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NRIC Advanced Reactor Demonstration Water Use Options at INL

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SUMMARY

The purpose of this paper is to inform advanced reactor developers of the conditions and requirements needed to manage the water used to reject heat from advanced reactor demonstrations at Idaho National Laboratory (INL). One of the important considerations in the deployment of demonstration plants is water use and its implications. Advanced reactor developers need to consider the limitations of the water consumption based on availability and physical conditions, as well as state and federal regulations. Water consumption may complicate reactor capacities and affect their subsequent commercial deployment.

While there are many advanced reactor concepts, all require heat rejection, and some plan to use water for heat rejection. Cooling water for heat rejection is frequently the largest water load for a nuclear reactor; therefore, it is the focus of water management. The type of reactor and its purpose, the physical conditions at INL, and the regulatory structure of the demonstration also influence the optimal method of heat rejection. Choosing the best method of rejecting heat will significantly influence the cost and probability of success for any advanced reactor demonstration.

NRIC acknowledges that the topic of aquifer use is important to many of the INL's stakeholders. This paper may spur discussions among stakeholder groups and INL's neighbors.

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FIGURES

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ACRONYMS

ACHE	air-cooled heat exchangers
ALARA	as low as reasonably achievable
ARD	advanced reactor developer
ARDP	U.S. Department of Energy Advanced Reactor Demonstration Program
CFA	Central Facilities Area
DOE	Department of Energy
EPA	U.S. Environmental Protection Agency
ESRP	Eastern Snake River Plain
GHEX	ground-coupled heat exchanger
IDAPA	Idaho Administrative Procedure Act
INL	Idaho National Laboratory
MCL	maximum contaminant level
MFC	Materials and Fuels Complex
MWe	mega-watt electric
MWth	mega-watt thermal
NEICA	Nuclear Energy Innovation Capabilities Act
NEPA	National Environmental Policy Act
NRIC	National Reactor Innovation Center
ROT	reactor outlet temperature
RWMC	Radioactive Waste Management Complex
SRB	Snake River Basin
SRP	Snake River Plain
SRPA	Snake River Plain Aquifer
TAN	Test Area North

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1. INTRODUCTION

The National Reactor Innovation Center (NRIC) was authorized by the Nuclear Energy Innovation Capabilities Act (NEICA). NRIC is led by Idaho National Laboratory (INL) and is charged with partnering with industry to enable the demonstration of advanced nuclear reactors. Multiple reactor demonstrations are anticipated through the U.S. Department of Energy Advanced Reactor Demonstration Program (ARDP) as well as independent of the ARDP and some are considering INL locations.

The purpose of this paper is to inform advanced reactor developers (ARDs) of the conditions and requirements to manage the water used to reject heat from advanced reactor demonstrations at INL. While there are many advanced reactor concepts, all of them require heat rejection, and some plan to use water for heat rejection. Cooling water for heat rejection is frequently the largest fresh-water load for a nuclear reactor; therefore, it is the focus of water management. The type of reactor and its purpose, the physical conditions at INL, and the regulatory structure of the demonstration also influence the optimal method of heat rejection. Choosing the best method of rejecting heat will significantly influence the cost and probability of success for any advanced reactor demonstration.

2. OBJECTIVE

This paper informs developers of the applicable INL conditions that affect heat rejection and water use in reactor demonstrations, presents a range of potential heat-rejection methods for reactor demonstrations, and discusses the general regulatory constraints for water use as it applies to heat rejection. Radioactive discharge is prohibited and will not be allowed. Limitations imposed by relevant regulatory constraints focus on monitoring of discharge waters after cooling (radioactive discharge is prohibited and will not be allowed). Six heat-rejection methods for advanced reactors in the range of 100 MW_{th} to 1000 MW_{th} are considered:

1. Cooling tower, rejecting heat to the atmosphere via evaporation.
2. Injection well, pumping water from the aquifer, through a heat exchanger, and injecting the clean heated water back into the aquifer.
3. Cooling pond, rejecting heat via evaporation and convection.
4. Ground-coupled heat exchanger (GHEX), rejecting heat back to Earth and Snake River Plain (SRP) aquifer.
5. Air-cooled heat exchanger (ACHE), rejecting heat to the air with an open loop.
6. Combinations of the methods listed above.

The outcome of the study is a comparison of INL heat-rejection options that includes regulatory compliance and high-level design considerations. By evaluating the six options and comparing the relative advantages and disadvantages, advanced reactor developers (ARDs) will be better informed in developing their strategy for heat rejection at INL.

3. BACKGROUND

This section describes the INL environment (physical and regulatory) in which advanced reactors will be demonstrated. The principle source of water for an advanced reactor developer (ARD) heat rejection is likely the Snake River Plain (SRP) aquifer (SRPA) and a summary of its characteristics is provided. A limited discussion of the atmospheric conditions at INL is included because those conditions will affect some methods of heat rejection and subsequently the use of water for those methods.

Discussion of the State of Idaho's regulatory framework, water rights, and water discharge requirements provide context and bound the evaluation. Not all water uses are included. For example, water for fire suppression could require a significant withdrawal from the SRPA, but that use is specifically exempted from the federally reserved water right; therefore, use of water for fire suppression is not evaluated. The regulatory evaluation is limited to cooling water for heat rejection. Not all heat-rejection methods are analyzed, but this section provides background for those that are analyzed.

3.1 INL Characteristics

INL is a multi-program laboratory that supports Department of Energy (DOE) missions of nuclear energy research, energy resources, science and technology, and national security. No permanent residents are on the Site, and ingress and egress are strictly controlled to and from one of five public highways.

INL is in the Pioneer Basin, which is a closed topographic depression. Three streams drain into the valleys to the north and west: the Big Lost River, Little Lost River, and Birch Creek. The integrity of these natural surface waters is protected by the Clean Water Act and the State of Idaho administrative policy protecting the waters of the state. Irrigation diversions, hydropower diversions, and infiltration losses along the channel bed often deplete stream flows before reaching INL.

The climate of INL is affected by the surrounding mountains and from the northeast-southwest orientation in the Pioneer Basin. The prevailing wind is from the southwest. The Centennial and Bitterroot Mountain ranges to the north act as a barrier to movement of most of the cold winter air masses passing to the south out of Canada. Air masses entering INL are relatively dry because most of the heavy precipitation occurs upwind in the mountain barriers. Therefore, annual rainfall is light, cloud cover is sparse, and the air is relatively dry (INL, 2020).

To provide context for the subsequent discussion, a map of INL and adjacent area is provided below in Figure 1.

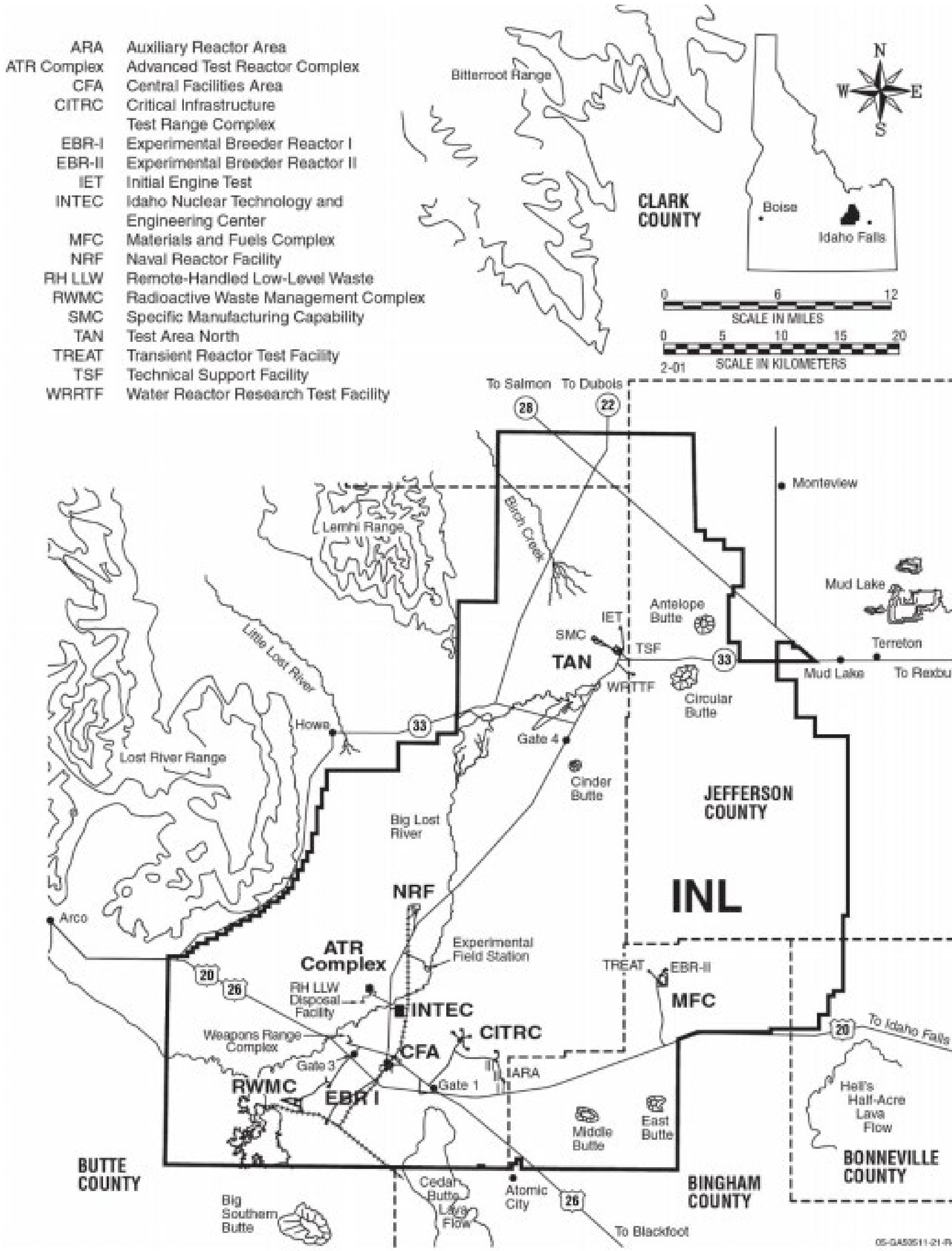

Figure 1. Map of INL and surrounding areas (INL, 2020).

3.1.1 Air

Wind speed and direction have been continuously monitored on and surrounding INL since 1950. Winds at INL typically blow from the southwest, moving up the Eastern Snake River Plain (ESRP). Winds from the northeast are also common, especially at night when movement of cool air back down the ESRP reverses the daytime flows. Conditions at the north end of the Site are somewhat different, as the northwest-to-southeast orientation of the Birch Creek valley channels strong north-northwest winds into Test Area North (TAN) and the surrounding area.

Average monthly near-surface (6 m [20 ft] height) wind speeds have been consistently observed as highest in April and May. Average wind speeds are 15 km/h (9.3 mph) at the Central Facilities Area (CFA) and 15.3 km/h (9.5 mph) at TAN in April. Average monthly wind speeds at the 10-m (33-ft) height were highest in the month of May at the Materials and Fuels Complex (MFC) with a wind speed of 17.5 km/h (10.9 mph). Considerably more wind-speed data are available for detailed design analyses (INL, 2020).

3.1.2 Air Temperature

Limited rainfall, relatively dry air, and infrequent low clouds permit intense solar heating of the surface during the day and rapid radiative cooling at night. These factors combine to produce a large daily temperature range near the ground. The Centennial and Bitterroot mountain ranges to the north keep most of the intensely cold, Canadian winter air masses from intruding into the ESRP. Occasionally, cold air spills over the mountains, producing low temperatures at INL for periods lasting a week or longer.

Temperatures at CFA and TAN best characterize surface air temperatures at INL. The annual average temperature at CFA is 5.7°C (42.3°F), with recorded extremes of −43.8°C (−47°F) and 40.5°C (105°F). Average daily temperatures range from a low of −14°C (7°F) in January to a high of 23°C (73°F) in late July.

The average daily air temperature at TAN ranges from a low of −10.5°C (13°F) during mid-January to a high of 21°C (70°F) in late July. The annual average temperature is 5.7°C (42.2°F). Recorded extremes are 39°C and −45°C (103°F and −49°F), respectively. Considerably more detailed temperature data are available for detailed design (INL, 2020).

3.1.3 Surface Water

The Big Lost River, the Little Lost River, and Birch Creek drain mountain watersheds are located to the north and northwest of INL as shown in Figure 1. The Big Lost River flows southeast between the Lost River Range and the Pioneer Mountains. The Mackay Dam, located upstream of Arco and upstream of the INL diversion dam, impounds and regulates the Big Lost River flow for irrigation. Discharge from the Mackay Dam flows southeastward past Arco and onto INL at the southern part of its western boundary, curves to the northeast past the Radioactive Waste Management Complex (RWMC) and flows northeast to the Big Lost River sinks (four terminal playas). Flow from the Big Lost River is frequently completely consumed in summer months for irrigation, prior to flow onto INL.

Birch Creek flows southeastward between the Lemhi and Bitterroot mountain ranges. Water in the creek is diverted northeast of INL for irrigation and hydropower during the summer months. In the winter months, water is returned to an artificial channel 6.5 km (4 mi) north of TAN where it infiltrates into channel gravel. The Little Lost River drains the slopes of the Lemhi and Lost River mountain ranges. The Little Lost River stream is diverted for irrigation north of Howe, Idaho, and does not normally flow onto INL (INL, 2020).

These sources of water are not evaluated for heat rejection in this report because at face value they are judged as unreliable sources of cooling.

3.1.4 Snake River Plain Aquifer

The Snake River Plain Aquifer (SRPA) is a continuous body of groundwater underlying the ESRP. Depths to the water table from the INL land surface range from approximately 61 m (200 ft) in the northern part of the Site to more than 274 m (900 ft) in the south. Aquifer boundaries are formed by contact of the aquifer with less-permeable rocks in the mountains on the west and north and to the Snake River on the east.

The SRPA has been studied extensively and there is extensive information available from the INL and the U.S. Geological Survey (USGS). The USGS has maintained an ongoing, long-term monitoring and studies program since 1949. Since the inception of the monitoring program in 1949, water-quality samples and water-level measurements have been collected from a network of more than 200 wells. Borehole geophysical data (natural gamma logs) from 333 wells and lithological data from numerous cores were used to create a two-dimensional geologic framework for a variety of facility-scale and INL-scale hydrologic investigations (Bartholomay, 2017). This data is available to ARDs for design of water-cooled heat rejection systems.

Most water in the SRPA moves horizontally through broken basaltic interflow zones and rubble zones between lava flows. The main water-bearing zones are the layers of fractured basalt, which are interbedded with numerous sedimentary or unfractured layers that are not readily permeable and contain little or no water. Flow is primarily in a southwest direction, although direction can be affected by recharge from rivers, surface water spreading areas, and heterogeneities in the aquifer. Figure 2 is a map of Idaho showing the location of INL, the Snake River Plain, and generalized flow lines of the SRPA.

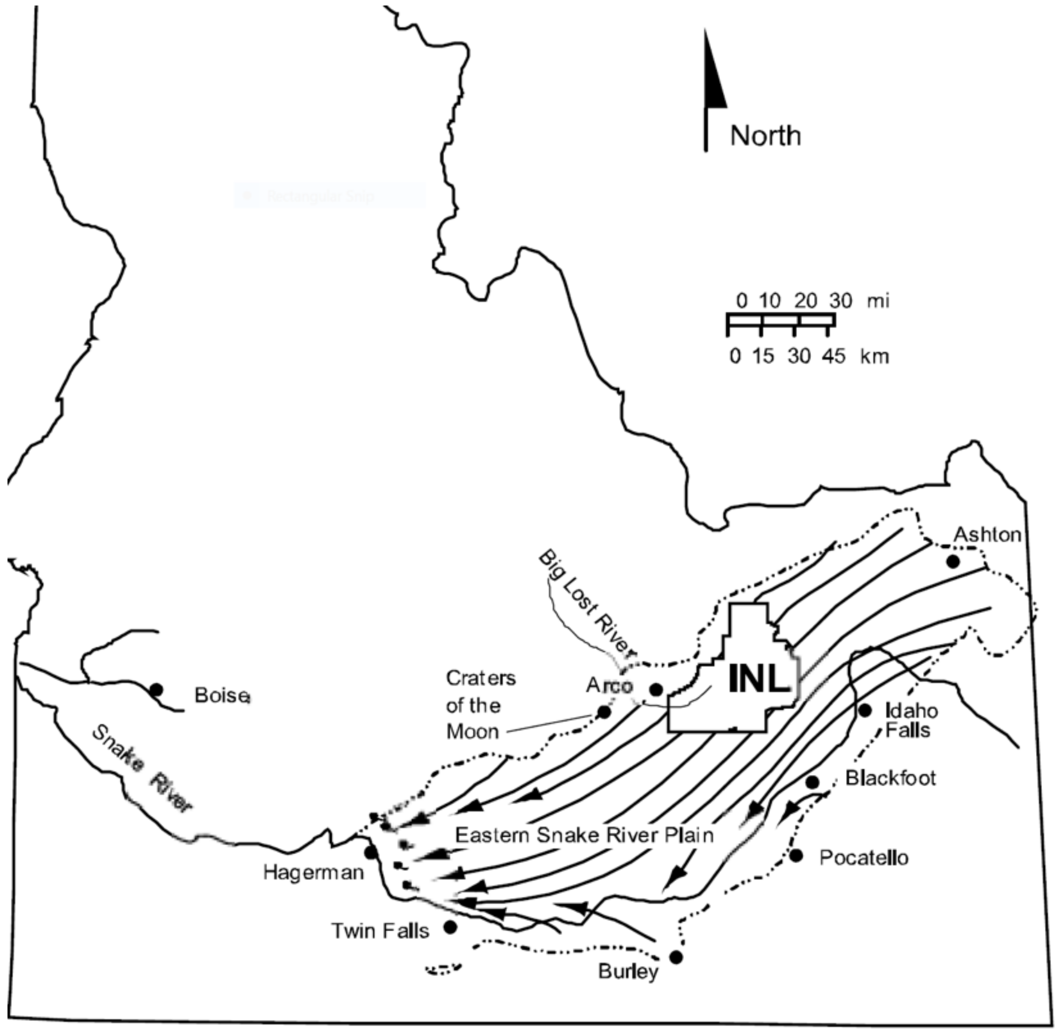

Figure 2. Location of INL in Idaho, the Snake River Plain, and generalized flow lines of the SRPA (INL, 2020).

The aquifer is approximately 325 km (200 mi) long, 65 to 95 km (40 to 60 mi) wide, covering an area of approximately 25,000 km^2 (9,600 mi^2). It extends from Hagerman, Idaho, on the southwest to near Ashton, Idaho, northeast of INL. The aquifer is composed of numerous, relatively thin basaltic flows extending to depths more than 1,067 m (3,500 ft) below land surface. Over time, some of these flows have been exposed at the surface long enough to collect sediment. These sedimentary interbeds are sandwiched between basaltic flows at various depths.

Estimates of the active thickness of the SRPA in the vicinity of INL are based on direct and indirect information obtained from wells and surface geophysical surveys. The active thickness of the aquifer ranges from 102 m (334 ft) to 368 m (1,207 ft).

Estimates of the SRPA capacity range from 2.5×10^{12} m^3 (2×10^9 acre-ft) to 4.9×10^{11} m^3 (4×10^8 acre-ft), of which approximately 6.2×10^{11} m^3 (5×10^8 acre-ft) is considered recoverable, roughly the size of Lake Eerie.

Transmissivity in the aquifer ranges from 100 to 10,000 m^2/day (1,000 to 100,000 ft^2/day) and, in places, exceeds 100,000 m^2/day (1×10^6 ft^2/day). Yields of wells drilled in the Snake River basalts are among the largest in the nation. Irrigation wells open to less than 30.5 m (100 ft) of the aquifer yield as much as 26,500 L/min (7,000 gal/min) with slight drawdown; yields of 7,500 to 11,400 L/min (2,000 to 3,000 gal/min) are common.

Most groundwater pumped from the aquifer is used to irrigate crops. However, because groundwater supplies the drinking water consumed within the ESRP and an alternative drinking water source or combination of sources is not available in some areas, the U.S. Environmental Protection Agency (EPA) designated the SRPA as a sole-source aquifer in 1991 pursuant to the Safe Drinking Water Act (42 USC 300f, et seq., 40 CFR 141–149).

Because the aquifer has been designated as a sole-source aquifer, no federal financial assistance may be committed for any project if the EPA determines that the project may contaminate the aquifer through the recharge zone, thereby creating a significant hazard to public health (INL, 2020).

4. REGULATIONS AND PERMITTING

4.1 Federal and State Water Rights

For privately-owned and operated demonstrations, acquisition of water rights, if needed, and their applicable use will be the responsibility of the ARD, working with state and federal governments. Many of the items discussed below are subject to Idaho Administrative Procedure Act (IDAPA) requirements and require permits or other formal arrangements. Individual ARDs will be responsible for meeting the applicable regulations and requirements.

4.2 Other Regulatory Considerations

Construction of any advanced reactor demonstration will require review under the National Environmental Policy Act (NEPA) of 1970 whether the reactor is licensed by the Nuclear Regulatory Commission (NRC) or authorized by DOE. Adherence to the multiple regulatory sources and DOE requirements typically would result in no significant impact from water use and quality perspectives. The DOE Orders are consistent with national standards and requirements. Use of water for heat rejection may result in release back to the aquifer, either on the surface or by direct injection.

ARDs subject to DOE Orders must maximize water efficiency and conserve natural resources as part of their design, and prior to generating wastewater during operations (DOE O 436.1, 2011). Further, they must ensure liquid releases containing radionuclides are managed in a manner that protects ground water resources now and in the future. Specific requirements for discharge to the ground surface include liquid releases that do not contain radionuclides must also be managed in a manner that maintains groundwater standards for beneficial uses. (DOE O 458.1, 2020):

- Characterization of planned and unplanned releases of liquids containing radionuclides, consistent with the potential for on- and offsite impacts. Provide an assessment of radiological consequences as necessary to demonstrate compliance.
- Liquid discharges containing radionuclides must not exceed an annual average (at the point of discharge) of either of the following:
  - 5 pCi (0.2 Bq) per gram above background of settleable solids for alpha-emitting radionuclides (typical banana contains 15 Bq of radioactive potassium).
  - 50 pCi (2 Bq) per gram above background of settleable solids for beta-gamma-emitting radionuclides."
- Controlled releases of tritium must be held as low as reasonably achievable (ALARA).
- Liquid effluents must comply with maximum contaminant levels (MCLs) in 40 CFR Part 141, "National Primary Drinking Water Regulations" for water.

Of note, the MCL for tritium is 20,000pCi/L and DOE 458.1 prohibits the use of soil as a filter for water discharged at the surface that migrates to the aquifer. Recent interpretation of wastewaters with concentrations below the MCLs can be considered "clean water"; therefore, it is not a discharge.

5. HEAT REJECTION AND ITS IMPACT ON WATER USE

This section presents five potential methods of heat rejection for an ARD, and a discussion of combining methods as a sixth option. While these methods generally bound the heat-rejection methods available for ARDs, they are not intended to represent detailed design decisions. The intent is to provide a framework to inform decisions regarding water use. Of note, in every potential method, the cooling water that is returned to the environment will not come in physical contact with the potentially radioactive cooling fluids in the reactor primary loop or pool. Although monitoring for radioisotopes may be included in the design out of an abundance of caution or for defense in depth, the water discharged back to the environment will not be radioactive (above naturally occurring sources).

5.1 Cooling Tower, Rejecting Heat to the Atmosphere via Evaporation

While there are several cooling tower configurations, all work on the principle of removing heat through evaporation. In the configuration shown in Figure 3, air flow is induced upward by the fan and relatively hot cooling water from the reactor secondary system is sprayed down in a counterflow direction. The hot water from the reactor is typically cooling water from the reactor's condenser and physically separated from the fluid in the reactor secondary system by condenser tubes. Heat is removed in the cooling tower by evaporation and the cooled water settles by gravity to the collection basin. The cooled water is pumped back to the condenser from which it again receives heat and then returns to the spray nozzles in a continuous cycle.

Ultimately, the reactor heat is rejected to the atmosphere taking a fraction of the cooling water with it. Internal components that change the direction of the air and remove droplets reduce the fraction of lost water. Improvement in heat transfer can be achieved with a variety of fill material in the cooling tower that increases surface area and/or improves the mixing of the air and water.

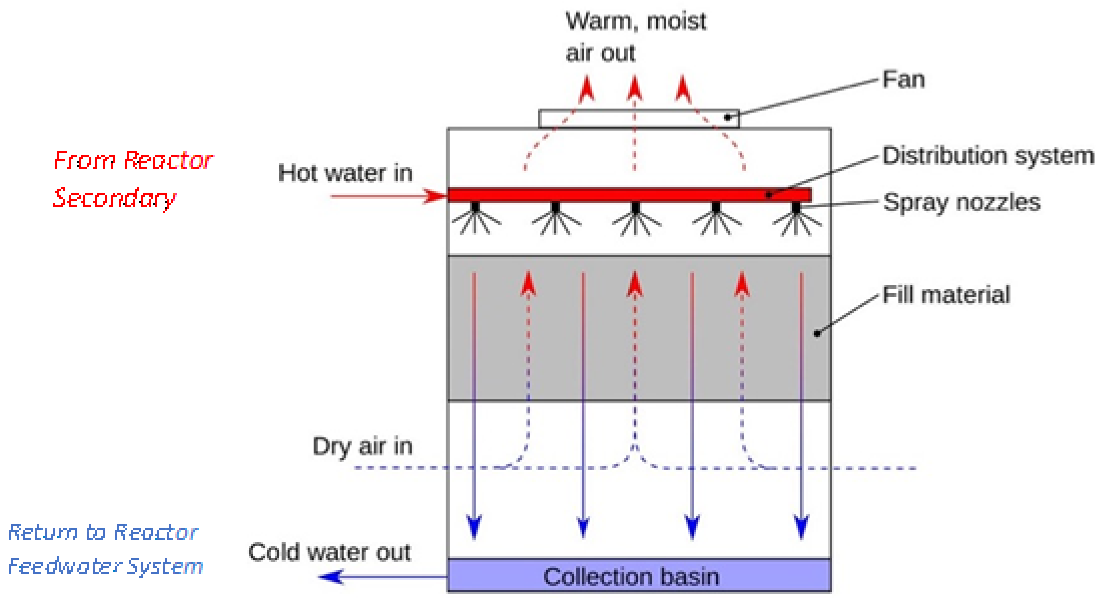

Figure 3. Counterflow Cooling Tower with Induced Flow.

5.2 Injection Well, Pumping Water from the Aquifer, through a Heat Exchanger, and Injecting the Heated Water Back into the Aquifer

Several types and variations of heat exchangers may be used to reject heat from a reactor's power cycle: cross flow, counter- or parallel- flow, baffled, multi-pass, etc. A Rankine cycle is the most common power cycle and uses the heat exchanger to condense the low-quality steam rejected by the turbine generators. Many operating plants are using water from the ocean or rivers to provide the cooling water to the condenser, but there is minimal surface water at INL.

In the Figure 4 example, a cross flow, tube-and-shell heat exchanger is used for condensation and heat rejection to the cooling water. Cooling water is pumped from the SRPA through the condenser, where it accepts the rejected heat from condensation. After heating, it is returned to the aquifer by an injection well. The condensed steam is returned to the Rankine feedwater system. Multiple variations on the power cycle and condenser are available and specific decisions will be made by the designer.

Of note, injection wells are regulated under the Safe Drinking Water Act and discharge of radionuclides to the aquifer is prohibited at INL. Further, only the cooling water used and returned to the aquifer could qualify as non-consumptive use; therefore, consumptive use would be minimal.

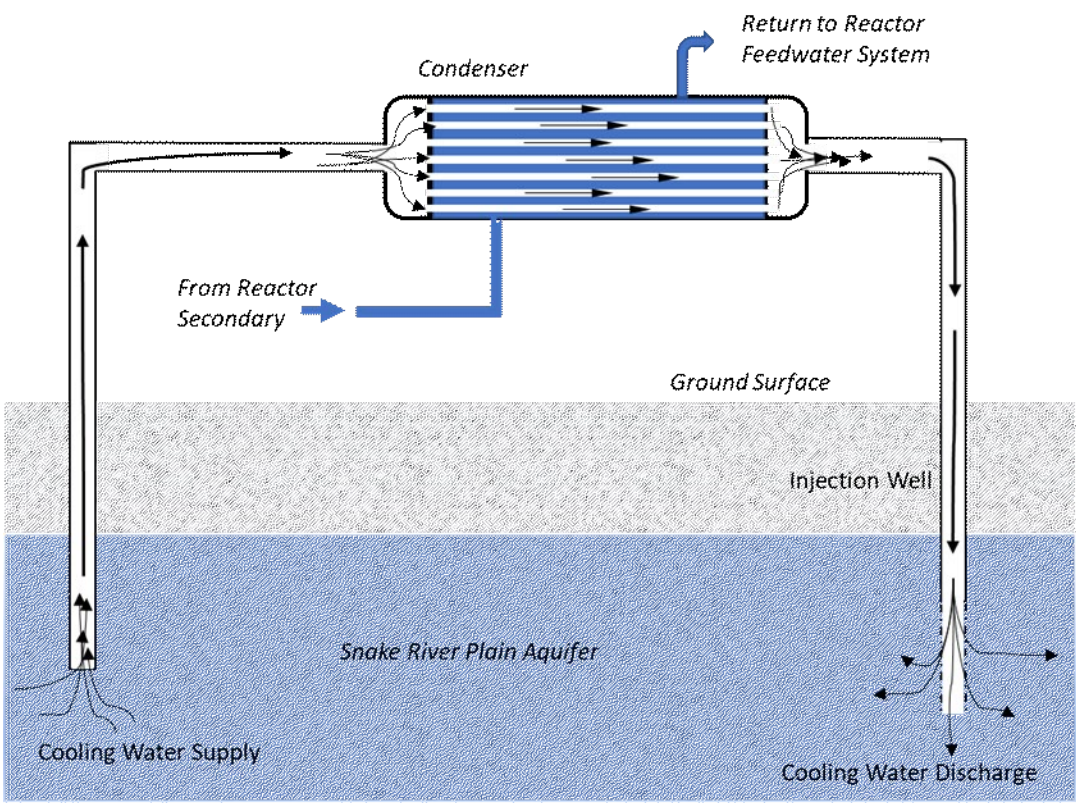

Figure 4. Counterflow condenser.

5.3 Cooling Pond, Rejecting Heat via Evaporation and Convection

A cooling pond is an engineered body of water formed for the purpose of cooling heated water and/or to store and supply cooling water to a nearby power plant. It serves as an intermediate heat sink by receiving the thermal energy rejected in the plant condensers and subsequently rejecting that energy to the atmosphere. Energy is added to the pond by direct heat transfer from the power plant condenser, absorption of naturally occurring solar and atmospheric radiation, and by make-up water transferred into the pond. Energy is removed by thermal radiation, conduction to the atmosphere, evaporation, and by water flowing from the pond. The pond's operating characteristics are determined by climate conditions, shape and depth of the pond, inlet and outlet geometry, and thermal hydraulic conditions in the pond (mixing, turbulence, flow direction, etc.). Variations in cooling pond designs may include numerous combinations of baffles, weirs, and/or spray nozzles.

An example of a pond that employs diking and baffling is the Cholla Steam Plant in Holbrook, Arizona. The pond has a surface are of 389 acres and services a plant with nominal generating capacity of 125 MW_e. The Cholla cooling pond also uses an inverted weir that was added in response to wind conditions at the site. Variations in design to account for unique environmental conditions at the Site are typical of cooling ponds. The Chola Cooling Pond is shown in Figure 5, which provides an order-of-magnitude example of a cooling pond's size.

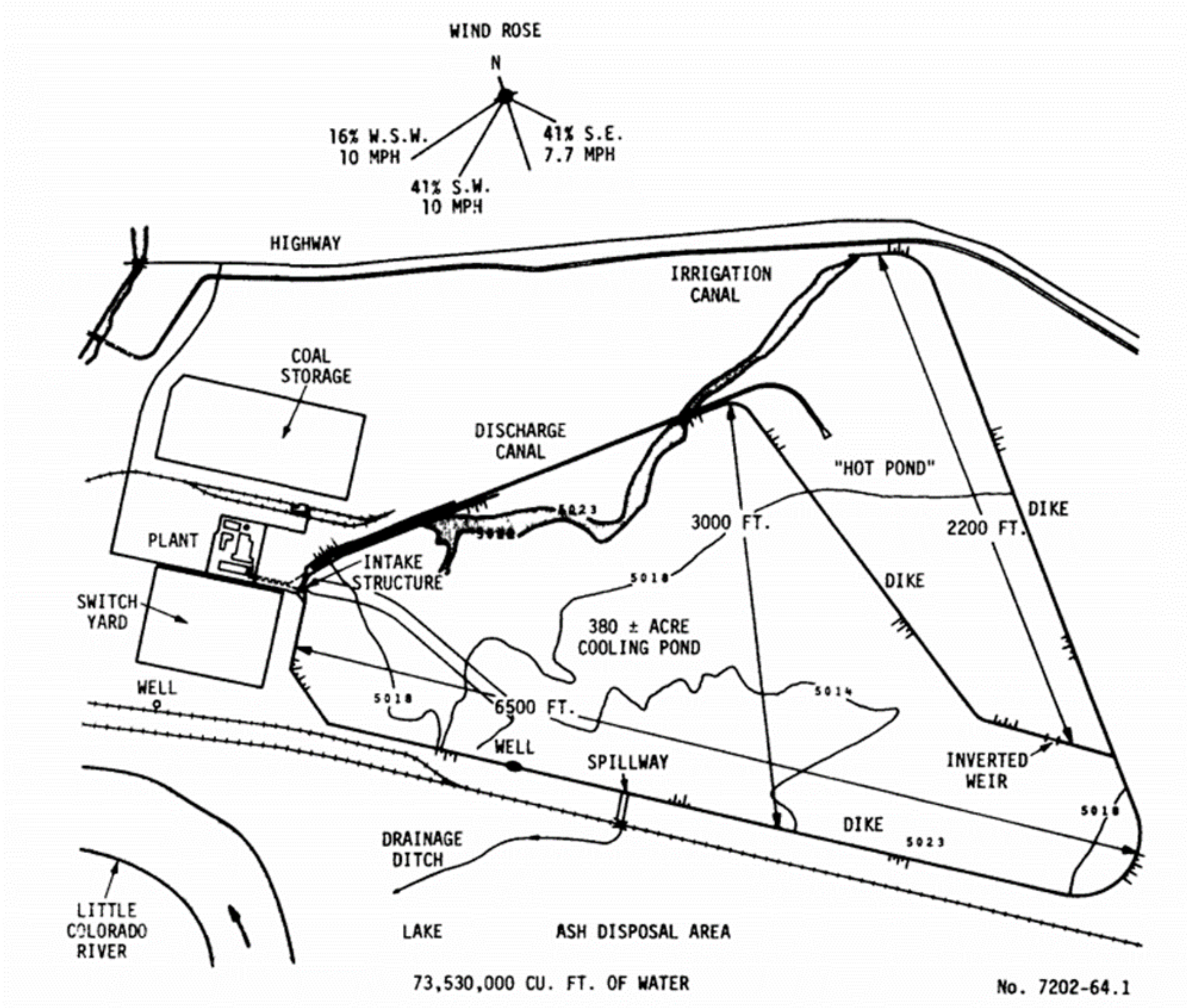

Figure 5. Cooling Pond Example—Cholla Steam Plant, Holbrook AZ (Hanford Engineering Development Laboratory, 1972).

For scoping studies only, the heat transfer performance of the cooling pond is approximately equal to that of once-through cooling as described above for an injection well. The condition that must be met to use this thumb-rule is that the pond surface area must be greater than or equal to one 1 acre for each 3-MW_{th} increment of reactor power (Littleton Research and Engineering Corporation, 1970).

All the groundwater transferred into the pond would be considered non-contact cooling water. Non-contact cooling water is defined here, consistent with IDAPA 58, as water used to reduce temperature that does not come in contact with any product or material other than heat which does not potentially negatively impact ground water (IDAPA 58.01.17). Water in the cooling pond would be physically separated from reactor process water and no radionuclides would be discharged to the cooling pond. Heating would occur through a physical barrier (condenser tubes).

5.4 Ground-Coupled Heat Exchanger, Rejecting Heat Back to the Earth and Snake River Plain Aquifer

A ground-coupled heat exchanger (GHEX) is an underground heat exchanger that dissipates heat to the ground and/or aquifer. The GHEX shown transfers to both. Another configuration might only transfer heat to the soil. The Earth's near constant subterranean temperature is the ultimate heat sink for the fluid(s) cooling the reactor or other nuclear demonstration. GHEX systems may be open or closed loop (most common) and configured in a variety of banks and/or loops. The GHEX shown in Figure 6 is a single pass closed loop that removes heat from the condenser in a Rankine power cycle. A benefit of this system is that it provides a physical barrier to inadvertent release of radionuclides compared to a direct injection.

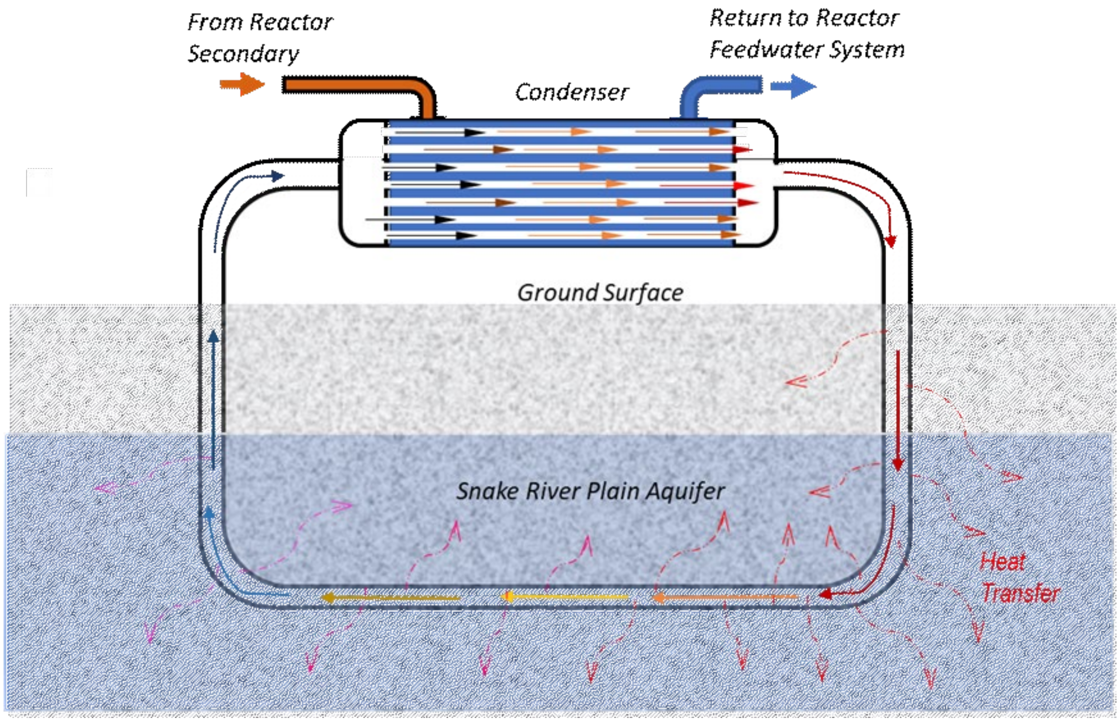

Figure 6. Ground-coupled Heat Exchanger (GHEX).

Heat transfer in this configuration may be greater once the loop reaches the SRPA as heat transfer by convection to the water may be more efficient than conduction into dry soil and rock. Groundwater flow of 5 m to 10 m per day will carry the heated water away from the pipe and replace it with water at a temperature of approximately 13°C. Further study to compare the thermal resistance of dry conduction to convection at low flow rates is needed.

This method of heat transfer is used widely around the world for cooling and heating and is significantly influenced by the type of earth (sand, rock, gravel, clay, etc.) in which it is located. The results of subsurface soil sampling at many locations across INL are available. GHEXs have not yet been used in nuclear applications; therefore, the GHEXs are relatively immature compared to the other methods of cooling.

Of note, at least two physical barriers exist between the reactor cooling fluids and the SRPA. No radionuclides would be discharged to the groundwater. In traditional LWRs, these take the form of the primary and secondary loops.

5.5 Air-Cooled Heat Exchanger, Rejecting Heat to the Air with an Open Loop

Air-cooled heat exchangers (ACHE) are common throughout industry, especially where access to water and the increasing cost of water are factors in design. Using an ACHE eliminates the need for water use for rejecting heat. The principle component of an ACHE is the tube bundle(s), typically comprised of finned tubes terminating in header boxes. Coolant flows through the tubes and heat is rejected through air flow around the tubes. However, the ACHE is large compared to other heat exchangers and requires free space around it for cooling air flow. This results in a large plot space at-grade or tall structure, each with unique design considerations. Air flow can be forced or natural draught, with tall structures an intuitive match for natural draught.

For the example shown in Figure 7, air is moved over the tubes in a single crossflow pass by axial flow fans, which may be arranged for forced or induced draught. Coolant from the reactor power cycle is circulated through the tubes and transfers heat to the air. A portion of the heated air is recirculated to enhance the heat transfer from coolant to the air and with standard industrial controls, the recirculating air flow can be adjusted for ambient conditions.

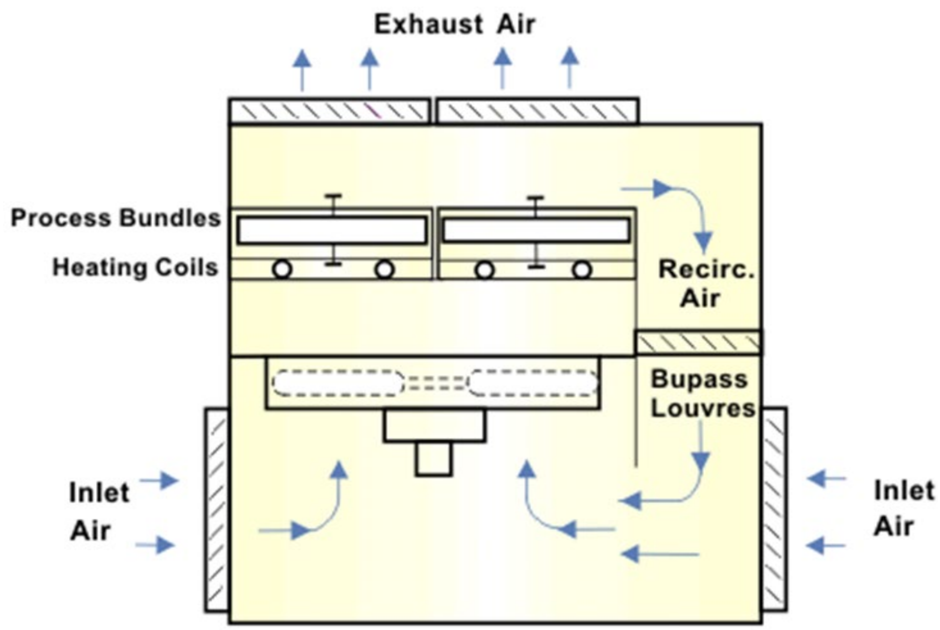

Figure 7. Air-cooled Heat Exchanger (ACHE)—crossflow configuration with recirculation.

The design of an ACHE is more complex than the design for a standard shell and tube heat exchanger as there are many more components and variables. The air side heat transfer properties dominate the coolant side characteristics, and almost all heat transfer optimization is for the secondary (air) side. Ambient air temperature is the most critical factor affecting the size of an ACHE and 3 meters per second is a typical face velocity. In industry, the maximum inlet temperature is typically set at the dry bulb temperature that equals or exceeds ambient temperatures for 95% of the year. For advanced reactor demonstrations this may limit operations during the summer and a higher inlet may be considered. High-level design choices will involve trade-offs between air flow rates and the resulting pressure drops and power requirements for the fan(s).

5.6 Combinations of the Methods Listed Above

It is possible that a combination of heat-rejection methods can provide an optimal solution for any specific ARD. The simplest solution—pumping water from the SRPA through a condenser and discharging to a surface impoundment—is likely the least expensive and most technically mature. However, DOE is obligated to minimize impact to the SRPA (DOE O 436.1, 2011) and that obligation is passed along to ARDs.

Opportunities for a hybrid heat rejection system to minimize SRPA impacts should focus on large daily and seasonal variations in ambient temperatures, the constant temperatures in the aquifer and Earth below approximately 10 meters, and in the aquifer, itself. For example, an ACHE or cooling tower sized for operations in winter could supplement the cooling provided by directly pumping from the SRPA to cool a condenser in the summer. Turning the pumps off during the winter would reduce one of the largest operating costs—electrical power—for a significant part of the year.

These types of trade-offs depend heavily on the specific design of the advanced reactor and the duration of the demonstration. A detailed evaluation and design will be needed for each ARD but a qualitative discussion of the relative advantages and disadvantages of each method and selected combinations of methods is provided in the subsequent sections.

6. TYPES OF REACTORS AND THEIR EFFECT ON COOLING WATER USE

The size and type of reactor demonstrated will affect heat-rejection methods and determine the amount of cooling water needed. The reactor's purpose (power production, industrial application, district heating, etc.) can also affect water use. A detailed analysis is beyond the scope of this study, so it was determined that the water use in all types of advanced reactors would be evaluated with power production using a Rankine cycle. This is appropriate even across the broad spectrum of possible reactor outlet temperature (ROT) ranges, which generally vary as shown in Table 1 (Ux Consulting, 2010).

Table 1 is not intended to list every possible reactor type or exactly identify the range ROTs, as advanced reactor designs continue to evolve. Instead, Table 1 establishes a rough range of temperatures over which the Rankine cycle can be evaluated.

Table 1. Advanced reactor types and approximate range of reactor outlet temperature (ROT).

Reactor Type	ROT (°C)	Examples
Pressurized and Boiling Water Reactors (PWR, BWR)	300–330	IRIS, mPower, NuScale, SMART, OKBM-40S, OKBM VBER-300
High Temperature Gas-cooled Reactors (HTGR)	750–1000	PBMR, HTR-PM, GT-MHR
Liquid Metal Reactors (LMR)	500–700	4S, Hyperion, PRISM
Molten Salt Rectors (MSR)	500–700	MSRE, MSFR, AHTR

Material limitations provide a better understanding of the constraints of a nuclear Rankine cycle. For steam in a Rankine cycle, approximately 650°C is the upper end of allowable steam temperature based on the pressures needed to drive the turbine (The Babcock and Wilcox Company, 2005). Some trade-offs between steam temperature and pressure can make modest improvements in efficiency, but 650°C is also approximately the lower end of the temperature range for a Brayton cycle. For power generation, a combined cycle typically switches from the Brayton cycle to a Rankine cycle at about 650°C. Hence, 650°C was selected as the upper steam temperature bound for evaluation with a Rankine cycle. The lower bound for steam temperature was selected as 300°C based on a ROT of 325°C representative of water-cooled reactors in Table 1 and a 25°C drop across the heat exchanger or steam generator.

Moisture content in the steam is determined by condenser vacuum and by heat sink temperature. For INL, heat temperatures are set by either the SRPA temperature, by ambient air temperature, or a combination of the two. The net efficiency of the Rankine cycle is the result of the difference between the steam temperature entering the turbine and the heat sink temperature. Efficiencies can be improved with reheat, open versus closed condensation schemes, and changes in condenser flow rates (water or air), but ultimately, these variables are not a function of ROT.

Therefore, ROT is not a discriminator in determining the best cooling method if a common Rankine cycle will be used for analysis and comparison. Cost, thermal efficiency, and environmental impact are more suitable as discriminators for the heat rejection method. These discriminators for heat rejection may be affected by the thermal capacity of the reactor but are not affected significantly by ROT. Heat rejection cost can be scaled linearly from the reactor's thermal capacity.

7. EVALUATIONS

The required cooling water for heat rejection from a Rankine power cycle, through a condenser and to the heat sink, was calculated through the basic heat flow relationships. The investigated plant output ranges were from 75 MW_e to 300 MW_e, where the plant efficiency was assumed to have a value of 33.3%. Without considering nonlinearities and loss of energy during flow, the required minimum flow rate of water for a once-through-cooling system for removing the waste heat can be simplified as follows:

$$Q = R * C_p * \Delta T \quad (1)$$

$$R = \frac{Q}{C_p * \Delta T} \quad (2)$$

Where:

R = the flowrate for the once-through-cooling system,

Cp = specific heat of water,

ΔT = temperature difference

Q = waste heat load

A demonstration plant with 150 MW_e-hours capacity is assumed to have a waste heat load, Q, of 300 MW-hours:

$$Q = 300,000,000\ \frac{W}{hour} \tag{3}$$

If the water flowing through the condenser rises, ΔT, with a value of 10°C, then the flow rate, R, through the condenser is calculated as follows:

$$R \approx 27,000\ \frac{m^3.}{hr.} \tag{4}$$

The flow rate can be calculated for several scenarios of different electricity outputs and temperature rises through the condenser. The electricity outputs are assumed to be 75,150, 225, and 300 MW_e, where the temperature rise through the condenser is assumed in the range of 5 to 25°C. Table 2 shows sample flow rates in gal/min and m^3/sec for different MW_e values and temperature rises. As expected, the required minimum flow rate increases if the desired temperature rise through the condenser decreases and the electricity output increases.

Table 2. Flow rates for different electricity outputs and temperature rises.

MW_e	ΔT (°C)	Flowrate (m^3/hr)
75.0	5.0	27,000
75.0	10.0	13,500
75.0	15.0	9,000
75.0	20.0	6,750
75.0	25.0	5,400
150.0	5.0	54,000
150.0	10.0	27,000
150.0	15.0	18,000
150.0	20.0	13,500
150.0	25.0	10,750
225.0	5.0	81,000
225.0	10.0	47,000
225.0	15.0	27,000
225.0	20.0	20,250
225.0	25.0	16,200
300.0	5.0	108,000
300.0	10.0	54,000
300.0	15.0	36,000
300.0	20.0	27,000
300.0	25.0	10,800

Figure 8 shows minimum required water for different plant output and varying rise in temperature through the condenser. The required cooling water exponentially decreases with increased temperature rise of the water passing through the condenser.

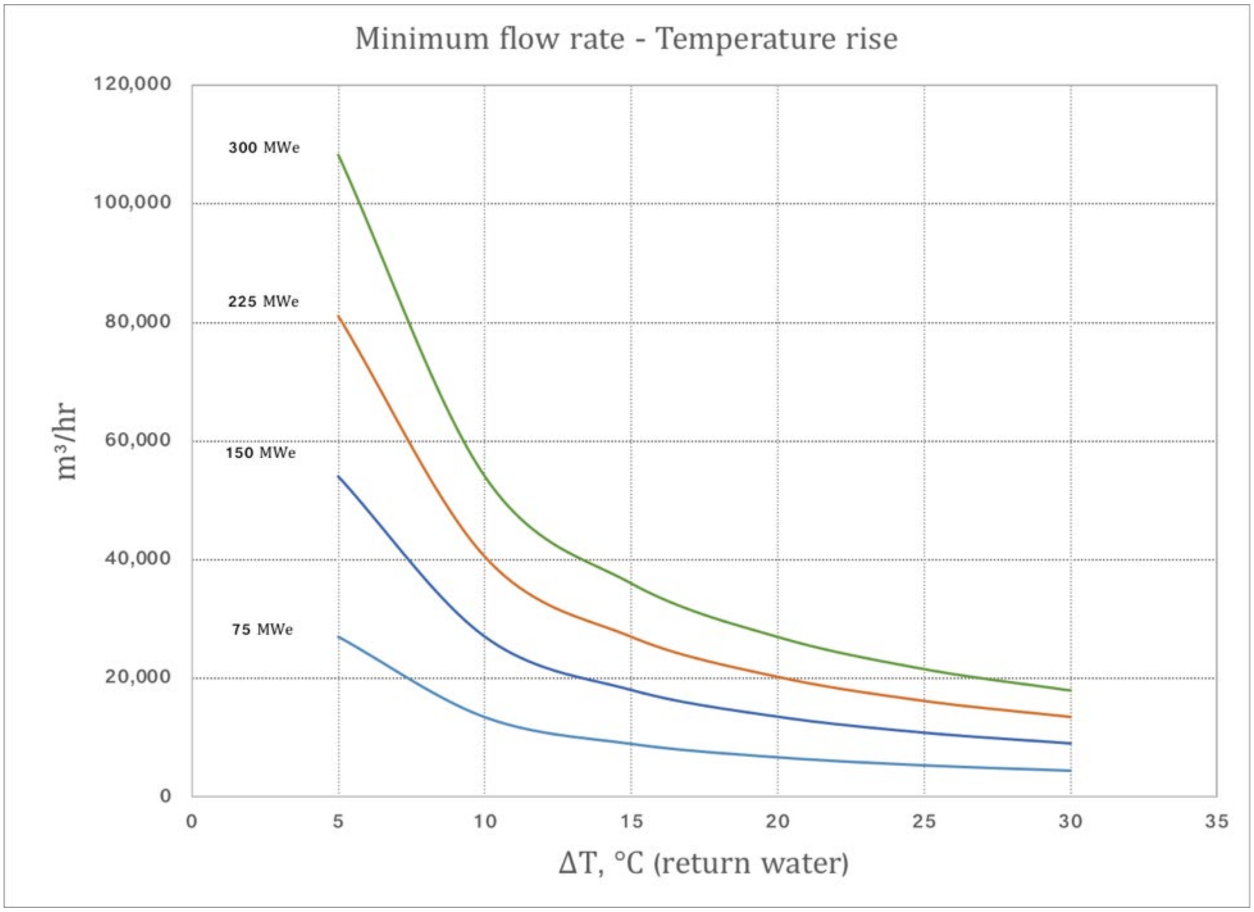

Figure 8. Minimum flow rate and temperature rise for 75, 150, 225, and 300 MW_e with the temperature rise range of 5 to 25°C.

7.1 Cooling Tower, Rejecting Heat to the Atmosphere Via Evaporation

Cooling tower water flow is based on the calculations given in the previous section. The outlet and inlet cooling water temperatures are assumed 25°C and 35°C (10°C difference), respectively. In an example calculation for 150 MW_e, the water required, R, is approximately 27,000 m^3/hr.

Total cooling duty handled in kcal, CD: $R * \Delta T \approx 270,000,000\ kCal/hr$ **(5)**

Evaporation loss, EL: $0.00085 * 1.8 * R * \Delta T \approx 415 \frac{m^3}{hr}$ **(6)**

For the blowdown requirement calculation, the cycle of concentration (CoC) is assumed as five for, consistent with cooling tower operations at the Advanced Test Reactor (ATR) on the INL Site.

Blowdown requirement, BD: $\frac{EL}{(CoC-1)} = \frac{415}{(5-1)} \approx 103 \frac{m^3}{hr}$ **(7)**

The total make-up water requirement: $EL + BD = 518 \frac{m^3}{hr}$ **(8)**

Figure 9 shows estimated total make-up water required for different reactor sizes and cooling water temperature change.

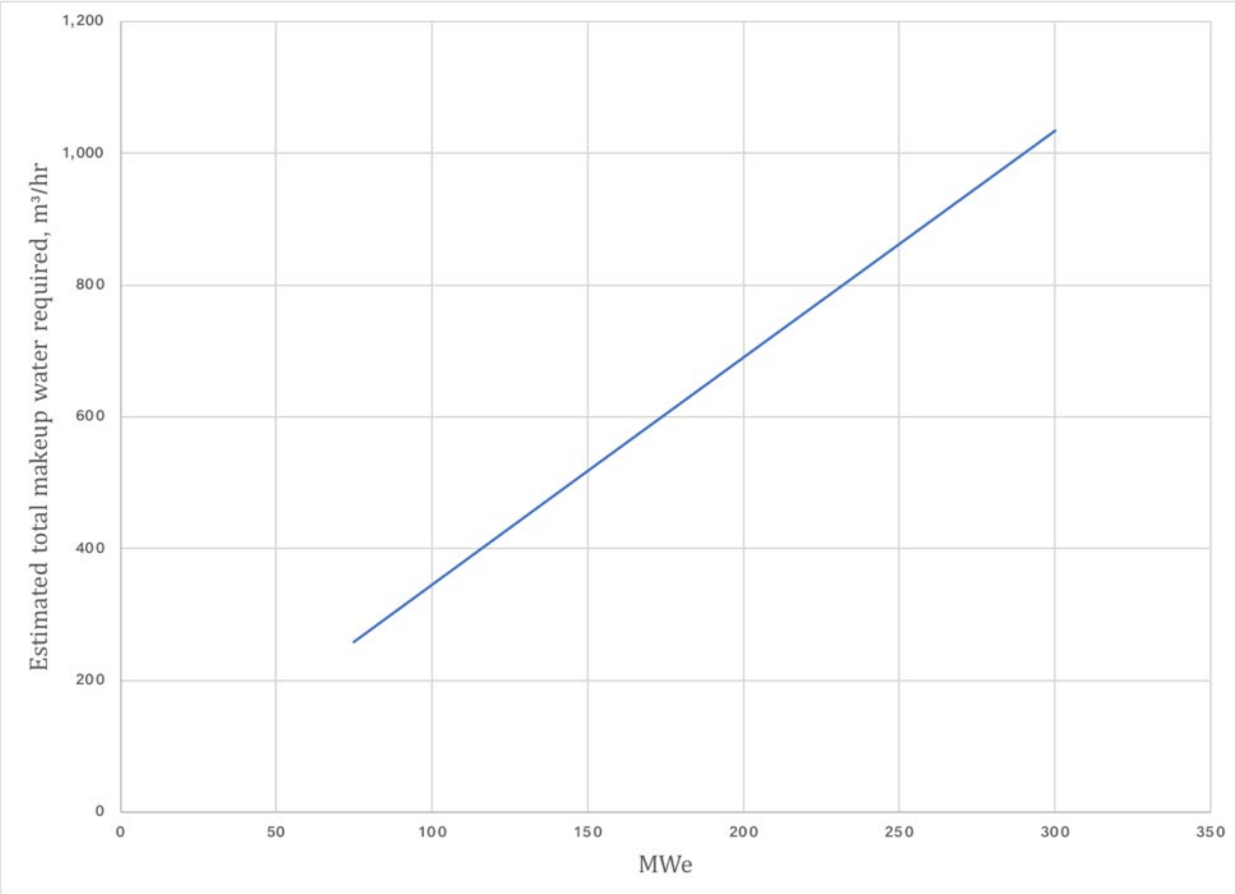

Figure 9. Estimated total make-up water required for different size reactors.

7.2 Injection Well, Pumping Water from the Aquifer, through a Heat Exchanger, and Injecting the Clean Heated Water Back into the Aquifer

In this heat-rejection option, cooling water is assumed to be pumped from the SRPA. The heated water is discharged to downstream of the aquifer by an injection well. Figure 10 shows a schematic overall view of using the SRP for cooling water purposes. Figure 11 shows the temperature gradient of the Eastern SRPA. Upstream temperature of the SRB around the INL Site is assumed to be13°C. The cooling water is pumped to the condenser with a flow rate of R', where the aquifer's flow rate is R. After leaving the condenser, the temperature of the water increases by ΔT'. Thus, the exit temperature, T', is equal to summation of the cooling water temperature, T, and ΔT'.

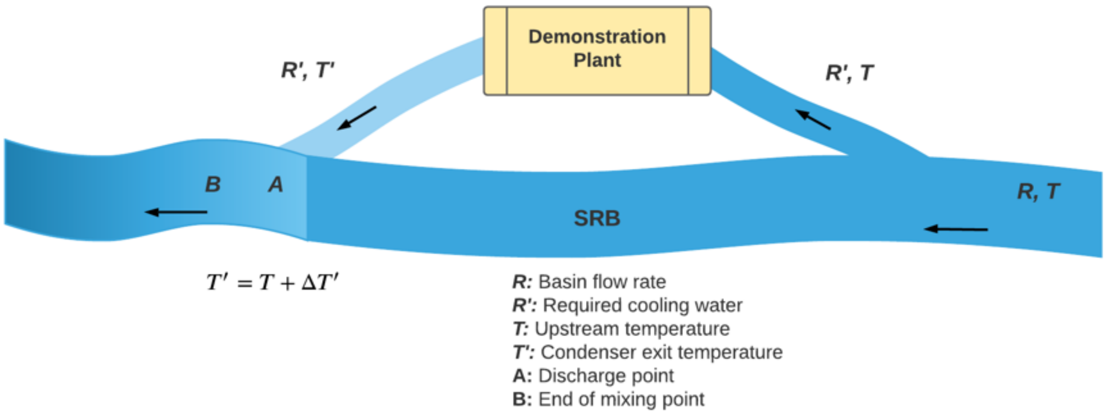

Figure 10. Schematic view of using Snake River Plain aquifer for cooling water purposes.

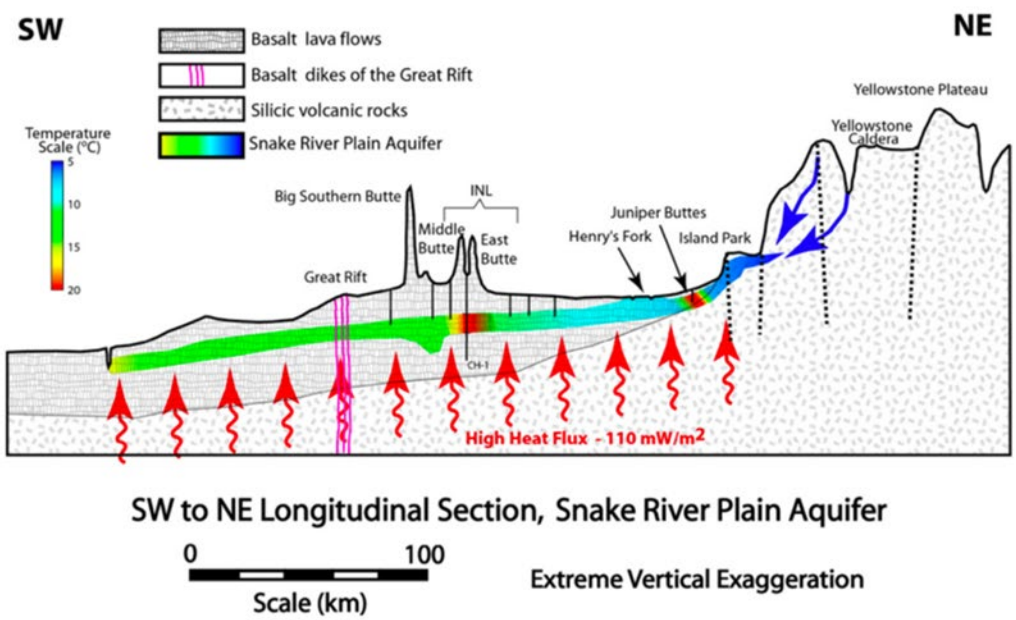

Figure 11. Temperature distribution of the simplified and idealized longitudinal section of Eastern Snake River aquifer (McLing, T. L. et al., 2016).

The temperature increase, ΔT, at the discharge location, A, can be simply calculated with relationships of the basin flow rate, R, and cooling water flow rate, R':

$$\Delta T = \frac{R\prime}{R}\Delta T' \quad (9)$$

The flow rate of the basin, R, requires some assumptions with an effective flow cross section and flow velocity. Basin flow rate, R ($h * b * v$), is calculated as $60\ {m^3}/{s}$, where the effective depth and width are assumed 100 and 10,000 meters, respectively. The flow velocity, v, is assumed as $5\ {m}/{day}$. Table 3 provides a summary of temperature estimations at the discharge location of A. The estimated temperature rises at the discharge location are below 1°C for all the investigated reactor outputs.

Table 3. Estimated temperature rise at discharge location A for different plant outputs.

Variable definition	Variable definition	75 MW_e	150 MW_e	225 MW_e	300 MW_e
Total effective aquifer flow rate (m^3/s)	R	60	60	60	60
Upstream temperature (°C)	T	13	13	13	13
Condenser flow rate (m^3/s)	R'	1.4	2.7	4.0	5.4
Temperature difference after condenser (°C)	$\Delta T'$	10	10	10	10
Temperature difference at A (°C)	ΔT	0.6	1.3	1.9	2.5
Temperature at discharge location, A (°C)	T''	13.6	14.3	14.9	15.5

The temperature rise at the discharge location will dissipate through the flow of the water in the aquifer. The decrease in temperature through the downstream flow is assumed as an exponential decay function that is based on empirical observations (IAEA, 1976). Δθ is the remaining temperature increment in the downstream flow. The relaxation distance, D, corresponds to an approximate reduction of ΔT to 1/3 of its initial value. The remaining temperature, Δθ, can be calculated as follows:

$$\Delta\theta = \Delta T * e^{-d/D} \quad (10)$$

In the relaxation distance, D, calculation, u is the wind speed and assumed zero for the aquifer. T'' is the surface temperature and kept equal to the aquifer temperature at A in the calculations.

$$D = \frac{h' * R}{h * b}\frac{864}{0.01 * T'' + 0.95 + (0.62 + 0.37 * u) * (1 + 0.87 * e^{0.05 * T''})} \quad (11)$$

Figure 12 shows the temperatures at the discharge location for different plant output capacities. The temperature rises at the discharge locations to the aquifer are less than 1°C for all investigated potential demonstration plants. However, these estimations are based on the assumptions discussed earlier, and the empirical and theoretical relationships. Detailed analytical approaches are needed to have better estimates of the effects of discharging heated water to the basin.

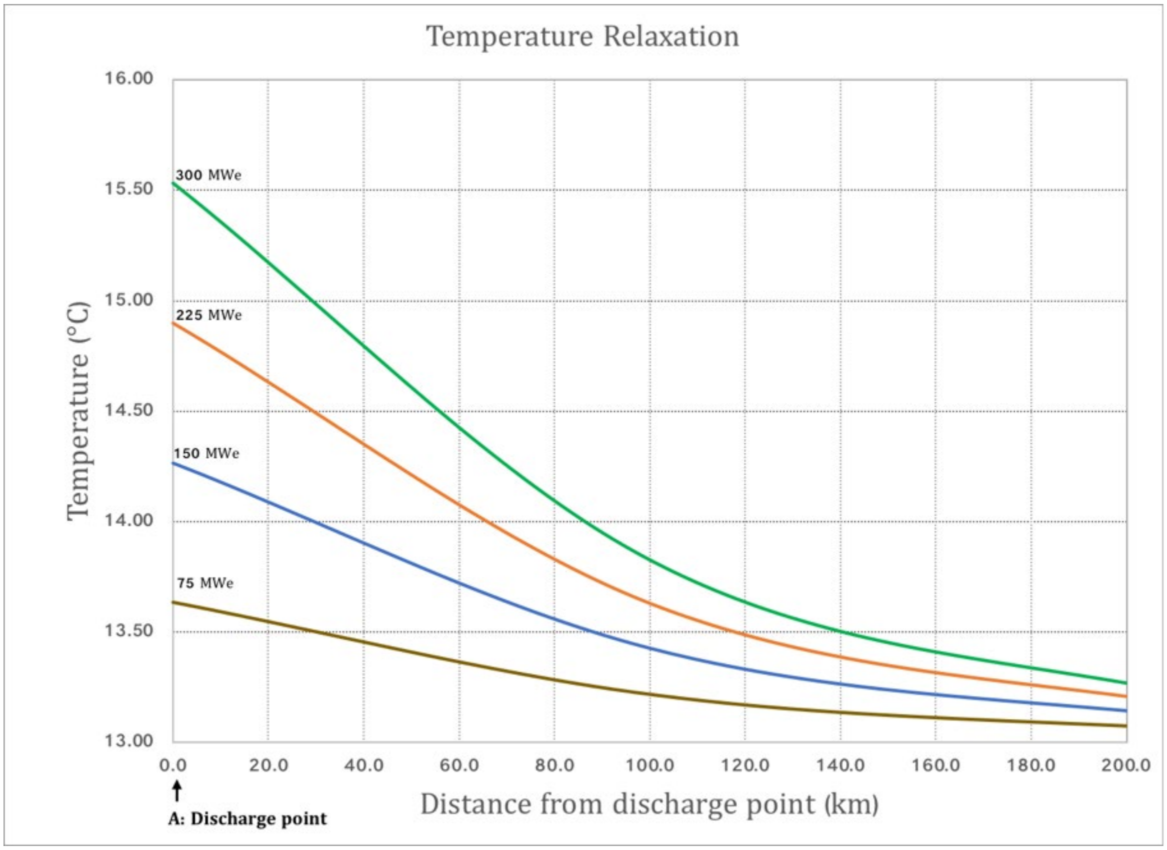

Figure 12. Temperature relaxation from the discharge location towards the downstream.

7.3 Cooling Pond, Rejecting Heat via Evaporation and Convection

The cooling pod is a once-through system, where the water is obtained from the water body with a temperature T_{cold} and flowrate, *R*. The cooling water is pumped with the water body temperature T_{hot} and flowrate of *R'*.

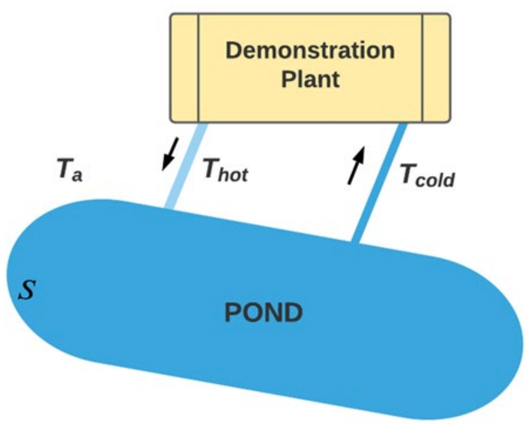

Figure 13. Cooling pond illustration.

The average temperature increment in the pond, $\overline{\Delta T}$, follows the overall heat balance (IAEA, 1974):

$$\overline{\Delta T} = \frac{\Delta T'}{\ln\left(1 + \frac{\Delta T'}{T_{cold} - T_a}\right)} \quad (12)$$

Where, T_{cold} is the inlet condenser temperature, T_a is the air temperature, and $\Delta T'$ is the temperature increment through the condensers, in °C.

The average water temperature in the pond, $\overline{T}$, is equal to $T_a + \overline{\Delta T}$. The pond surface area, S, can be estimated as follows:

$$S = \frac{R'}{\alpha} \ln\left(1 + \frac{\Delta T'}{T_{cold} - T_a}\right) \quad (13)$$

The term α represents the average heat transfer coefficient per unit area:

$$\alpha = 1.16 * (0.01 * \overline{T} + 0.95 + (0.62 + 0.37 * u) * \left(1 + 0.87 * e^{0.05 * \overline{T}}\right)) \quad (14)$$

If it is assumed that a minimum cold temperature of 25°C is maintained throughout the year with changing air temperatures and an average wind velocity of 1 m/s, then Figure 14 shows the required pond surface area for different plant outputs and air temperatures.

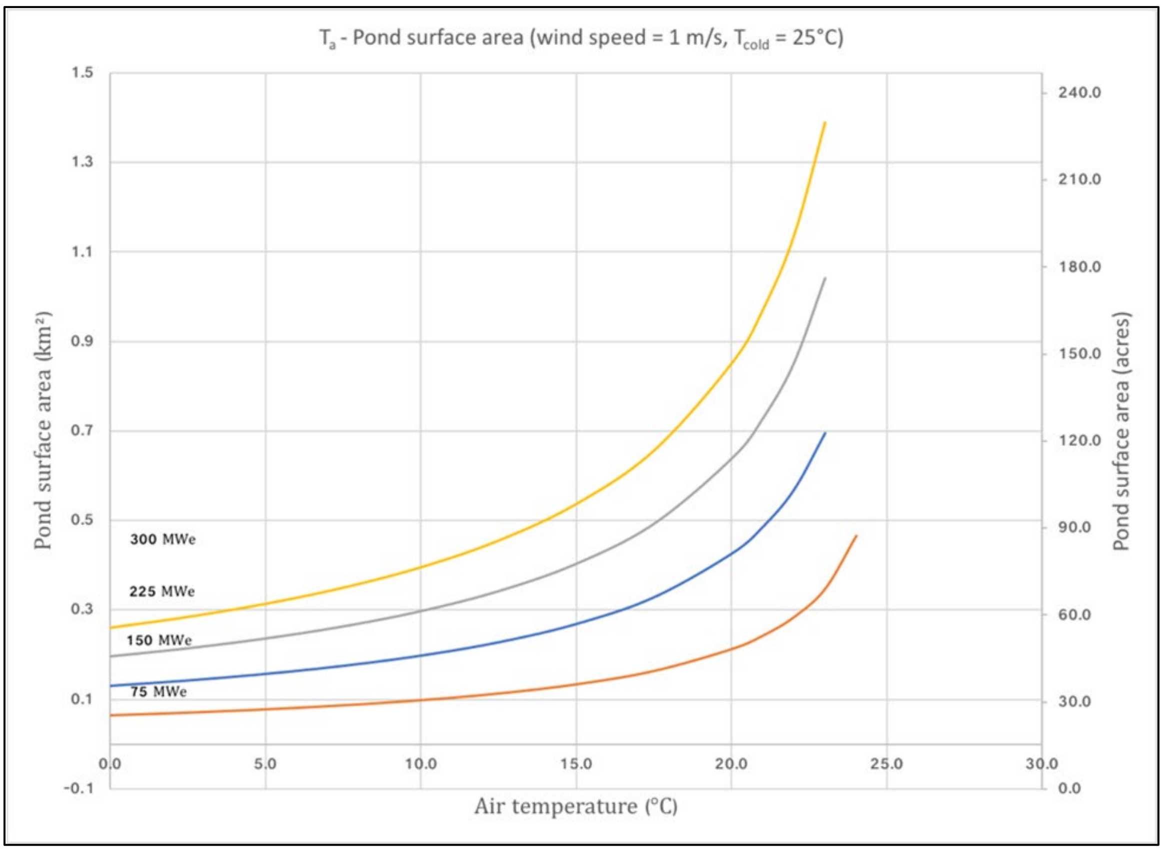

Figure 14. Required pond surface area to maintain a minimum of 25°C cold temperature.

7.4 Ground-Coupled Heat Exchanger, Rejecting Heat Back to the Earth and Snake River Plain Aquifer

Two conditions of ground-coupled systems are considered: inside the soil and inside the water. The solution for a heat conduction from an underground pipe installed horizontally at a finite depth can be simplified as (Kusuda, 1981):

$$Q = \frac{2\pi L k_m (T_p - T_m)}{\ln(\frac{d}{r} + \sqrt{((\frac{d}{r})^2 - 1)}} \quad (15)$$

Where:

Q = heat loss

k_m = average thermal conductivity of the medium surrounding the pipe

d = depth of the pipe measured from the surface to the center line of the pipe

r = external radius of the pipe

T_p = pipe temperature

L = length of pipe.

The above equation can be approximated as follows when d/r >> 1 and heat loss per unit length:

$$Q = \frac{2\pi k_m (T_p - T_m)}{\ln(\frac{2d}{r})} \quad (16)$$

Figure 15 shows a schematic view of the cross section for a single buried pipe system. Although the representative calculations and discussion is for a single pipe, the system can be composed of multiple pipes with or without insulation.

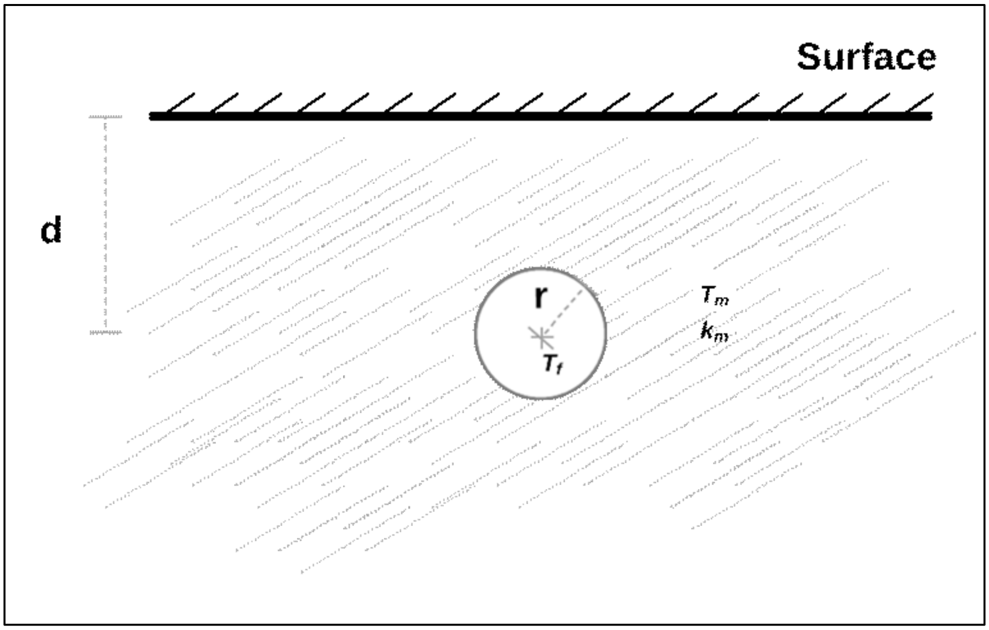

Figure 15. Single pipe system cross-section buried in ground.

Figure 16 shows thermal conductivity values for different forms of soil, moisture content of soil. Figure 17 shows a sample soil profile from INL, where moisture, clay, and sand contents are provided along with the depth of the soil profile. If a moisture content of 15% in a sandy/clay is assumed, then the thermal conductivity can be assumed as 1.5 W/K-m for the soil from Figure 16. If the pipe is embedded inside the aquifer, then the thermal conductivity is assumed as 0.65 W/K-m. For a soil medium with average temperature of 20°C and aquifer with average temperature of 13°C, Figure 18 shows the heat loss of the pipe per unit length. It can be concluded that a piping system to dissipate the heat from the demonstration plants is not the most viable solution, as it will require a lengthy underground piping system.

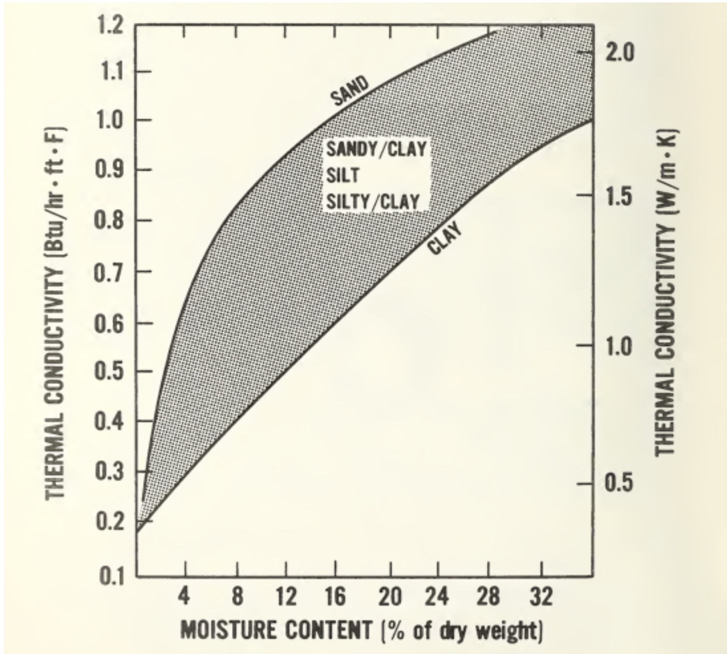

Figure 16. Sample soil profile from INL Site (Nimmo et al., 1999).

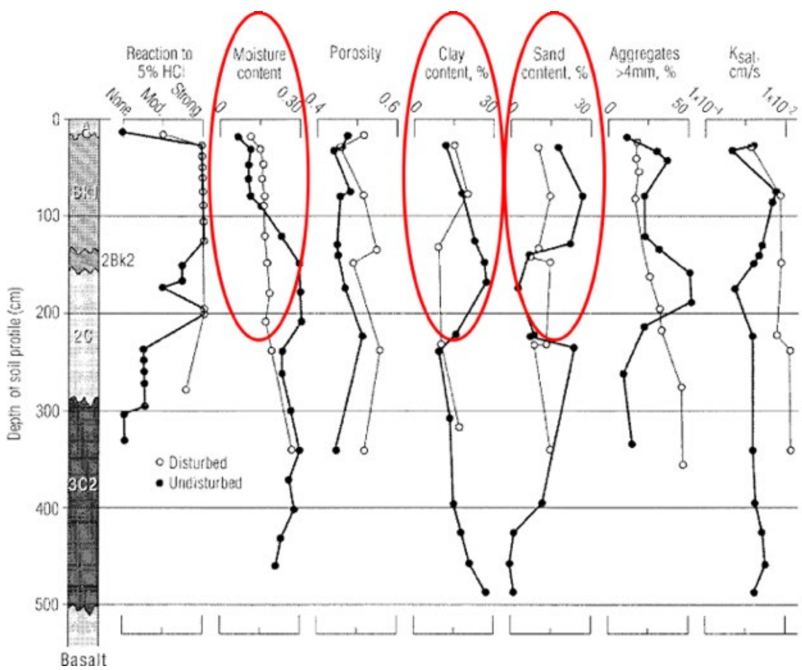

Figure 17. Thermal conductivity-moisture content for soils (Kusuda, 1981).

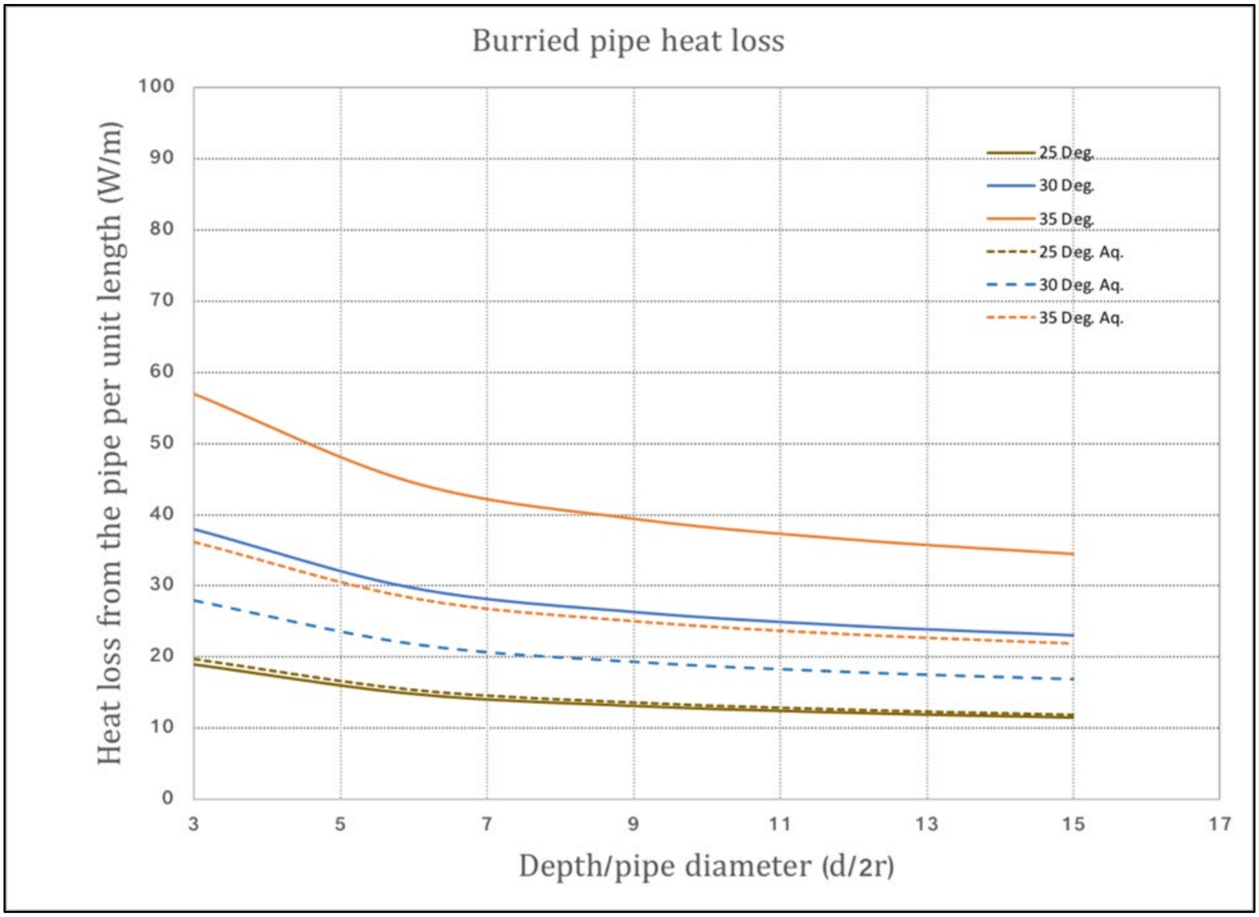

Figure 18. Buried pipe heat loss with different inlet temperatures and surrounding mediums.

7.5 Air-Cooled Heat Exchanger, Rejecting Heat to the Air with an Open Loop

Dry cooling towers are more costly than wet cooling options. Air-cooled dry systems may cost up to three times more than a comparable wet cooling system (Davis et al., 2002). Additionally, they may cover relatively larger land surface for their operations (EPRI, 2005). However, air-cooled systems can be good candidates if there are concerns related to water use. One of the important parameters in sizing and designing air-cooled heat-rejection systems is the ambient air temperature. Figure 19 shows the average design dry bulb temperature for the Idaho Falls area (ASHRAE, 2005).

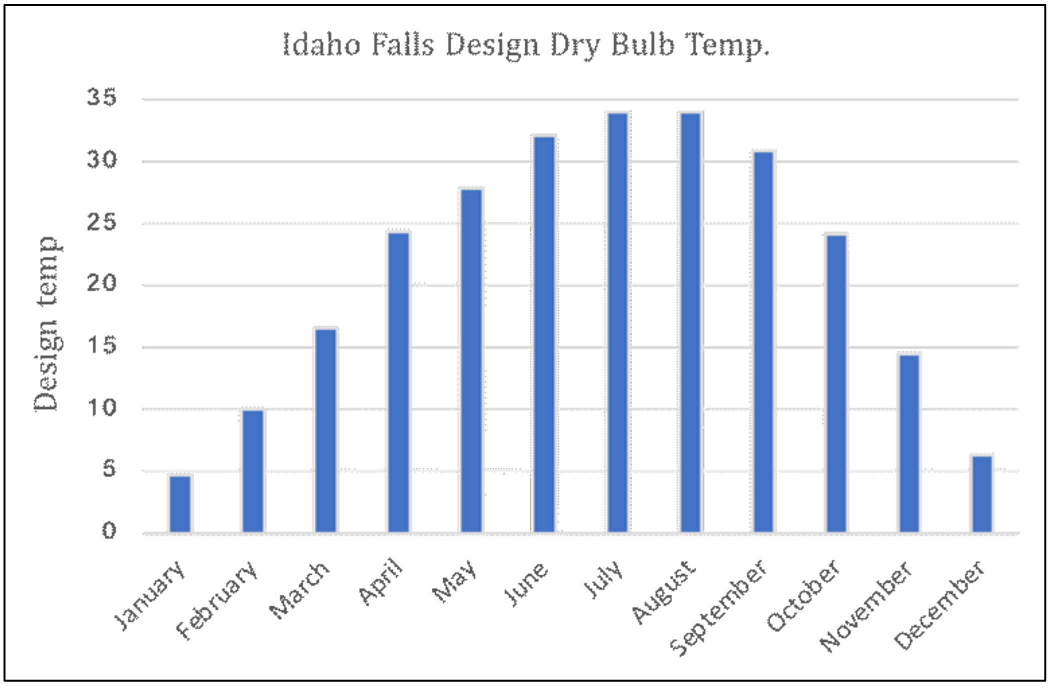

Figure 19. Average design dry bulb temperature around the Idaho Falls area (ASHRAE).

7.6 Hybrid Wet/Dry Cooling Systems

Hybrid wet/dry cooling systems can be used with the goal of reducing water consumption and having an overall cost-efficient system. As an example, dry cooling can be used during cooler temperature seasons while a wet cooling option is more relied upon during warmer seasons. Figure 20 shows an example distribution of thermal duty of wet and dry cooling options in a parallel hybrid system with seasonal dry bulb temperatures similar to the Idaho Falls area. The wet portion of the system starts to handle the thermal duty after 30°C and rejects up to 25% of it. As a result, water consumption can be decreased while the heat-rejection system is available throughout the year.

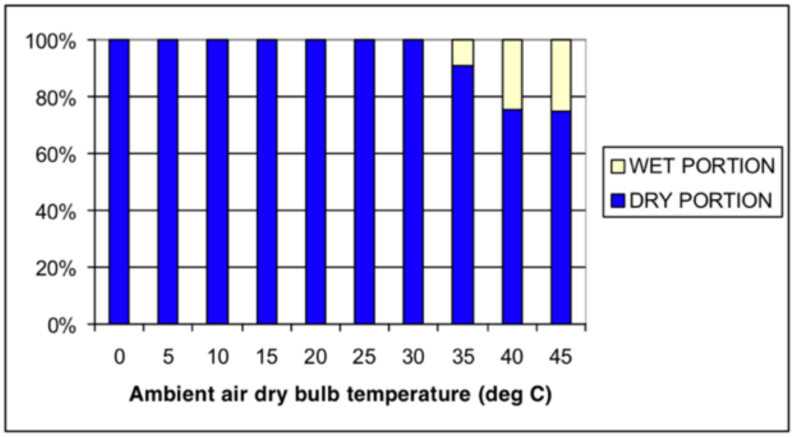

Figure 20. Wet and dry cooling options' thermal duty as a function of ambient dry bulb temperature (Backer and Wurtz, 2003).

8. COMPARISON OF HEAT-REJECTION OPTIONS

In addition to water use, cost stakeholder concerns may influence the selection of heat rejection methods. Depending on the location of the cooling systems, an air plume can be a concern as the viewshed from INL roads is a concern for some stakeholders. A plume may be prominent for the cooling pond and wet cooling towers, but not for other options.

Cost is also a major concern for ARDs. Without a detailed design, a detailed comparison of cost is not possible. However, Figure 21 shows capital cost comparison of different cooling options for a generic 1000-MW_e power plant. Although the reported values in Figure 21are based on several assumptions and can change for different plant variables, but the capital cost ratio between different options is assumed to remain the same for different plant conditions. The wet cooling option is considered as the base cost. The once-through using the aquifer option remains below the base cost, whereas other options are above the base cost. Sources for the operation and maintenance (O&M) costs are related to mechanical maintenance, such as pump and fan, and water pumping and discharging costs.

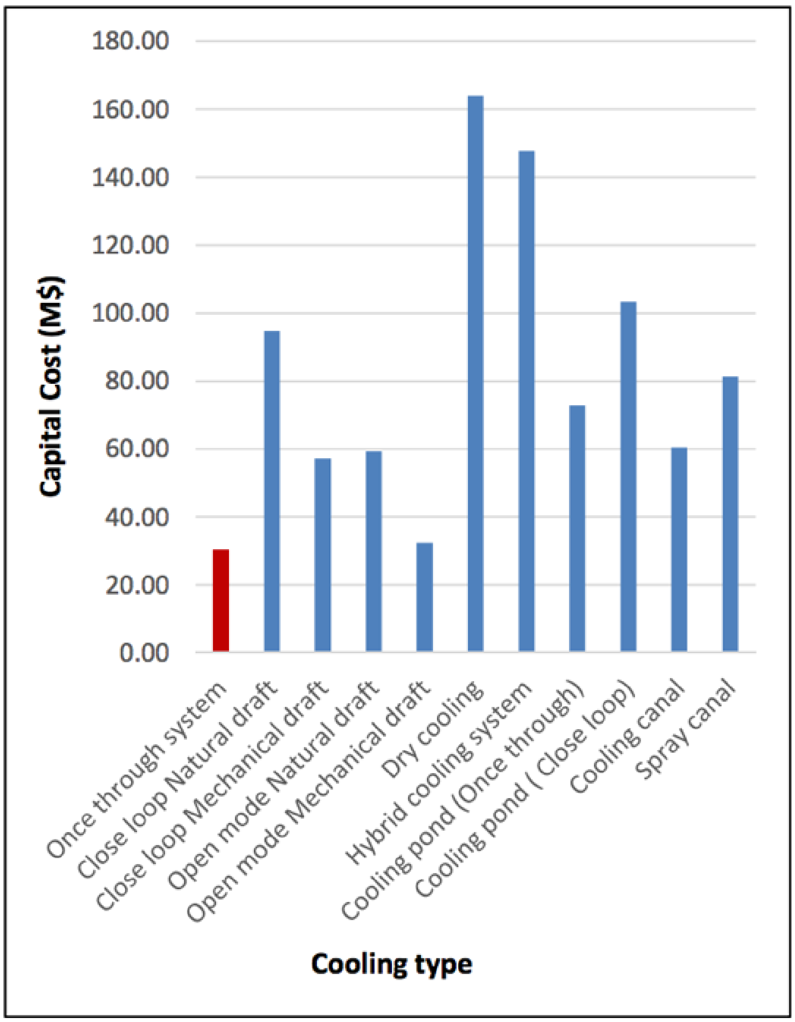

Figure 21. Capital cost comparison of different heat rejection systems (Shadid and Rashid, 2017).

Table 4 provides a comparison of different heat rejection methods based on water use, relative cost, and visibility of a steam plume (if it exists). In the table, water withdrawal is the normalized estimated value of water required with 10 °C increase through the condenser. For the once-through cooling system using the aquifer and cooling pond, the water withdrawal amounts are similar, but the withdrawn water is discharged back to the water source. Thus, it is not considered that the water is consumed during this process. The ground-coupled system is a closed system, where water withdrawal or consumption is negligible. Wet cooling tower options require water withdrawal to replace the water due to evaporation losses and blowdown. Only the losses due to evaporation are assumed to be consumed and the blowdown water is assumed to return to the aquifer through seepage.

Table 4. Comparison of different heat-rejection methods by their water use and baseline cost.

	Once-Through (Aquifer)	Cooling Pond	GHEX	Wet Cooling	Dry Cooling	Hybrid Wet/Dry	
						Plume Abatement	Water Conservation
Water Withdrawal	$\sim 800 \frac{m^3/min}{MWe}$	$\sim 800 \frac{m^3/min}{MWe}$	-	$\sim 0.055 \frac{m^3/min}{MWe}$	-	~equal to wet CT	can be reduced from wet CT
Water Consumption	Minor	Minor	Minor	$\sim 0.040 \frac{m^3/min}{MWe}$	-	~equal to wet CT	20-80% of wet CT depending on design
Discharge	$\sim 800 \frac{m^3/min}{MWe}$	$\sim 800 \frac{m^3/min}{MWe}$	-	$\sim 0.015 \frac{m^3/min}{MWe}$	-	$\sim 0.015 \frac{m^3/min}{MWe}$	variable, $<\sim 0.015 \frac{m^3/min}{MWe}$
Plume	-	Visible on cold and humid days	-	Visible on cold and humid days	-	-	-
Capital Cost	< base	> base	> base	base	2-3x base	1.1-1.5x base	~3x base
O&M Cost	Pump maintenance, condenser cleaning	Pump maintenance, condenser cleaning	Pump maintenance, condenser cleaning	Fan-pump, water treatment, tower fill, condenser cleaning	Surface cleaning, gearbox maintenance,	Fan-pump, water treatment, tower fill, condenser cleaning	Fan-pump, water treatment, tower fill, condenser cleaning

9. SUMMARY and CONCLUSIONS

One of the important considerations in the deployment of the demonstration plants at the INL site is water use. Heat rejection is often the largest water use in nuclear reactors. This paper provided information on the applicable INL conditions that affect heat rejection and water use in reactor demonstrations. Information on regulatory considerations and the INL site characteristics is provided including the wind speed, air temperature, surface and underground water conditions.

Five different heat rejection systems were investigated: 1) wet cooling tower, 2) air-cooled heat exchanger, 3) once-through systems using the SRB aquifer, 4) cooling pond, 5) ground-coupled heat exchanger. Additionally, a discussion of the relationship between ambient dry bulb temperature and thermal duty was provided for hybrid wet/dry cooling systems. The heat rejection methods' water use was estimated and discussed to have an initial understanding of their impact at the INL site.

Advanced reactor developers must consider the limitations of water consumption based on state and federal regulations, as well as stakeholder consultations Water consumption may complicate reactor capacities and affect their subsequent commercial deployment.

An additional consideration is the stakeholder acceptability for creating a visual plume. A visible steam plume may be at the site may be an issue with cooling pond and wet cooling tower options, depending on where they are located. Other observations from the analysis include the assessment that at current technical maturities, a ground-coupled heat exchanger is not an efficient approach; thus, it is not currently recommended. Finally, a hybrid design option can be considered for a scalable heat rejection system in case the demand increases with increased demonstration reactor outputs.

NRIC is aware of the importance of water resources in the high-altitude desert of southern Idaho and looks forward to engaging with local and regional stakeholders in order to explore these ideas further as the ARDs proceed towards demonstration.

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