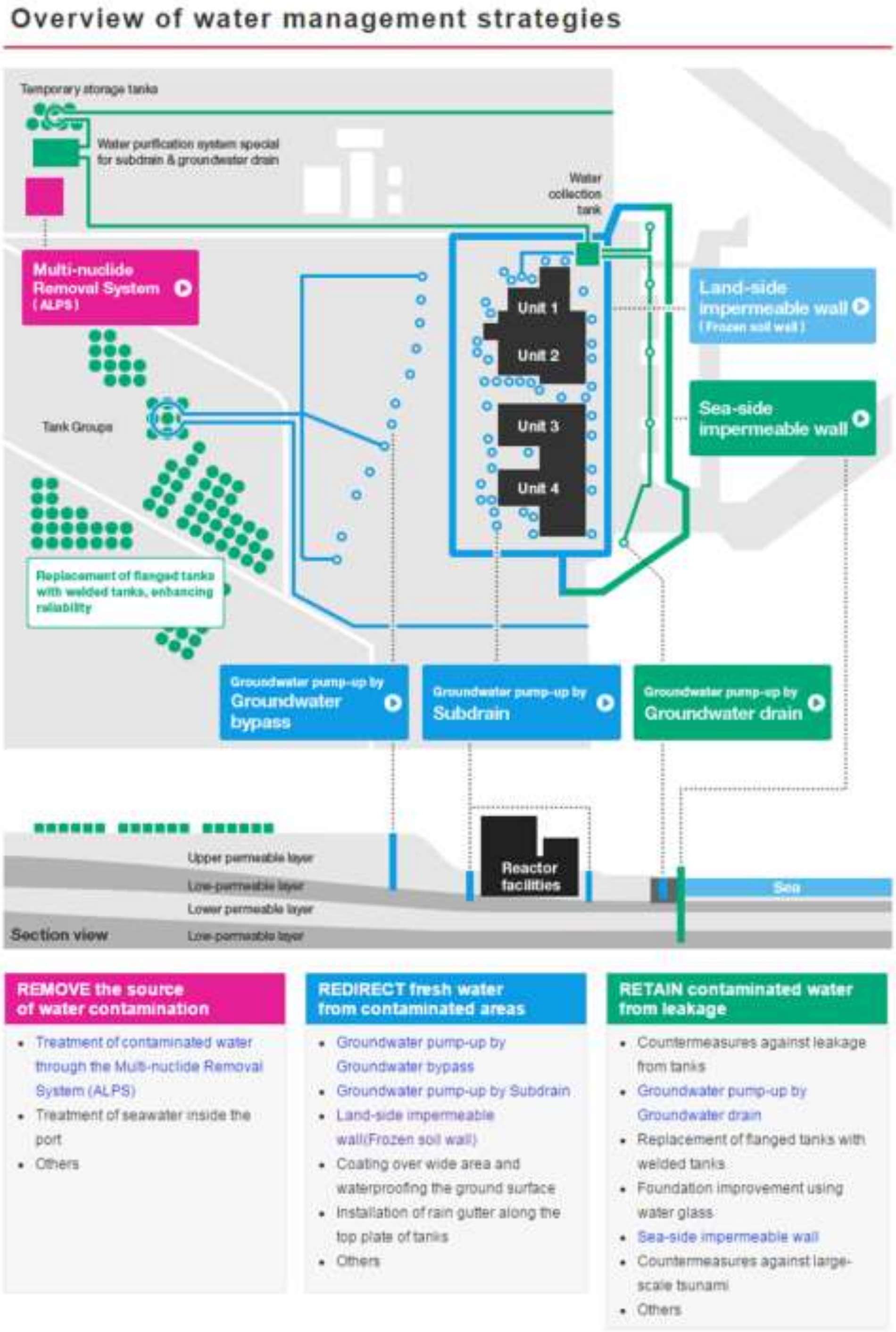
Reactor buildings and support facilities at the Fukushima Daiichi Nuclear Power Station (F1 Site) were damaged by a March 2011 tsunami. In response, the Tokyo Electric Power Company (TEPCO) is implementing a number of countermeasures to limit the releases and impacts of contaminated water to the surrounding environment. The diverse countermeasures work together in an integrated manner to provide different types, and several levels, of environmental protection. In general, the strategy represents an 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, reduce the amount of water entering damaged reactors, and reduce the resulting volume of contaminated water that requires treatment and storage. The frozen soil barrier was designed and installed by a team from TEPCO and Kajima Corporation. A group of scientists and engineers from US Department of Energy National Laboratories provided independent evaluation of the frozen barrier design and operational plans along with technical recommendations to the TEPCO team. The frozen soil barrier design extends to about 30 m depth; the bottom of the barrier is in a low permeability interval, and the total barrier length around the reactors is just over 1.5 km. The barrier required 1927 total boreholes: 1568 for freeze pipes plus 359 for temperature monitoring arrays. Drilling of all of the boreholes was completed November 9, 2015. Construction of the refrigeration plant is complete and all of the above ground piping/manifolds are in the final stages of construction. The DOE laboratory independent assessment of the frozen soil barrier concluded that the technical characteristics of a frozen barrier are relatively well suited to Fukushima-specific hydrogeologic conditions and the need for reducing the inflow of water into damaged reactors at the F1 Site. 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 and supported the full scale design parameters. These factors increase the confidence in the frozen soil barrier project underway at Fukushima. TEPCO is currently working with the Japanese Nuclear Regulatory Authority (NRA), providing operational plans/strategies for the frozen soil barrier and modeling results of the projected performance. Full scale frozen soil barrier operations are to begin after authorization from NRA.

## INTRODUCTION

TEPCO is installing a "land-side impermeable wall" (frozen soil 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" that are being implemented to minimize future impacts from the nuclear reactor facilities that were damaged by the March 2011 tsunami, which was triggered by the offshore Tōhoku earthquake. The various countermeasures focus on three goals: a) REMOVE the source of water, b) REDIRECT fresh water from contaminated areas, and c) RETAIN contaminated water on-site. The diverse countermeasures work together to provide different types, and several levels, of protection. The strategy represents an example of a "defense in depth" concept that is used for nuclear facilities around the world. Key countermeasures are depicted and categorized in Figure 1. (note: the figures and descriptions summarized in this background section were adapted from [1]).

Treatment of contaminated water pumped from inside the damaged buildings is one of the most active and important countermeasures (Figure 1). This treatment is being performed using a state-of-practice multi-nuclide treatment system (ALPS). The excess treated water is being stored in tanks. Secondary wastes from the treatment are being staged for disposal.

Outside the damaged buildings, potential contamination 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 and the subdrain system (Figure 1) pump up groundwater to tanks. For the bypass system, the water is analyzed for contaminant radionuclides. If concentrations are significantly below World Health Organization (WHO) guidelines, the water is discharged to the ocean. The bypass system pumping wells are installed upgradient of the damaged reactors and removal of the uncontaminated upgradient groundwater reduces the amount of groundwater flowing past the damaged reactor area toward the ocean. The subdrain system removes relatively clean groundwater in the vicinity of reactors to lower water levels and limit inflow into contaminated facilities. The operation of the subdrain systems is similar to the groundwater bypass system with additional processing steps to remove low-level contamination to assure that water released meets agreed 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 F1 Site. Key stakeholders, such as fishermen, have concurred with the operational protocols and guidelines for the release of water from the bypass and subdrain systems and the closure of the seaside barrier. These countermeasures are currently operating.



**REMOVE the source of water contamination**

- Treatment of contaminated water through the Multi-nuclide Removal System (ALPS)
- Treatment of seawater inside the port
- Others

**REDIRECT fresh water from contaminated areas**

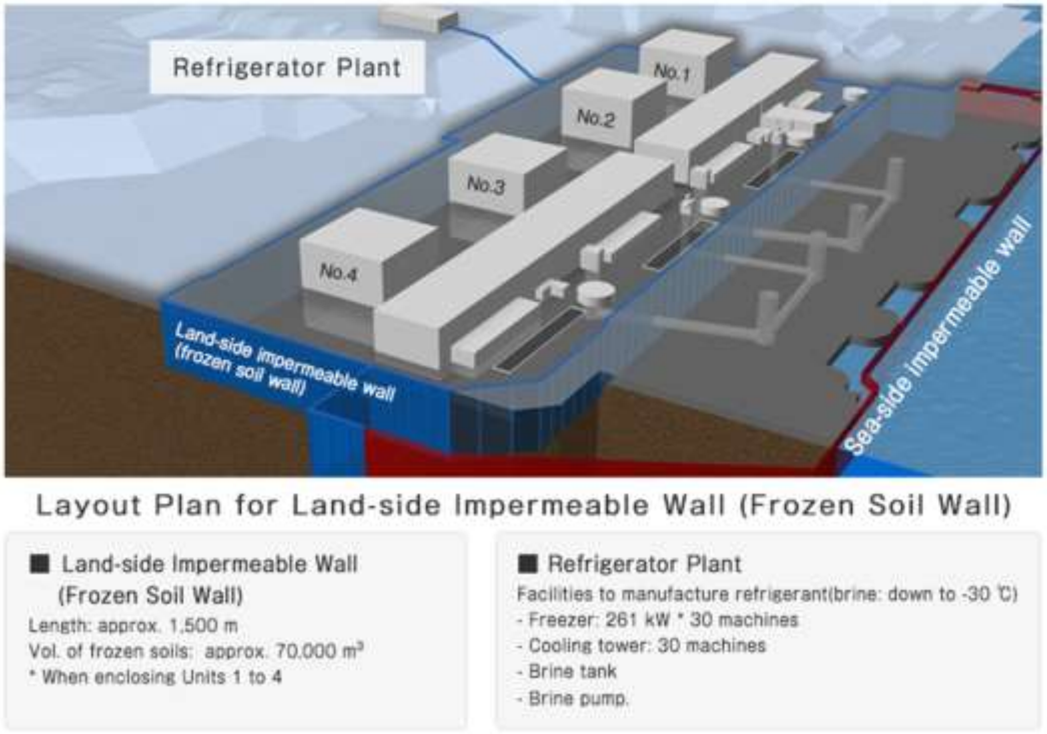
- Groundwater pump-up by Groundwater bypass
- Groundwater pump-up by Subdrain
- Land-side impermeable wall(Frozen soil wall)
- Coating over wide area and waterproofing the ground surface
- Installation of rain gutter along the top plate of tanks
- Others

**RETAIN contaminated water from leakage**

- Countermeasures against leakage from tanks
- Groundwater pump-up by Groundwater drain
- Replacement of flanged tanks with welded tanks
- Foundation improvement using water glass
- Sea-side impermeable wall
- Countermeasures against large-scale tsunami
- Others

Figure 1. Summary of Contaminated Water Countermeasures being implemented by TEPCO at the F1 Site [1]

As shown in Figure 2, 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 area. Most important will be the option to reduce groundwater levels in the upper aquifer inside the barrier and explicitly control 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.



Layout Plan for Land-side Impermeable Wall (Frozen Soil Wall)

■ Land-side Impermeable Wall (Frozen Soil Wall)
Length: approx. 1,500 m
Vol. of frozen soils: approx. 70,000 $m^3$
* When enclosing Units 1 to 4

■ Refrigerator Plant
Facilities to manufacture refrigerant(brine: down to -30 ℃)
- Freezer: 261 kW * 30 machines
- Cooling tower: 30 machines
- Brine tank
- Brine pump.

Figure 2. General diagram of frozen soil barrier [1]

The current strategy of the TEPCO/Kajima team is to isolate the groundwater around the four reactors using the landside frozen soil barrier. The groundwater levels inside the barrier will be slowly drawn down by continued water leakage into the buildings and using the subdrain system. As the water levels decrease, the rate of inleakage will slow down. Water levels in the buildings and surrounding groundwater will be carefully monitored. In the final stage of implementation, water levels outside the buildings will be maintained approximately slightly above the water levels inside the buildings. This will result in a slow-controlled inleakage to assure that contamination from the buildings will not flow out into the surrounding soil and groundwater. The stabilized and reduced inleakage conditions will support accessing and repairing the damaged buildings and eventual discontinuation of frozen barrier operations.

## History of Artificial Ground Freezing and Relevant Case Studies

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 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 [2,3]. 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 F1 Site.

Three basic systems have been employed for full scale artificial ground freezing. The most common system (Figure 3) 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. Alternative ground freezing systems use either: a) an expendable refrigerant such as liquid nitrogen, liquid air, or solid/liquid carbon dioxide, or b) a two phase thermosiphon – a heat pump – using a liquid refrigerant (such as pressurized anhydrous ammonia, butane, carbon dioxide, or freons) in the freeze pipes – the refrigerant transfers heat from the subsurface to the atmosphere through “passive” evaporation and condensation in cool climates [3]. Based on the climate and characteristics of the F1 Site, the DOE Laboratory independent technical experts supported the selection of a brine system by the TEPCO/Kajima team as appropriate.

Figure 4 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 chilled brine ($\cong$ -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 ($\cong$ -25°C) exits the freeze pipe assembly into an insulated return manifold.

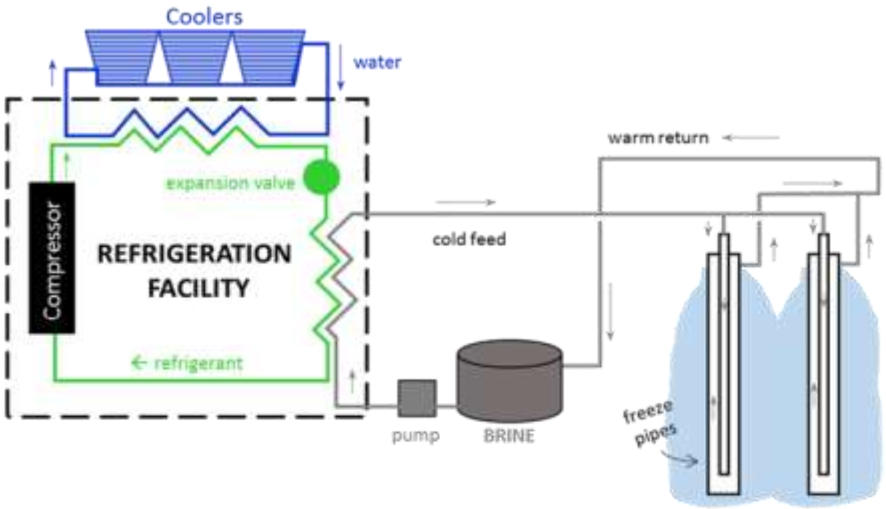


Figure 3. Ground freezing using a brine system (primary refrigerant facility with a pumped secondary coolant loop)

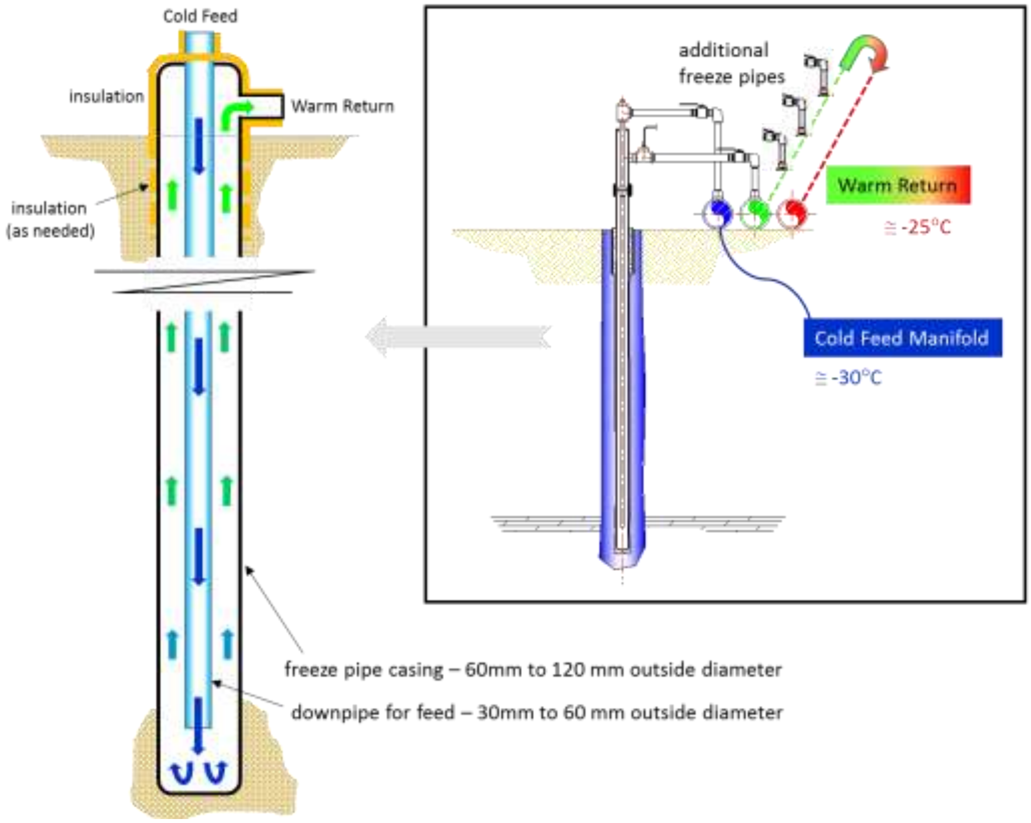


Figure 4. Typical freeze pipe deployment and configuration

Artificial ground freezing was first documented in the late 1800s and has been in engineering use since the 1950s. Artificial ground freezing has been specifically used for foundation stabilization, water control, and to provide mechanical stability to soil to allow safe excavation, tunneling, or mining. Artificial ground freezing is relatively expensive, but the technology provides unique capabilities and advantages that can justify its use. There are hundreds of artificial ground freezing case studies ranging in size and complexity. Importantly, a number of case studies are relevant to Fukushima. For example, MORETRENCH installed a frozen soil barrier to control groundwater at the Aquarius mine in Ontario, Canada. 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 the F1 Site.

Use of artificial ground freezing and frozen soil barriers for long term management of groundwater and control of the release of arsenic trioxide contamination has been demonstrated at the Giant Mine in Yellowknife Northern Territory, Canada. At this site, Arctic Foundations and their collaborators are isolating former mine shafts that contain large volumes of arsenic trioxide dusts generated during the processing of gold. 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, thermosipon technology will be deployed in parallel with a standard brine system. This allows a more rapid freezing and with a transition to the long term energy saving benefits of the thermosiphons in a cold climate.

A second MORETRECH case study, the No. 7 Line Subway Extension in New York NY, demonstrates the suitability of frozen soil barriers for installation in crowded areas that have limitations on access and the presence of underground interferences. This project was performed in an urban area using rotosonic angle drilling to install over 100 boreholes. Freezing system access and equipment were located between busy roadway and adjacent buildings, working around underground utilities (water, telephone, electrical and fiberoptic). Another urban application of a frozen soil barrier, by SoilFreeze, supports the Elliott Bay Seawall Project Waterfront Refurbishment in Seattle WA. This project will rebuild and upgrade the existing seawall (originally constructed between 1916 and 1936) and nearby structures and services (such as new fiber optic cables). Artificial ground freezing was added to this project to control the infiltration of water from the seaside harbor and to stabilize the ground to avoid the possibility of damage to the important Alaska Way Viaduct (a multilevel automobile highway immediately adjacent to the construction). The No. 7 Line Subway Extension and the Elliot Bay Seawall Project are two of many case studies related to large ground freezing applications in urban or industrial settings.

Artificial ground freezing is relatively expensive, but the technology provides unique capabilities, advantages and offsetting cost savings that can justify its use on a site specific basis. At the F1 Site, the potential to reduce the amount of water requiring costly treatment and storage is a major factor that substantiates the implementation of a frozen soil barrier. As described above, the Fukushima frozen soil barrier is generally bounded in scale, objectives and installation complexity by some of the large past commercial applications.

## Frozen soil barrier implementation at the F1 Site

The frozen soil barrier design extends to about 30 m depth; the bottom of the barrier is in a clayey interval, and the barrier length is just over 1.5 km. The barrier required 1927 total boreholes: 1568 for freeze pipes plus 359 for temperature monitoring arrays. Drilling of all of the boreholes required approximately one year and five months and was completed November 9, 2015. Construction of the refrigeration plant is complete and all of the above ground piping/manifolds are in in the final stages of construction (December 2015). Initial pilot testing was performed prior to the full scale design and construction. Test freezing with temperature monitoring of several portions of the full scale barrier have been completed in preparation for full scale operations which are expected to begin early in CY 2016.

## Site Specific Evaluation for F1 Frozen Soil Barrier

As part of the design, planning and construction activities for the frozen soil barrier at the F1 Site, a range of site specific characteristics and factors were independently evaluated [3]. These included: local geology and hydrology, projected barrier geometry, chemical impacts of freezing (fractionation), performance monitoring, expected impacts on water levels, and engineering topics (system operation, freezing around barrier penetrations, frost heave/damage, barrier overtopping/flooding, and contingency strategies). For example, based on the DOE pilot study of frozen soil barriers performed at the Oak Ridge National Laboratory [4], the "cylinders" around each freeze pipe will exhibit a slight distention at the base and narrowing at the top due to thermal and density effects (Figure 5). This overarching geometry of frozen soil around each freeze pipe provides insight into where the barrier will be the thickest (near the base of the barrier) and where the barrier will be the thinnest (between freeze pipes near the top of the barrier) – these expected freeze geometry behaviors were incorporated into the recommended monitoring strategies to be used during barrier installation and maintenance.

The TEPCO/Kajima design was based on state of practice numerical modeling of the barrier formation. The independent evaluation team supplemented the conceptual level evaluation of the barrier geometry and detailed TEPCO/Kajima numerical modeling with a parametric application of closed form analytical design equations [1,5]. The analytical design equations calculate a critical groundwater flow rate (Darcy velocity) for which a barrier would effectively merge (as a function of freeze pipe spacing/design, soil properties and water properties). For an adequate design, measured groundwater flow in the field should be less than the calculated critical groundwater flow velocity. Using the TEPCO/Kajima design, the calculated critical groundwater flow rate for F1 Site conditions is 0.76 to 1.0 m/day. Based on field measurement, the actual bulk groundwater flow rate at the F1 Site ranges from 0.04 to 0.14 m/day. The field values are significantly below the lower bound of 0.76 m/day for the critical Darcy velocity. Thus, the barrier is generally projected to merge in a reasonable timeframe (e.g., less than two months). The only potential concern identified with respect to freeze wall closure would be high permeability heterogeneities with localized high groundwater flow rates, such as coarse sand and gravel lenses. 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 F1 Site frozen soil barrier. In the unlikely event that a portion of the barrier was not adequately merging, the independent technical evaluation team developed a list of nine straightforward contingencies based on the parameters and mathematical relationships in the analytical design equation. Potential contingencies included several techniques to alter the groundwater flow rates through the site, to modify freeze pipe spacing, brine temperature or upgradient groundwater temperature, and/or to allow additional time for freezing.

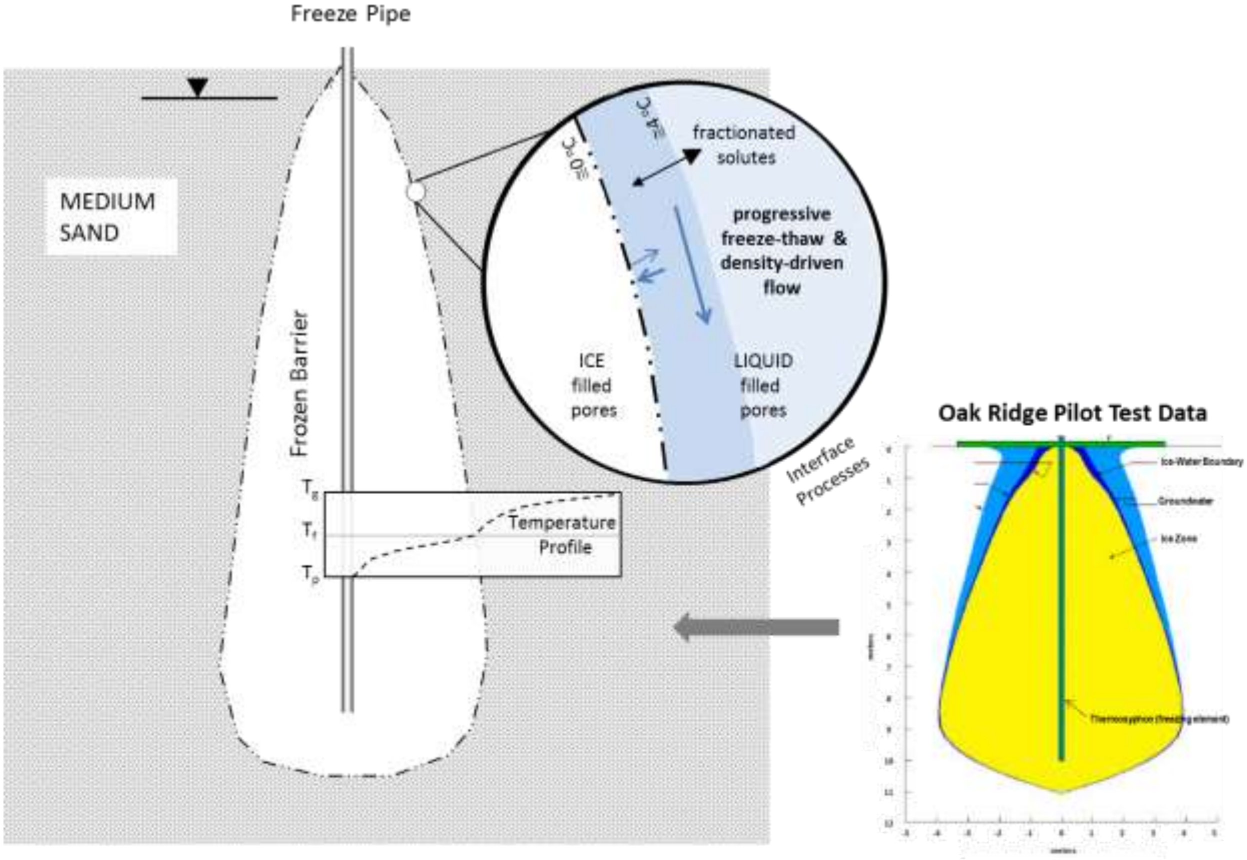
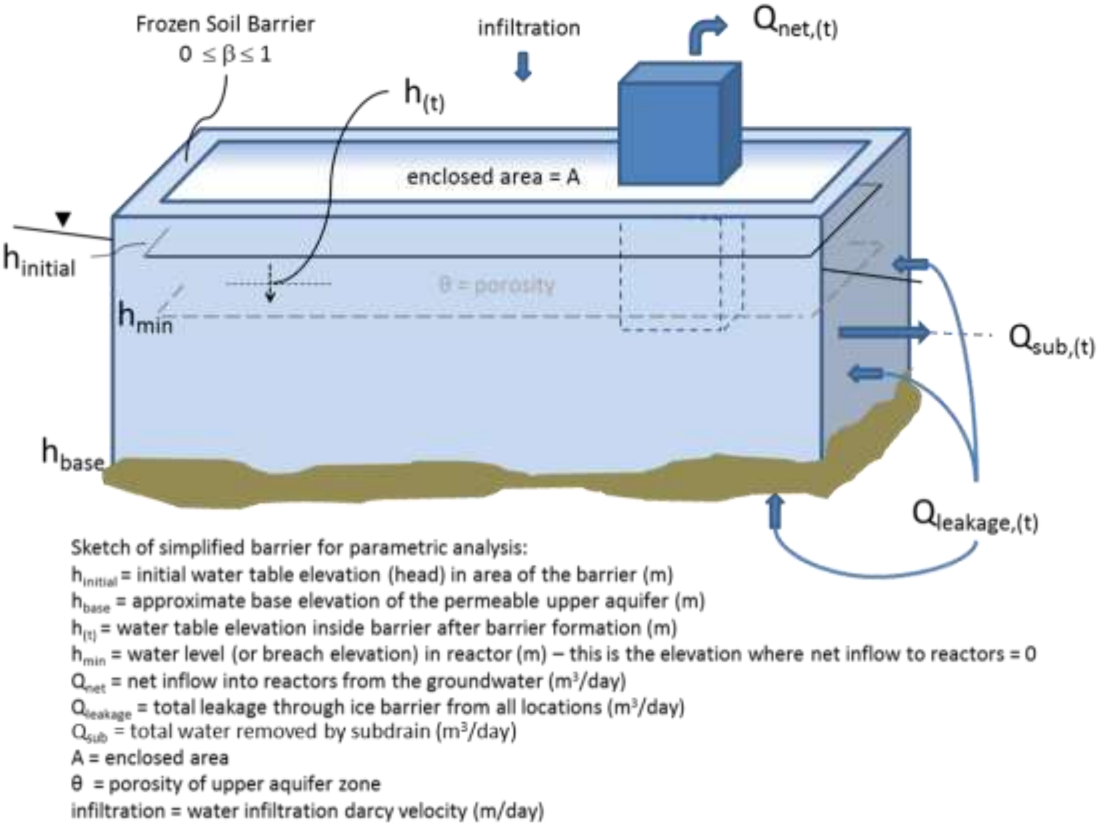


Figure 5. Frozen soil zone for an individual freeze pipe in a relatively homogeneous material based on the theory and the freeze profile measured at a pilot test at the Oak Ridge National Laboratory [2,4]

Once the frozen soil barrier is installed, the hydrologic situation in the vicinity of the damaged reactors will be closed -- inputs and outputs of water will be monitored and controlled. 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 (measured) and subdrain water removal (measured). In this case, facilities and subdrains 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 soil barrier. As shown in Figure 6, the barrier can be envisioned as a "bathtub" with a clayey base and frozen soil walls and a water balance as depicted. Evaluation of the F1 Site water balance indicated that the frozen soil barrier would provide substantive control to limit the infiltration of water into the damaged reactor facilities.



Sketch of simplified barrier for parametric analysis:
$h_{initial}$ = 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
$Q_{net}$ = net inflow into reactors from the groundwater ($m^3$/day)
$Q_{leakage}$ = total leakage through ice barrier from all locations ($m^3$/day)
$Q_{sub}$ = total water removed by subdrain ($m^3$/day)
A = enclosed area
θ = porosity of upper aquifer zone
infiltration = water infiltration darcy velocity (m/day)

Figure 6. Geometry and water balance of the F1 Site frozen soil barrier

Importantly, evaluation of the water balance indicated that water level changes are expected to occur slowly due to the large volume encased by the barrier and the relatively slow water flow rates in/out of the system (i.e., net inflow to reactors, water removed by subdrains, etc.). After full implementation, water levels inside and outside the reactors will be controllable so that inflow will continue at a slow rate (this will assure that contaminated water cannot flow out into the surrounding soil/groundwater). The projected timeframe to reach the target water levels and reactor inflow objectives is approximately 4 to 8 months. The presence of the barrier and the gradual nature of the change in groundwater levels allow time for careful monitoring and robust management of the hydrology impacting the damaged reactors.

Additional results of the independent technical evaluation of the F1 Site barrier included:

- Based on existing data, there are no Fukushima-specific groundwater conditions that would cause problems for the frozen soil barrier installation
- Projected fractional freezing effects are minimal
- The frozen soil barrier does not need to be 100% effective to meet TEPCO's key objective of limiting groundwater flow into the damaged reactors.
- 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.
- Based on the conditions and layout at the F1 Site, the risks of frost heave and subsurface utility damage are low.
- The F1 Site frozen soil barrier is an integral component of a set of comprehensive countermeasures addressing contaminated water at the Fukushima Daiichi Nuclear Power Station. Concurrent operation of some of the other countermeasures, particularly the groundwater bypass system and the subdrain system will assist the frozen soil barrier in achieving its objectives and minimizing the potential for operational problems.
- At the end of barrier operations, after repairs to the leaks in the damaged reactors have been performed, the frozen soil 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.

## Conclusions

Independent assessment of the frozen soil barrier concluded that the technical characteristics of a frozen barrier are relatively well suited to Fukushima-specific hydrogeologic conditions and the need for reducing the inflow of water into damaged reactors at the F1 Site. The frozen soil barrier at Fukushima represents one of the largest frozen soil barriers in the world and a unique-important use of the technology for a nuclear facility. 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 and supported the full scale design parameters. These factors increase the confidence in the frozen soil barrier project underway at Fukushima. TEPCO is currently working with the Japanese Nuclear Regulatory Authority (NRA), providing operational plans/strategies for the frozen soil barrier and modeling results of the projected performance. Full scale frozen soil barrier operations are to begin after authorization from NRA.

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