WNA Position Statement

Is the Cooling of Power Plants a Constraint on the Future of Nuclear Power?

World Nuclear Association

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Summary

While cooling is clearly an essential factor in the siting of individual nuclear plants, this necessary function is a readily manageable aspect of nuclear power operations and constitutes no constraint on the future growth of nuclear power as a large-scale low-cost provider of clean energy with highly stable prices and strong security of supply.[1]

Steam-driven turbines generate most of the world's electricity. These "thermal" power plants produce the necessary heat using uranium fuel or a fossil fuel - coal, natural gas, or oil.[2] In the physics of the steam cycle - as water is vaporized and then cooled, condensed and recycled - the production of surplus heat is inherent.

To achieve the requisite heat discharge, power plants normally employ various techniques of "wet" cooling, which use water to transfer heat to the air through evaporation or to a nearby water body with adequate absorptive capacity.

Looking ahead, the question of wet cooling for 21st century power plants will focus mainly on those fuelled by uranium and coal. Oil-fuelled thermal plants are increasingly rare for reasons of cost, and traditional gas-fired plants are giving way to combined-cycle gas plants in which very high efficiency yields less surplus heat and a greatly reduced cooling requirement.

Cooling for coal-fired and nuclear plants is plainly not an issue where the availability of water is unlimited, as when the plant is sited by a large body of water. The wet cooling problem can arise for plants sited on rivers and other locations where water availability is limited in quantity or by regulations on the temperature of returned water.

[1] For a detailed discussion, see the WNA Information Paper entitled "Cooling Power Plants".

[2] Current global shares of electricity generation are approximately as follows: coal 40%, natural gas 20%, nuclear and hydro 16% each, oil 6% and others (including geothermal, solar and wind) 2%.

The amount of cooling required for a steam-cycle plant of any given size is determined by its thermal efficiency. By this measure, coal plants generally have a slight edge over nuclear plants and a correspondingly somewhat lesser need for cooling water.

This distinction does not, however, impede nuclear operations. Unlike coal-fired plants, nuclear plants - which use a fuel that delivers nearly 200,000 times more energy per kilogram - may be sited with no cost or constraint from fuel logistics. For nuclear energy planners, this characteristic offers wide flexibility in site selection as they seek to ensure the availability of reliable cooling while optimizing costs.

Key factors in this calculation are the comparative extra expense of longer electricity transmission and of alternative and supplemental cooling technologies. In those instances where cooling needs might require longer transmission distances or adaptive use of various cooling technologies, the cost increment will usually be relatively minor, particularly when averaged with the costs of a larger nuclear fleet.

The Role of Cooling in Fossil and Nuclear Power Plants

Generally, fossil and nuclear power plants use water for heat transfer in two ways:

- Internal Energy Transfer. To convey steam heat created by the energy source - either the coal furnace or the reactor core - to power an electricity-generating turbine; and
- Cooling and Surplus Heat Discharge. To cool and condense the after-turbine steam and then discharge surplus heat from the steam circuit to the environment.

In the internal energy-transfer function, water is circulated continuously in a closed-loop cycle. The primary heat source turns water to steam to drive the turbine, and the water is then condensed and returned to the heat source. In this internal circuit, hardly any water is lost, so only a very small amount of make-up water is required. This function is much the same whether the power plant is nuclear, coal-fired, oil-fired, or conventionally gas-fired. Today most of the world's non-hydro electricity is produced in this way.

Cooling is needed to condense the after-turbine steam in the internal circuit and recycle it. As the steam condenses back to water, the surplus heat must be discharged to the air or a body of water. Any steam-cycle system must discharge about two-thirds of the energy produced by the heat source due to the physics of turning heat into mechanical energy - in this case the turning of a turbine generator.

Just how much heat must be discharged for any given electricity output is determined by a plant's thermal efficiency, which is the proportion of internal heat that becomes electrical output. Higher thermal efficiency means not only a reduced cooling requirement but also more electricity from a given amount of fuel. Thermal efficiency depends on the temperature difference between the internal heat source and the external environment, and can be increased by expanding the temperature differential – at either end.

With a higher temperature heat source, a greater percentage of heat is converted to electricity, leaving less surplus heat to be discharged for a given electricity output. Similarly, a lower temperature of cooling water yields higher efficiency. For example, a UK plant sited on the North Sea is more efficient than an identical plant on that country's Gulf Stream-warmed southern coast; and a new Turkish plant would have higher efficiency if sited on the Black Sea rather than the warmer Mediterranean.

Looking ahead, the question of cooling for 21st century power plants will focus mainly on those fuelled by uranium and coal. Oil-fuelled plants are phasing down for reasons of cost, and traditional gas-fired plants are giving way to combined-cycle gas turbine (CCGT) plants in which very high efficiency yields less surplus heat and a greatly reduced cooling requirement.[3]

[3] In a CCGT plant, the burning of gas drives one turbine, and the exhaust heat produces steam to drive a second turbine, which commonly uses wet cooling. If water limitations arise, operation of the steam turbine can be suspended and the gas turbine's exhaust heat vented to the air.

Both nuclear and coal plants show a range of efficiencies. Nuclear plants currently being built have about 34-36% thermal efficiency, while one of the new reactor designs boasts 39%. In comparison, new coal-fired plants approach 40% and CCGT plants reach 60%.[4] In determining the cooling requirement, these distinctions are not insignificant. For example, a power plant running at 39% thermal efficiency will discharge about 24% less heat than one providing the same electrical output while running at 34%.

As these figures indicate, coal plants currently have slightly higher thermal efficiency and require somewhat less cooling than nuclear plants. A key source of this difference is the temperature limit imposed in nuclear plants by the need to ensure the physical integrity of nuclear fuel assemblies.[5] In future, as new supercritical coal plants are introduced and as nuclear plants move from Generation III and III+ to Generation IV, coal-fired generation may not continue to hold this edge. A notable advantage of the high-temperature gas-cooled reactor (HTGR) designs now in development is their projected thermal efficiency of 70%, which will greatly lessen cooling requirements.[6]

In both fossil and nuclear plants, a water circulation system is normally used to accomplish heat discharge through two types of wet cooling: "once-through" and "recirculating".

Wet Cooling: Once-Through

Where the power plant is next to a large water body, cooling is achieved simply by running a large amount of water through the condensers in a single pass and discharging it back a few degrees warmer in almost the same amount.[7] In this simple method, the water may be salt or fresh. There is hardly any on-site water use in the sense of depletion, though some extra evaporation will occur off site due to the water being slightly warmer.

Many nuclear power plants have once-through cooling, since their location is not influenced by the source of the fuel, and depends first on where power is needed and secondly on water availability for cooling. A number of countries are able to use once-through seawater cooling for all of their nuclear plants. Among these are the UK, Sweden, Finland, South Africa, Japan, Korea and China. Canada uses once-through cooling from the Great Lakes.

Any nuclear or coal-fired plant that is normally cooled by drawing water from a river or lake will have regulatory limits imposed either on the temperature of the returned water or on the temperature differential between inlet and discharge. In hot summer conditions, when even the inlet water from a river may approach the limit set for discharge, the plant will be unable to run at full power using one-through cooling only, as has happened in France. In these circumstances, recirculating wet cooling and various dry cooling technologies can be used to help.

[4] The CCGT process achieves this efficiency by combining the gas and the steam cycles. If the surplus heat is utilized for combined heat-and-power (CHP), efficiency can increase further to 85%. Because of its great efficiency CHP, also known as cogeneration, is also viewed favourably for use in future nuclear plants.

[5] The need for flue gas desulphurization in coal plants may negate this edge by adding to water consumption and reducing overall efficiency.

[6] High temperature will also support the thermo-chemical separation of hydrogen as a transportation fuel.

[7] The cooling function in a nuclear plant is performed in the turbine hall, so the cooling water carrying discharged heat is never in contact with the nuclear part of the plant.

Wet Cooling: Recirculating

Where the power plant does not have abundant water, power plants can discharge surplus heat to the air using recirculating water systems that capitalize on the physics of evaporation. Cooling towers with recirculating water are indeed a common visual feature of power plants, whether fossil or nuclear. Tall towers, usually hyperboloid in shape, employ a natural draft "chimney effect". Shorter towers use a forced draft created by large fans. Recirculating cooling systems reduce the overall efficiency of a power plant by 3-5% compared with the once-through use of water from a sea, lake or major river.

In recirculating systems, water passes through the condenser and is pumped to the top of the tower. From there it sprays downward to a collection basin while being cooled by an updraught that carries heat away, mainly by evaporation and with some direct heat transfer to the air.[8] In temperate climates, an on-site pond can also be used to accomplish the same cooling function.

As the cooled water is returned to the condenser, 4-5% of the flow is lost to evaporation and must be continuously replaced. The water loss commonly equates to some 1.75-2.5 litres per kilowatt-hour. Moreover, because evaporation concentrates impurities in the water, some bleed of water (called "blow-down") is required, raising the need for replacement water by another 50%.

Typical water consumption for a 1000 MWe plant - providing electricity to perhaps 1 million people in an industrial country - might be 75 megalitres per day, or the equivalent of 25 Olympic-sized swimming pools. This equates to about 0.05% of the average flow rate of the Rhine, Rhone and Danube Rivers.

In the USA, where inland siting causes more than half of coal and nuclear plants to use wet cooling towers, electric power generation reportedly accounts for 3% of all freshwater consumption. A similar distribution between recirculating and once-through systems is found in other countries. A significant example is France, where 58 nuclear reactors produce most of the nation's electricity. There 32 reactors use cooling towers, drawing replacement water from rivers and lakes, while 26 reactors use once-through cooling from seawater and major rivers.

Dry Cooling

Some power plants use "dry" cooling - i.e., cooling through heat transfer to the air without the physics of evaporation. This works like an automobile radiator, with a high-flow forced draft past a system of finned pipes through which the steam passes. Alternatively, there may still be a condenser cooling circuit with the enclosed water cooled by a flow of air.

Dry cooling involves much greater cost for the cooling set-up and is less efficient than wet cooling towers that use the physics of evaporation. Large fans consume much power, and cooling solely by heat transfer is relatively inefficient.[9]

[8] Although commonly perceived as a source of pollution, the plumes over cooling towers consist of water vapour.
[9] With high thermal efficiency and low cooling needs, CCGT plants can sometimes use dry cooling technologies.

Cooling Requirements and the Future of Nuclear Power

For any power plant, once-through cooling systems using fresh water and seawater are less costly to build and more energy-efficient than systems using wet recirculation through cooling towers or ponds. Thus, the sitting of coal and nuclear power plants on coastlines is usually preferable where other considerations allow.[10]

For both coal and nuclear plants, this siting preference - yielding simple and inexpensive cooling - must be balanced against the cost benefit of proximity to electricity load centres. In many instances, this balance is easily struck in favour of coastlines. In the UK, for example, all nuclear plants are on the coast and total electricity transmission losses in the system are only 1.5%.

For many coal plants, the transport of fuel can be a significant cost factor, as each 1000 MWe coal plant consumes over three million tonnes of coal annually.[11] Another constraint can arise from aesthetic considerations associated with transporting and storing this huge fuel supply.

For nuclear plants, these fuel-related siting considerations simply do not exist. Uranium fuel holds energy in a concentration nearly 200,000 times greater than coal and is correspondingly smaller in volume. Nuclear fuel is delivered infrequently, in small volume, and economically by lorry rather than constantly, in large volume, and expensively by train or ship.

For nuclear energy planners, the flexibility to site reactors without consideration of proximity to fuel supply offers a wide range of options as they optimize costs while meeting the essential requirement of reliable, affordable generation.

Key factors in this cost-optimization are the cost of longer-distance electricity transmission and the availability of a variety of cooling technologies, usable in back-up mode, that are relatively unaffected by water availability and regulations governing heat discharge into water bodies. Where the cooling of nuclear power plants might require longer transmission distances or alternative cooling technologies, the cost increment will usually be comparatively minor, particularly when averaged over the costs of a larger nuclear fleet.

Thus, the cooling requirement, while essential to nuclear plant operations, is not a constraint on the future worldwide growth of nuclear power as a large-scale low-cost provider of clean energy with highly stable prices and strong security of supply.

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[10] Generally, freshwater systems are less expensive than seawater systems, which must be designed to resist corrosion from brine. On the other hand, freshwater systems often face regulatory constraints on the temperature of returned water and may therefore need back-up systems using recirculation and dry cooling technologies.

[11] This cost factor does not always inhibit lengthy coal transport. For example, U.S. plants use low-sulphur coal trained from far away in order to meet pollution limits, and the UK imports coal from Russia, Australia, Colombia, South Africa and Indonesia.

The World Nuclear Association is the international private-sector organization **supporting the people, technology, and enterprises** that comprise the global nuclear energy industry.

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