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Potential Signatures and the Means of Detecting a Hypothetical Ground Source Cooled Nuclear Reactor

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ABSTRACT

This preliminary study considers the feasibility of cooling a small nuclear reactor (tens of megawatts thermal) with a well doublet that taps groundwater and injects heated fluid beneath the surface. The associated signatures differ substantially from those of conventional cooling systems. Instead of a plume of steam or outflows of heated water, only wellheads may be observed at a site without access to surface water. Other potential signatures include surface thermal anomalies, geomorphological alterations, induced seismicity, and altered groundwater chemistry. As these signatures may be faint and lag reactor operations, an understanding of the system's operating principles and telltales of hydrogeological conditions conducive to groundwater flow become more critical for detection of such reactor by remote sensing.

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Introduction

Nonproliferation analysts often seek signatures of a cooling system when assessing a suspect nuclear reactor site.[1] As most reactor systems are concealed within structures, components of the cooling loop directly linked to the ultimate heat sink are often the most exposed to observation. Billowing plumes of steam from natural draft cooling towers and torrents of heated water spilling into a nearby body of surface water are amongst the most iconic images of nuclear power. Dry cooling systems are another possibility, but are rarely used by nuclear power plants due to their inefficiency and cost, and are ordinarily conspicuous in size and thermal signature (Figure 1).[2]

It may be possible to suppress the signatures of a reactor's cooling system and so avoid detection. A case of thermal signature suppression comes from the early days of the Soviet nuclear program. In a letter to Lavrenti Beria, Igor Kurchatov urged siting the Mayak plutonium production complex near a lake for

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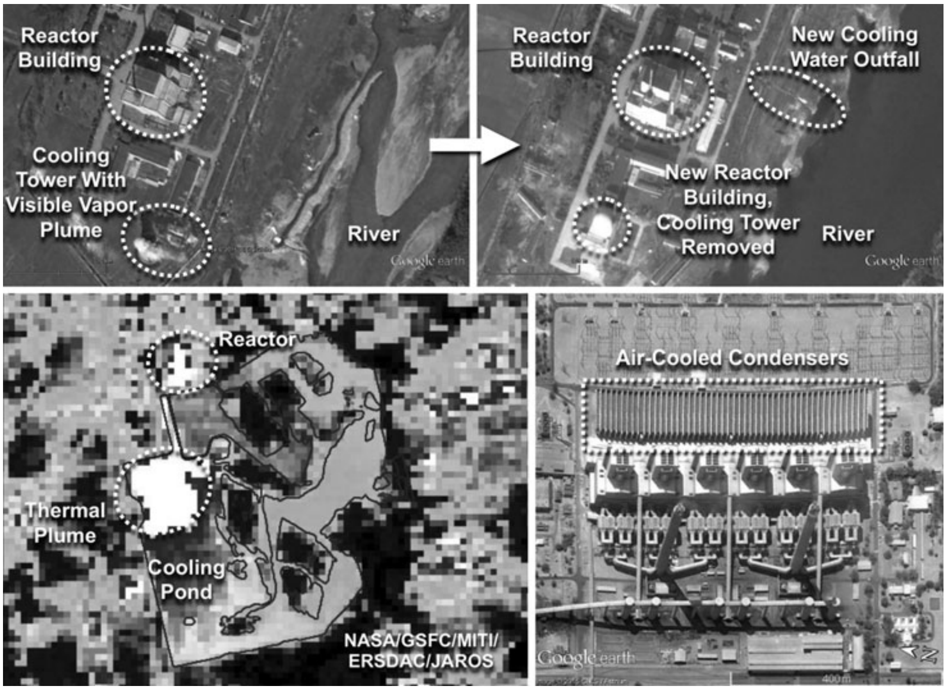

Figure 1. Examples of cooling systems and ultimate heat sinks: steam plume from a cooling tower (top left)[3]; the same site after removal of the cooling tower, construction of new reactor, and a possible cooling water outfall (top right)[4]; infrared image of a power reactor and its cooling water pond (bottom left)[5]; the Matimba Power station, a 4GWe coal power plant – the world's largest direct dry-cooled power plant (bottom right)[6]; additional annotations by authors.

cooling, rather than using cooling towers: "The resulting steam [from cooling towers] which would be inevitably produced in large quantities (especially during winter), would thereby compromise the concealment ...."[7] Though such subterfuge is less effective today, dilution with larger flows of air or water can conceal thermal signatures from satellite-borne visual and thermal infrared imagers.[8]

Another possibility may be below the surface. Kurchatov's lake and other surface sources of freshwater only account for approximately 0.3 percent of the Earth's unfrozen freshwater resources. Nearly all of these resources occur as groundwater within the pores and fractures of soil and rocks, and have supplied human needs for millennia.[9] Today, energy-related applications for groundwater include geothermal energy production, thermal energy storage, and cooling and heating. In some arid areas of the United States, for example, groundwater is a significant source of cooling water for power plants.[10]

By tapping groundwater, the thermal and visual signatures of a ground source cooling system can differ substantially from conventional reactor cooling systems. As illustrated in Figure 2, a well doublet could extract groundwater from an aquifer to cool a reactor and subsequently inject the heated water beneath the surface. Groundwater flow would then transport the thermal plume away from the extraction well, dissipating thermal energy to the subsurface.[11] While

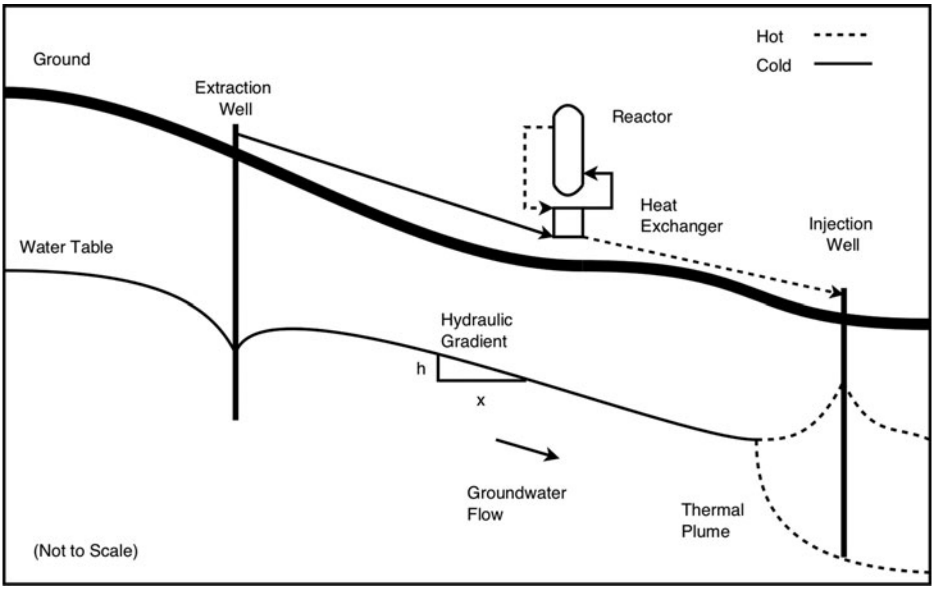

Figure 2. Conceptual schematic of a ground source-cooled nuclear reactor and the hydraulic gradient driving groundwater flow.

a ground source cooled reactor may be unprecedented and unfamiliar to nonproliferation analysts, its development may only be a matter of connecting the dots between two established technologies: nuclear reactors and water wells. A prior study suggested that cooling large power plants in this manner might be "…economically feasible, especially in arid regions…" from reductions in evaporative water losses and the recovery of stored energy for industrial or agricultural applications.[12]

To explore the implications of ground source cooling from a nuclear nonproliferation perspective, this study investigates the feasibility of a hypothetical ground source cooled reactor, and then identifies potential signatures and the means of detecting such a system. A prerequisite understanding of aquifer systems and groundwater temperature is developed first. Operating principles of a well doublet are then investigated by parametrically estimating the minimum well doublet separation necessary to avoid thermal breakthrough. The design of water production and injection wells is then explored to evaluate the sufficiency and reliability of cooling water flow, and to identify features relevant to their detection. Lastly, additional potential signatures are identified by drawing upon a literature review of the remote sensing of groundwater and geothermal reservoirs. For interested readers, the appendices contain estimates of production well drawdown and pumping power requirements (online Appendix A), an overview of analogous well doublets at geothermal power plants (online Appendix B), an estimate of emergency core cooling requirements (online Appendix C), an estimate of the areal extent of the thermal plume (online Appendix D), and a discussion of the surface energy balance

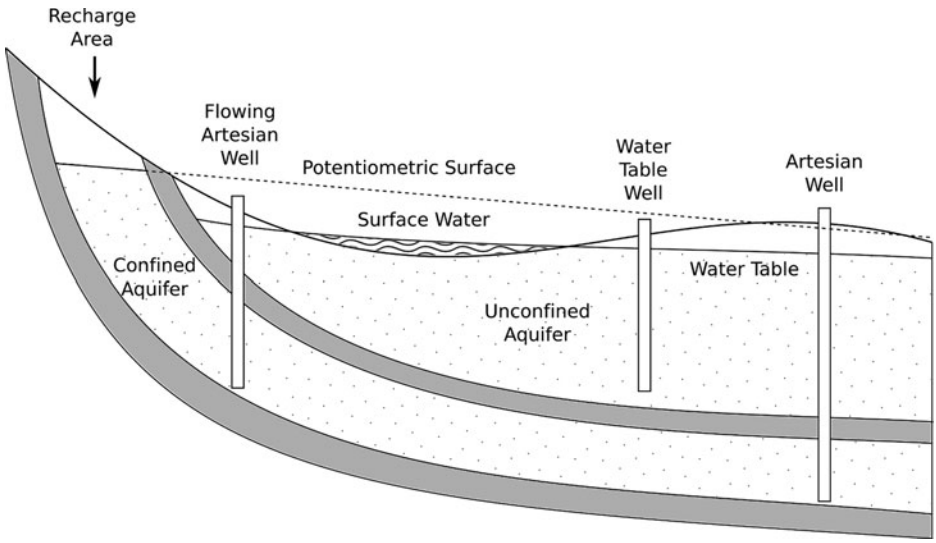

Figure 3. Diagram of unconfined and confined aquifers. Adapted.[14]

with an estimate of ground surface temperature from a buried heat source (online Appendix E).[13]

Groundwater and aquifers

Unlike the sight of surface water familiar to nonproliferation analysts, aquifers are geologic formations with water-bearing interstices that support the economic extraction of groundwater. An aquifer's water balance is affected by recharge inflows (e.g., rainfall, snowmelt), storage in the aquifer, and outflows from discharge zones (e.g., wells, springs, streams). Aquifers are broadly categorized as unconfined or confined in structure. Water infiltrates directly from the surface into unconfined aquifers whereas confining low permeability layers bound water flow paths that recharge confined aquifers (Figure 3).[14]

Within the aquifer, groundwater flows through pores and fractures under the influence of the hydraulic gradient, trading-off gravitational potential energy for pressure and velocity. Flow through the "hard sponge" of porous geologic media is described by Darcy's law where the flux of groundwater, q, flows under the influence of the hydraulic gradient, ∇h or I (Figure 2), through geologic media of hydraulic conductivity, K, by the relationship,

$$q = -K\nabla h = -KI \tag{1}$$

The average velocity of water, v, through geologic media of porosity, ϕ, is related to the flux of groundwater by,[15]

$$v = q/\phi \tag{2}$$

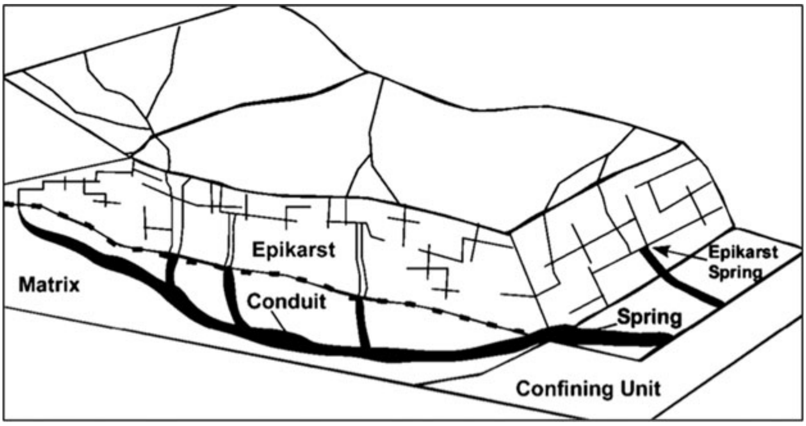

Figure 4. Diagram of a karst aquifer with matrix, fracture, and conduit water flow paths.[17]
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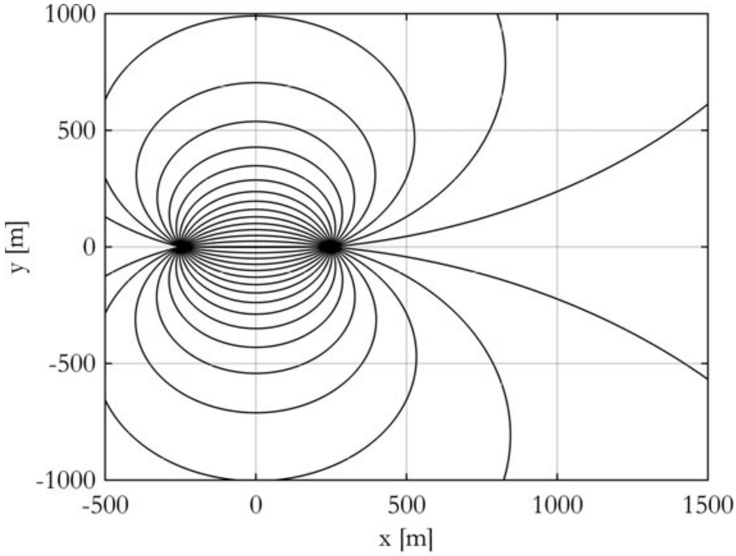
Fracture-dominated flows are more difficult to characterize than porous flows, requiring detailed knowledge of fractures that behave much like an interconnected piping network.[16] In some cases, such as in karst limestone aquifers, subterranean streams flow through large solution-enhanced conduits resembling natural subterranean pipeline (Figure 4).[17]

Groundwater temperature varies with depth from the influence of the surface energy balance and the geothermal gradient. Shallow groundwater located 10–25 m below the surface is typically 1–2°C warmer than the mean air temperature, exhibiting diurnal and seasonal variations from the propagation of a thermal wave through the ground. Below the zone affected by the surface energy balance, groundwater temperature increases with the geothermal gradient at a rate ranging from 1.8°C per 100 m in thick sedimentary rock to 3.6°C per 100 m in areas of recent volcanic activity.[18]

Ground source cooling

To utilize an aquifer as the ultimate heat sink, the ground source cooling system diagrammed in Figure 2 extracts water via an extraction well and returns heated water to the subsurface via an injection well. Subsurface hydrodynamic and thermal fronts develop around the injection well with the thermal front lagging behind, typically travelling three to five times more slowly as contact with the geological matrix cools the hydrodynamic front.[19]

Thermal breakthrough is a limiting factor in the design and operation of a ground source cooling system. Increasing water temperature from the migration of the thermal front to the extraction well reduces cooling efficiency. Locating the injection well sufficiently downstream of the extraction well in a region with groundwater flow diminishes the risk of thermal breakthrough by transporting the thermal plume



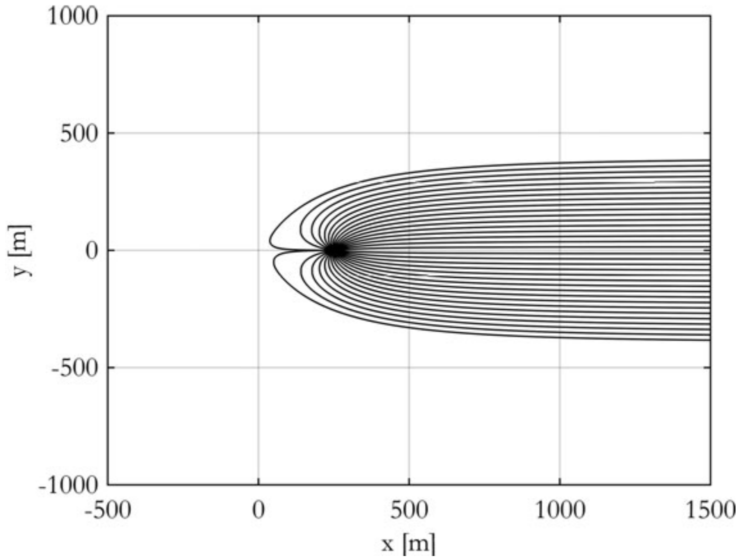


Figure 5. Top-down view of streamlines between a well doublet separated by 500m without regional groundwater flow (top, hydraulic gradient of 0, time to breakthrough of 2.5 years) and with groundwater flow (bottom, hydraulic gradient of 0.15) for an extraction/injection rate of 8900m^3/day with a temperature rise of 70 °C into a 50m thick aquifer with a hydraulic conductivity of 1.74×10^{-5} m/s, porosity of 0.14, and a volumetric heat capacity of rock approximately half that of water.

down the hydraulic gradient. As illustrated in Figure 5 using the Thermal Recycling Simulator (an openly available code for simulating thermal recycling between wells), groundwater flow inhibits recirculation of the injected flow to the extraction well.[20]

The minimum well separation, L, to limit the risk of breakthrough under porous flow conditions is dependent on the volumetric rate of water injection (assumed equal to the extraction rate), $\dot{V}$, and the properties of the aquifer (thickness, b, hydraulic conductivity, K, and hydraulic gradient, I) can be estimated by,

$$L > \left(2\dot{V}\right) / (\pi bKI) \tag{3}$$

The volumetric flow rate $\dot{V}$ is determined by reactor thermal power, $\dot{Q}$, the temperature rise across the well doublet, ΔT, and the volumetric heat capacity of water (the product of density, ρ, and heat capacity, C_W),[21]

$$\dot{V} = \dot{Q} / (\rho C_W \Delta T) \tag{4}$$

Parametric evaluation of well doublet separation

Minimum well separation (Eq. 3) is evaluated parametrically over a wide range of thermohydraulic and hydrogeological conditions as listed in Table 1. Thermal power from a small nuclear reactor (10–30 MWt) is entirely transferred to the cooling system for a range of temperature rises across a well doublet. A 20°C groundwater source is assumed for an arbitrary location with a comparable annual mean air temperature.[22] As shown in Figure 6, hydraulic conductivity spans several orders of magnitude and varies by the type of geologic media.[23] The hydraulic gradient is based upon Yucca Mountain, a proposed nuclear waste repository with three hydrological regions: one with a "large" hydraulic gradient of 0.15 or more that might coincide with a deep carbonate aquifer, a second region with a "moderate" gradient of about 0.015, and a third region with a "very small" gradient of 0.0001.[24] An aquifer thickness of 50 m is assumed based on a prior study of ground source cooling.[25]

As thermal pollution is largely inconsequential in a relatively lifeless aquifer, higher injection temperature could reduce cooling water flow to within the capacity of a large municipal or agricultural water production well. Increasing the temperature rise across the well doublet from 10°C to 70°C (corresponding to an injection temperature of 90°C) results in a seven-fold reduction in cooling water flow from 62,000 m^3/day down to 8,900 m^3/day for a 30 megawatt thermal (MWt) reactor (Eq. 4 and Table 1)—within the capacity of a single water production well approximately 0.5 m in diameter.[26] Under these conditions, a 30 MWt reactor producing 1 g of plutonium per MWD of thermal energy produces a significant quantity (8 kg) of plutonium in approximately 270 days and injects approximately 2.4×10^6 m^3 of cooling water in the process.[27] Increasing injection temperature

Table 1. Values of thermohydraulic and hydrogeological parameters.

Category	Parameter	Value
Thermohydraulic	Reactor thermal power, $\dot{Q}$ (MWt)	10–30
	Temperature rise, ΔT (°C)	10–80
	Cooling water heat capacity, C_W (kJ/kg K)	4.2
	Cooling water density, ρ (kg/m^3)	1000
Hydrogeological	Aquifer thickness, b (m)	1–50
	Hydraulic conductivity, K (m/s)	10^{-13}–10^{-2}
	Hydraulic gradient, I	0.01–0.15
	Groundwater temperature (°C)	20

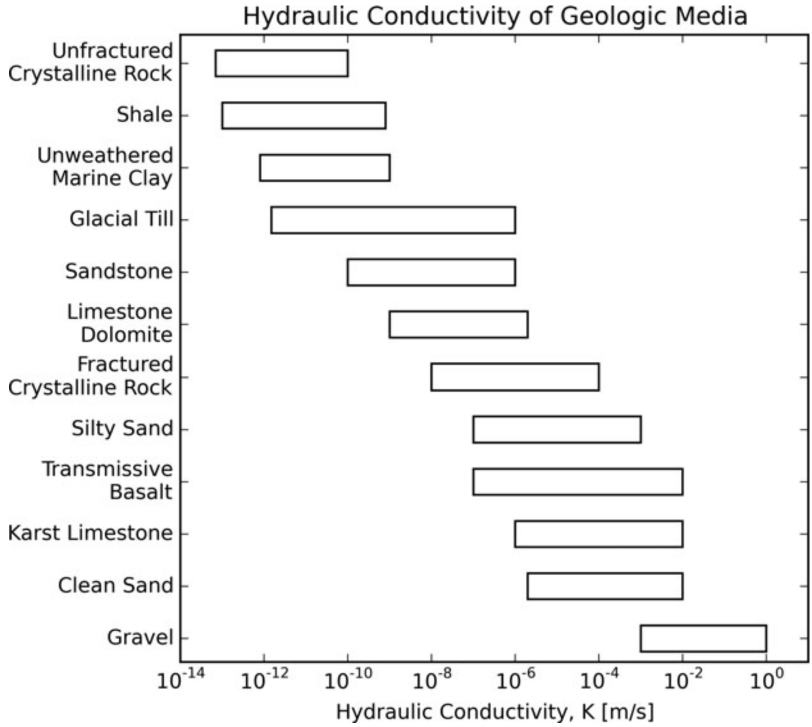


Figure 6. Values of hydraulic conductivity. Adapted.[30]

further reduces demands on the extraction well, but two-phase flow complicates injection and intensifies thermal signatures.[28]

A large well separation may be required in typical aquifers, but thicker aquifers with faster groundwater flow could accommodate more closely spaced wells. A large separation of approximately 6.5 km would be required in a "hydrogeologically typical" aquifer ($Kb = 0.001$ m^2/s, $I = 0.01$) to support a 30 MWt reactor with a 70°C temperature rise (Figure 7, top left, Eq. 3 and Eq. 4).[29] Though widely separated wells may not be readily associated with a distant reactor, a compact configuration may be more practical. Should this be the case, well spacing is reduced by faster groundwater flow caused by a steeper hydraulic gradient (Figure 7, top right) or higher hydraulic conductivity (Figure 7, bottom left). Injection into a thicker aquifer further reduces well spacing due to a reduction in the lateral velocity of the injected flow (Figure 7, bottom right). While a wide range of operating regimes appear feasible, Table 2 lists minimum values of hydraulic conductivity to achieve a 500 m well separation under specified thermohydraulic and hydrogeological parameters. Under these conditions, suitable values of hydraulic conductivity can be found in gravel, sand, karst limestone, transmissive basalt, and fractured crystalline rock (Figure 6).[30]

Structural engineering challenges could be expected on these permeable foundations. In mature karst limestone areas, for example, hazards include variable surfaces with open cavities where water extraction and injection activities exacerbate the risk of ground subsidence, ground uplift, and sinkhole formation. However, in many karst limestone formations, the vast majority of the area (> 95 percent) may

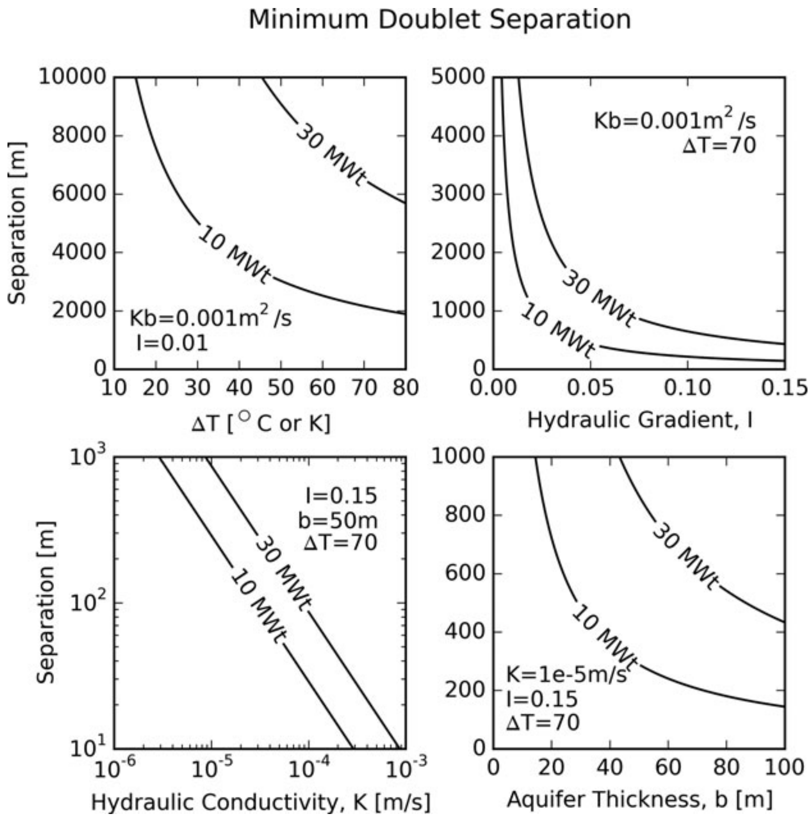


Figure 7. Minimum well separation for various thermohydraulic and hydrogeologic conditions.

be sound rock with a safe bearing capacity of 2 to 4 megapascals (MPa). Construction practices in these areas involve thorough characterization of the subsurface via geophysical techniques to avoid areas prone to collapse, control water drainage, and distribute building loads (e.g., raft or mattress construction techniques).[31]

Provided that these structural risks are acceptable, these results suggest the feasibility of reducing well doublet spacing to practical distances to cool a reactor. Should thermal breakthrough nevertheless occur, rising cooling water temperature may eventually lead to shutdown and intermittent operation.[32] Reactor refueling outages could be timed to coincide with thermal breakthrough, resuming operations after the thermal plume migrates down-gradient. While flow through fractures may lead to premature breakthrough, injecting into a hydrogeologically separate stratum of the aquifer (e.g., beneath a low permeability layer) or possibly into a solution-enhanced conduit leading away from the extraction well (Figure 4) renders breakthrough improbable.[33]

Extraction and injection wells

Extraction and injection wells are essential for reliable operations and distinguish a ground source cooling system from conventional cooling systems. The loss of heat sink event caused by extraction well failure not only interrupts plutonium production, but also potentially results in core damage and the release of detectable radionuclides into the environment. Operations could be sustained after failure of the injection well, but are likely accompanied by visible water flows expelled to the surface.

Extraction wells

Signatures of extraction wells arise from their physical design and hydrogeological setting. The principal components of a typical drilled water extraction well include the well casing, filter pack, well screens, and pump. The well casing is the main conduit for water and houses the pump. Groundwater enters the casing through the filter pack and perforated well screens that limit the ingress of particulates into the well. A cone of depressed water level forms around a pumped water well, establishing a hydraulic gradient that drives groundwater flow radially inward. Well dry-out can occur during droughts and from overpumping when drawdown (the difference between the static water level, H, and the pumping water level, h) drops to the level of the pump intake (Figure 8).[34]

Visible characteristics of the well, particularly the wellhead's footprint, are determined by the well's yield and the size of the pump. A well is sized to accommodate the pump, and to limit frictional flow losses across the well screen (screen entrance velocity < 0.03 m/s) and up the well casing (up-hole velocity < 1.5 m/s). Applying these limits, a well capable of producing 8,900 m^3/day (sufficient for a 30 MWt reactor with a 70°C temperature rise) ranges in size from 0.36–0.51 m in diameter.[35]

Well development and periodic redevelopment to improve and maintain well yield may also be observed. Overpumping, backwashing, mechanical surging, air surging, and air or water jetting are development techniques used to repair damage to aquifer caused by drilling. Aquifer stimulation via acid treatment, explosives, or hydrofracturing may also be employed to increase permeability to flow. Periodic well redevelopment through chemical and physical methods (e.g., acid treatment, mechanical scrubbing, radiation) reverses well degradation mechanisms such as fine particle accumulation, chemical incrustation, and biofouling that clog the well intake—the latter of which can lead to rapid well failure if exponential bacterial growth is left unchecked.[36]

Table 2. Minimum hydraulic conductivity to achieve a well separation of 500 m.

Category	Parameter	Value
Thermohydraulic	Temperature Rise, ΔT (°C)	70
	Reactor Power (MWt)	10–30
	Cooling Water Flow (m^3/day)	3000–8900
Hydrogeologic	Well Separation (m)	500
	Hydraulic Gradient, I	0.15
	Aquifer Thickness, b (m)	50
	Hydraulic Conductivity, K (m/s)	$>6\times10^{-6}$–$>2\times10^{-5}$

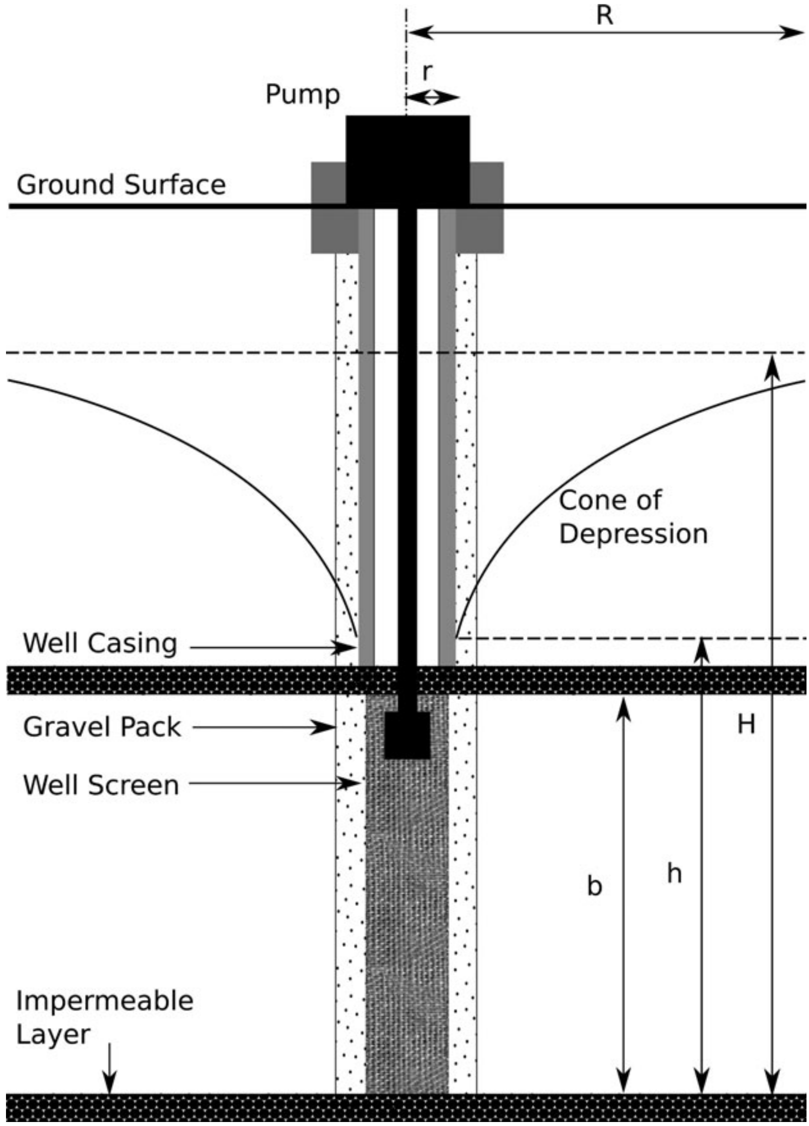


Figure 8. Cross-section of a drilled water extraction well and the cone of depressed water level drawing upon a confined aquifer. Adapted.[34]

Extraction wells are more likely to be sited in aquifers with favorable hydrogeological conditions to reduce drilling cost and pumping power. For example, a few MW of mechanical pumping power may be necessary to overcome a few kilometers of drawdown (ignoring vertical rise and frictional losses through piping) in a low permeability aquifer (10^{-6} m/s) to cool a 30 MWt reactor for 270 days—possibly requiring multiple wells to supply the required flow. By contrast, a higher permeability aquifer (10^{-4} m/s) may only require a few dozen kW to overcome a few dozen meters of drawdown. Deeper water tables require additional pumping power to overcome the vertical rise above the static water level (online Appendix A).

Adequate precipitation is also required to recharge the aquifer and avert well dry-out.[37] While the overall water balance of the aquifer is unaffected by a doublet that returns extracted fluids, localized over-pumping may occur if water flow from well capture zones to the well screens inadequately balances extraction.[38] As an estimate of the well capture zone, balancing the flow required by a 30 MWt reactor requires 500 mm of annual precipitation falling over a 6.5 km^2 capture zone or 2.2 km^2 for a 10 MWt reactor assuming complete infiltration and capture by the extraction well. Steeply sloped ground surfaces lessen recharge flows, but natural and artificial preferential flow paths (e.g., depressions, fractures, diversions, water spreading areas, pits, shafts, dams) promote water infiltration to the subsurface.[39]

Injection wells

Injection wells share many features of extraction wells but face additional thermal design and maintenance challenges. Injection wells range in design from simple open boreholes to those with well screens. Unlike extraction wells, the casing, cement material, and seal packers of injection wells must tolerate elevated thermal stresses and corrosion rates to prevent well-casing cracking, pull-out, and buckling.[40] Moreover, unlike extraction wells where fine particles are continuously removed by pumping, injection wells tend to be less reliable from the accumulation of fine particles and other processes that clog the well (e.g., silica and calcite scaling, entrained gas bubbles, precipitation of dissolved solids, bacterial growth). Injection wells are often designed with longer screens than comparable extraction wells (typically twice as long) to reduce maintenance intervals.[41] Multiple injection wells may be required should injection pressures exceed the limits of a single well.

Despite these difficulties, injection wells are used by a number of industrial processes to inject thermal fluids (e.g., oil and gas production via hydraulic fracturing, environmental remediation of soil and aquifers via steam injection, sulfur extraction via the Frasch process, disposal of flash water from geothermal power plants, etc.). For example, steam generators used in oil and gas production range in power from 3–53 MWt and supply a network of steam injection wells operating at up to 370°C. Injection of wastewater from geothermal power production is a close analogue to reactor cooling. Injection rates vary widely by the type of plant and geothermal source characteristics. For example, a geothermal plant drawing upon a 200–300°C source injects 430–1700 t/day of 100–200°C wastewater per MWe of power (Figure 9 and online Appendix B).[42]

These industrial uses suggest the viability of using a well doublet as an ultimate heat sink. Though well reliability issues can complicate operations, nuclear power plants have been designed to draw upon groundwater for emergency and process cooling water.[43] Multiple wells or an emergency core cooling system compensate for deficiencies in extraction well reliability. Injection into the subsurface also appears feasible, sharing similarities to wells used by geothermal power plants to dispose of wastewater.

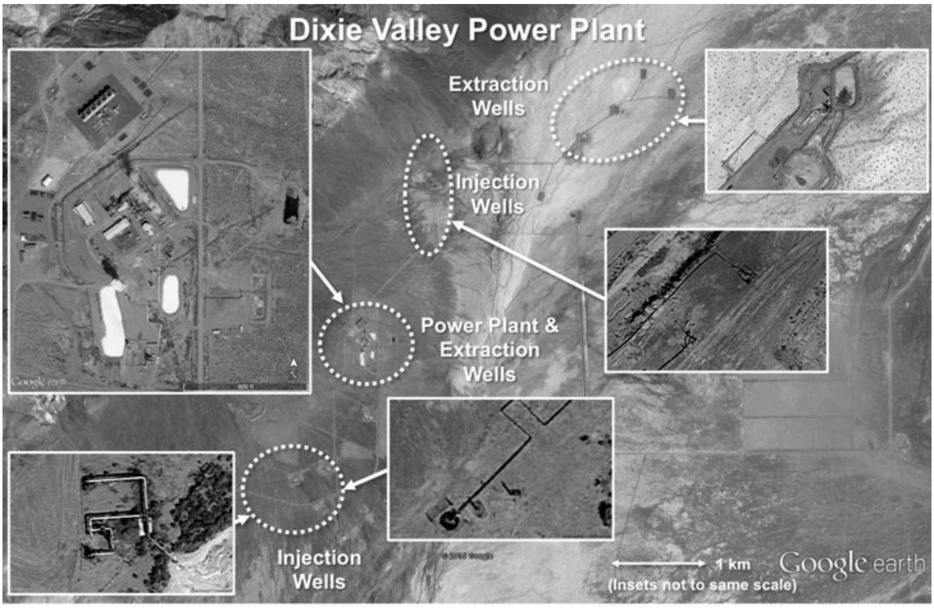


Figure 9. Dixie Valley geothermal power plant (Nevada, United States).[44]

Potential signatures and means of detection

Signatures associated with a ground source cooling system may be very different and less obvious than those of conventional cooling systems, but are not entirely absent. Potential visual, thermal, seismic, chemical, and radiological signatures are identified drawing upon a literature review of the remote sensing of groundwater and geothermal resources. Potential signature suppression methods are also discussed to identify signatures robust to proliferator action (Table 3). Combined with signatures of a hypothetical reactor, knowledge of potential signatures and suppression methods associated with ground source cooling aids detection and diminishes errors that contribute to misidentification.

Visual

Observed from overhead, visual signatures of a ground source cooling system may not be obvious, and deliberate camouflage and concealment efforts could make them even less so. Activities accessing the wellhead (e.g., drilling, development, and maintenance) may be visible and could discharge fluids to the surface.[45] Evidence of electrical power sources and backup sources (e.g., power lines, batteries, diesel generators) necessary for pumps and other support systems may also be visible. A loss of heat sink emergency initiated by extraction well failure could generate aboveground thermal signatures such as steam plumes from the boil-off of emergency cooling water (online Appendix C). Failure of the injection well or leaks through surface fractures may lead to aboveground water discharges.[46] However, many of these features (e.g., wells and pipelines) could be concealed within buildings or underground.

Table 3. Potential signatures of a ground source cooling system and potential means of suppression.

Category	Potential Signatures	Potential Means of Suppression
Visual	Construction activities (e.g., pipe laying and well drilling)	Camouflage & concealment, tunneling
	Electrical power for pumps and other equipment for normal operation and emergencies	Underground power lines from off-site
	Well development during construction and maintenance activities	Camouflage & concealment, capture of fluids
	Inadvertent water discharges	Capture of fluids
	Geomorphological alterations (e.g., ground subsidence/uplift, sinkholes, altered moisture conditions)	Dependent upon on detection mechanism (e.g., irrigation of dry spots to limit impacts on vegetation)
	Steam plumes or thermal signatures from emergency cooling, water deliveries from off-site	Increased cooling air flow, reversed flow from an injection well
Thermal	Elevated ground surface temperature (e.g., hot pipelines, injection well, thermal plume)	Increased cooling flow; emplacement of insulating material; location in vegetated, rainy and cloudy regions; interference from nearby objects; deep injection
	Unusual groundwater and surface water temperature variations	Dilution with subsurface flows, long subsurface residence time
Seismicity	Induced seismicity during and post operation	Site location, optimization of withdrawal and injection activities
Chemical & Radiological	Leakage of fission products into cooling water during operation, reduced noncondensable gas concentration, mobilization of chemical front	Leak tight heat exchanger, water treatment (e.g., ion exchange resin), reintroduction of gases, reduced injection temperature, distance to discharge zones

In addition to these engineered features, fluid extraction and injection may lead to geomorphological alterations detectable via remote sensing. Multispectral imagery as well as laser- and radar-based measurements may reveal surface depressions, surface uplifting, and altered moisture conditions indicative of water extraction and injection activities. For example, interferometric synthetic aperture radar (InSAR) can measure elevation with 1 mm accuracy in dry environments and have detected surface deformations at geothermal sites.[47]

Thermal

The thermal signatures of a ground source cooling system may be indiscernible in the coarsely pixilated images of satellite-borne thermal infrared imagers (Figure 1). Detectable thermal anomalies must be hot enough or large enough to have a temperature that exceeds the temperature resolution of the imager (0.2–1°C) when spatially averaged over a pixel's field of view (60–120 m).[48] Subtle sub-pixel sized thermal signatures can be obfuscated by nearby objects (e.g., roads, buildings); by interference from rainfall, vegetation, and cloud cover; and by false thermal anomalies (e.g., differential solar heating arising from varying topography and thermophysical properties of the ground).[49]

The heated zones around the injection well, hot buried pipeline, and underground thermal plume are potential targets for thermal imaging. Shallow burial exposes these heat sources to detection, particularly at night in the absence of irregular patterns of daytime solar insolation and possibly in the winter from altered snow cover. The injection wellhead may present the most concentrated thermal signature—unless thermally decoupled from the surface by emplacing an insulating plug in the borehole above the active well section. Likewise, deep burial and high thermal resistivity insulation can substantially reduce the heat flux from the pipeline to the surface.[50]

In contrast to these localized heat sources, the subsurface thermal plume is likely to be the largest thermally affected area and is not readily insulated. In the absence of groundwater flow, injecting 2.4×10^6 m^3 of heated water (sufficient for 1SQ of plutonium from a 30 MWt reactor) into a 50 m thick porous limestone aquifer results in a cylindrical displaced water zone 660 m in diameter and a temperature-affected zone 330 m in diameter (online Appendix D). The actual plume is elongated in the direction of groundwater flow (Figure 5) and depends upon aquifer geometry and the nature of flow (e.g., intergranular, fracture, and/or conduit flow). In the presence of fractures, the thermal front initially moves rapidly but slows as the surface area between fractures and geological matrix increases with distance.[51]

The thermal plume may leave few observable traces if surface expressions resemble hard-to-detect blind geothermal resources. While geothermal resources are often marked by hot springs, fumaroles, and hydrothermally altered ground, blind geothermal resources remain underground as a deep lateral flow under a confining hydrogeological stratum. Techniques to correct thermal infrared imagery for diurnal solar heating effects that mask geothermal sources (e.g., false thermal anomalies associated with variable slope orientation, albedo, and thermal inertia) are considered useful for regional studies, but ill-suited for identifying subtle thermal anomalies.[52] A simplified estimate suggests that a few meters of limestone may be sufficient to reduce peak ground surface temperature below the detection threshold of satellite-borne thermal infrared imagery (online Appendix E). A study accounting for the complexities of the surface energy balance found that groundwater below a critical depth (approximately 1 m for well-drained sandy soil and several meters in clayey soil) is undetectable by thermal infrared imagery.[53] Unusually warm groundwater presumably increases critical depth from the effects of heat transfer to the surface, but the necessary analysis is beyond the scope of this paper.

The possible emergence of the thermal plume from the aquifer into a discharge zone presents another detection opportunity, but discharges may lag reactor operations and may not be obvious after thermally equilibrating with the subsurface.[54] Unless the flow is fracture dominated, the plume's hydrodynamic front slowly travels at the regional groundwater flow velocity following reactor shutdown. Groundwater flows at approximately 0.7 km/year through a limestone aquifer of average porosity ($\phi = 0.14$) supporting a 500 m well doublet separation (e.g., I = 0.15, K $= 2 \times 10^{-5}$ m/s, Table 2) using Eq. 2. The thermal front lags behind the hydrodynamic front, progressively dropping in temperature as it encounters cooler aquifer matrix.[55]

While such discharges may not be obvious in overhead imagery, a network of ground-based sensors may be able to discern reactor operations from natural thermal patterns. For example, the temperature of springs and monitoring wells in a karst limestone aquifer can be correlated to: air temperature and rainfall via epikarst (a geological layer, Figure 4) groundwater flows during wet periods; air temperature via shallow groundwater flows during dry periods; and deeper, near-constant temperature groundwater sources. Analyzing patterns of groundwater temperatures and levels from a network of ground-based loggers might detect anomalies unrelated to environmental factors that might be associated with reactor operations.[56]

Deep injection virtually eliminates thermal signatures of the plume altogether. Due to the geothermal gradient, the temperature of the subsurface matches the temperature of the injected fluid (90°C) approximately 5 km below the surface.[57] By minimizing the temperature difference between the plume and the subsurface, the impact of the injected fluid on ground surface temperature may be virtually undetectable. However, drilling operations may be challenging to conceal and sequestering fluids deep underground may disrupt the aquifer's water balance, potentially depriving downstream users in regions of water scarcity.

Induced seismicity

Seismicity induced by water extraction and injection may also signal anomalous activities, but can be difficult to distinguish from background. Induced seismicity might be differentiated from natural seismicity by correlating the timing and location of seismic events with injection activities, either with semi-quantitative scoring methods or quantitative statistical techniques.[58] While cases of induced seismicity felt by the public tend to involve injection of large fluid volumes at high rates over extended periods, well doublets that balance extracted and injected fluids disturb the aquifer to a lesser extent and tend to produce fewer felt seismic events. However, thermal stresses from injection have been associated with induced seismicity in geothermal fields. Generally, avoiding significant changes to net pore pressure (e.g., reducing injection intensity), avoiding areas with near-critical states of stress along fracture or faults, and avoiding geological media susceptible to brittle failure minimize the potential for induced seismicity.[59]

Chemical and radiological signatures

Detectable chemical fronts might develop from the injection of chemically altered fluids and the action of the hydrodynamic and thermal fronts. However, unless cooling water is treated (e.g., to control corrosion, heat exchanger fouling, etc.) or radionuclides inadvertently leak into cooling water, injected fluids are largely unaltered and have limited potential to form subsurface chemical or radiochemical fronts. However, the off-gassing of noncondensable gasses within the plant may deplete gas concentrations in the aquifer.[60] Injected water may also mobilize a chemical front in manner similar to remediation techniques using injected steam to flush contaminants from an aquifer.[61] The precipitation of dissolved minerals might contribute to visible staining around discharge zones. Airborne hyperspectral surveys, for example, have detected geothermal indicator minerals, and when coupled with in-field ground temperature measurements, provided indications of a blind geothermal reservoir.[62]

Conclusions

Though there are no confirmed ground source cooled reactors, this preliminary study identifies a potential gap in a nonproliferation analyst's catalog of systems. Cooling a small plutonium production reactor via a well doublet appears feasible over a range of thermohydraulic and hydrogeological conditions. Injecting heated cooling water into the subsurface, possibly into a natural subterranean pipeline, could dissipate thermal energy beneath the surface. And by injecting into an aquifer at high temperature, a single extraction well could supply sufficient cooling water flow for a small reactor.

Should such a reactor be constructed, nonproliferation analysts unfamiliar with ground source cooling could be misled. Instead of plumes of steam or cooling water flows, seemingly innocuous water wells might cool a reactor at sites without access to surface water. Thermal anomalies that do appear may be subtle and substantially lag reactor operations. Seismic tremors induced by fluid withdrawal and injection may be unfelt or unremarkable. These and other signatures, such as geomorphological alterations and construction activities, may be overlooked or ascribed to something other than a reactor.

Nevertheless, knowledge of ground source cooling advantages detection. Though water wells are ubiquitous, sites can be prioritized for further scrutiny based on telltales of suitable infrastructure and hydrogeological conditions conducive to groundwater flow. Definitive conclusions may require on-site inspection as thermal signatures may not be obvious. Ultimately, an awareness of technological possibilities informs the level of intrusiveness required to verify the absence of clandestine nuclear reactors and to deter such attempts through the risk of early detection.

While the concept of a ground source cooled reactor may only be a matter of connecting the dots between two established technologies, its realization requires research and development efforts beyond the scope of this this study. Heeding Admiral Rickover's admonition on the facile nature of "paper reactors," the challenges of ground source cooling and the nature of its detectable signatures may only be fully understood after detailed analysis in a realistic hydrogeological environment.[63]

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