IAEA Nuclear Energy Series

No. NP-T-2.6

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# Efficient Water Management in Water Cooled Reactors

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EFFICIENT WATER MANAGEMENT
IN WATER COOLED REACTORS

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IAEA NUCLEAR ENERGY SERIES No. NP-T-2.6

EFFICIENT WATER MANAGEMENT IN WATER COOLED REACTORS

INTERNATIONAL ATOMIC ENERGY AGENCY
VIENNA, 2012

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FOREWORD

One of the IAEA's statutory objectives is to "seek to accelerate and enlarge the contribution of atomic energy to peace, health and prosperity throughout the world". One way this objective is achieved is through the publication of a range of technical series. Two of these are the IAEA Nuclear Energy Series and the IAEA Safety Standards Series.

According to Article III.A.6 of the IAEA Statute, the safety standards establish "standards of safety for protection of health and minimization of danger to life and property." The safety standards include the Safety Fundamentals, Safety Requirements and Safety Guides. These standards are written primarily in a regulatory style, and are binding on the IAEA for its own programmes. The principal users are the regulatory bodies in Member States and other national authorities.

The IAEA Nuclear Energy Series comprises reports designed to encourage and assist R&D on, and application of, nuclear energy for peaceful uses. This includes practical examples to be used by owners and operators of utilities in Member States, implementing organizations, academia, and government officials, among others. This information is presented in guides, reports on technology status and advances, and best practices for peaceful uses of nuclear energy based on inputs from international experts. The IAEA Nuclear Energy Series complements the IAEA Safety Standards Series.

Water scarcity is becoming one of the most pressing crises affecting the planet. A reliable supply of water and energy is an important prerequisite for sustainable development. A large number of nuclear power reactors are being planned in many developing countries to address these countries' increasing energy demands and their limited fossil resources. New construction is expected in the USA, Europe and Asia, as well.

Reducing water use and consumption by nuclear power plants is likely to help developing countries in introducing nuclear power into their energy supply mix. A large number of the countries that have recently begun to consider the introduction of nuclear power are in water scarce regions, which would certainly limit the possibility for deployment of nuclear power plants, in turn hindering these countries' development and energy security. Thus, there is a large incentive to enhance efforts to introduce innovative water use, water management practices and related technologies.

Water management for nuclear power plants is gaining interest in IAEA Member States as an issue of vital importance for the deployment of nuclear power. Recent experience has shown that some nuclear power plants are susceptible to prolonged drought conditions, forcing reactors to be shut down or power to be reduced to a minimal level. In some cases, environmental issues have resulted in regulations that limit the possibility for water withdrawal as well as water discharge. Regarding the most common design for cooling nuclear power plants, this has led to a complicated siting procedure for new plants and expensive retrofits for existing ones.

The IAEA has already provided its Member States with reports and documents that address the issue. At the height of nuclear power expansion in the 1970s, the need for guidance in the area resulted in publications such as Thermal Discharges at Nuclear Power Stations — Their Management and Environmental Impact (Technical Reports Series No. 155) and Environmental Effects of Cooling Systems (Technical Reports Series No. 202). Today, amid the so-called nuclear renaissance, it is of vital importance to offer guidance to the Member States on the issues and possibilities that nuclear power water management brings.

Management of water at nuclear power plants is an important subject during all phases of the construction, operation and maintenance of any nuclear power plant. Water management addresses the issue of securing water for condenser cooling during operation, for construction (during the flushing phase), and for inventory control, including make-up to the primary coolant system and discharge from the radioactive liquid waste treatment system. Providing an overview of and guidance on the available options will be particularly helpful to newcomer countries considering embarking on nuclear power in their decision making with respect to a water management strategy.

In order to assist Member States in resolving water management issues for nuclear power, the IAEA has compiled this report based on experience, best practices and expectations for the foreseeable future of nuclear power technology. The information presented here is intended to clarify the technical issues, available solutions and economic implications for nuclear power.

CONTENTS

1. INTRODUCTION

1.1. BACKGROUND

Water withdrawal today presents a vital issue for the countries planning to build nuclear power plants (NPPs) while having a deficit in their water resources. It is also an issue that creates conflict among the socio-economic activities that require and depend on water. With the expansion of nuclear power and the relatively large need it has for cooling and service water, a situation is looming in which deployment of new reactors may become restricted. Economic development is no longer a process that is necessarily at the expense of the environment.

Recently nuclear power has come back into focus during debates on energy generation, often in relation to wider issues such as global warming and climate change. Accordingly, estimates consider that a capacity of between 447 GW and 691 GW of electricity may be installed by nuclear power by 2030 [1]. Reasons for the expected growth include the technological advances of modern reactors. Yet whether this growth will materialize also depends on social, economic and environmental factors. Water, needed for various purposes in a nuclear power plant, can be placed in every one of those categories.

In this report the concept of water use will be discussed. Water use involves two processes that can occur separately or simultaneously: water consumption and water withdrawal. Water consumption occurs when water either ceases to exist as a liquid, through evaporation (direct evaporation in a cooling tower or increased surface evaporation from the source due to the elevated temperature) or when water is degraded through contamination so that it is not fit to be returned directly to its original source. Water withdrawal occurs when water is removed from a source. It may subsequently be consumed and not returned to its original source, or it may be returned to the original source in practically the same condition as when it was withdrawn, that is, discharged in compliance with applicable environmental law.

The distinction between water consumption and water withdrawal is crucial to any discussion about water use. For instance, open loop cooling systems may withdraw substantially more water than recirculating cooling towers, but consume substantially less. Other systems may withdraw no water at all, but still consume water, as in reservoir evaporation at a hydroelectric power plant. However, when making such comparisons, differences in cooling water temperature as well as power plant thermal efficiency must be kept in mind.

Water requirements for nuclear power plants vary, depending on the cooling system they involve, the thermal efficiency of the nuclear power plant, the need for service water, safety and non-safety system designs, as well as the waste disposal techniques. It is also crucial to select a site where suitable cooling water, and/or atmospheric conditions are available, all allowing higher plant efficiencies at lower water withdrawal rates.

As the main water use and consumption occurs in the cooling system of the nuclear power plant, it is of high importance to carefully choose and design these systems. There is a variety of cooling technologies that can reduce the water use and consumption drastically. Their implementation though, comes at a cost which is a matter of tradeoff when making a choice for nuclear power implementation and benefit analysis.

Cooling water requirements of current nuclear power plants exceed those of fossil fuel power stations by 20–25 percent on average (Table 1). This is due to the lower thermal efficiency in most of the existing NPPs, as they operate with lower steam pressures and temperatures. These parameters can be increased, but only to a limited extent, because of the limits imposed by the common use of zircaloy as a material for fuel cladding, and coupled neutronic and thermal hydraulic considerations in conventional light water reactors (LWRs). Another limiting condition is the manufacturing capabilities of the main reactor heavy components.

TABLE 1. WATER USE FOR DIFFERENT COOLING SYSTEMS (M^3/MW·h) [2]

	Once-through (withdrawal)	Cooling pond (consumption)	Cooling towers (consumption)
Nuclear	95–230	2–4	3–4
Fossil-fuelled	76–190	1–2	2
Natural gas/oil cc	29–76	—	1

For standard 1000 MW(e) power output units with once-through cooling, a nuclear plant would require 26–64 m^3/s, a fossil-fuelled plant 21–53 m^3/s and a natural gas combined cycle plant 8–21 m^3/s. These numbers depend on the temperature of the cooling water and the temperature difference with the steam in the condenser, as well as the condenser efficiency. Still, the largest potential for reducing water consumption in power generation lies in an improved thermal efficiency for the process. A 1000 MW(e) plant with 33% efficiency will have a 14% higher thermal load than one with an equal power generation capacity and 36% efficiency. Under equal conditions with regard to cooling water temperatures and condenser technologies this would also represent a 14% higher cooling water demand.

Water, once considered a nearly inexhaustible resource, is increasingly limited, and water requirements for electricity production must compete with other demands, such as agriculture and sanitation. Additionally, the simplest and most economical condenser cooling systems, which represent the largest heat rejection system in an NPP, are the once-through systems which have the highest cooling water withdrawal per MW·h. As environmental and technical issues arise, the nuclear community should find new solutions for water use in NPPs. These should allow NPPs to operate according to stringent environmental regulations protecting aquatic ecosystems, as well as to reduce the importance of water availability for the deployment of NPPs.

Options for avoiding the conflict over the issue of fresh water use and consumption also involve a variety of options. Technologies for water treatment, physical as well as chemical, have been developed, allowing for a broader choice of water sources. These sources also include gray or physically and chemically impaired waters. Sewage, mine and groundwater, seawater, internally generated wastewater and system blow-down, can all be treated to a level that will satisfy the requirements of cooling towers or primary and secondary circuits.

Additionally, innovation led to new strategies for the reduction of water use and consumption in nuclear power plants. From variable speed cooling pumps, drift eliminators and higher cycles of concentration for cooling towers, to the use of the waste heat for industrial, agricultural and residential purposes, the possibilities to reduce the water requirements of a nuclear power plant are numerous.

Three examples can be presented to demonstrate the importance of water availability. The first one took place in the summer of 2003, in France, where a problem was experienced with 17 reactors out of a total of 58 working with reduced capacity or shutdown due to drought conditions and a lack of water [3]. The second was the 2007 drought in southeastern USA, when several nuclear power plants in the region had to reduce their output by up to 50% due to low river water levels. Most of these plants use the once-through cooling system which, at the time of their construction, was a technically simple and economical solution. The last example took place in 2008, concerns about potential impacts to an aquifer used for water supply to local population resulted in a search for a new site for a 4000 MW(e) nuclear power plant project on the Peace River, Canada [4]. These examples show how water users nowadays have to compete for this resource and it is often a central point in planning and development activities.

In the USA, migration to the Sun Belt has increased water use in the nation's most arid and drought prone regions. Severe water shortages are becoming more common, threatening the availability of NPPs. Reduced tolerance for environmental impacts is challenging the once-through mode of operation even in areas of the USA with plentiful water supplies. Water supply and electric power generation are inter-related. Approximately 38% of all water withdrawals in the USA are attributed to thermal power plants. The Electric Power Research Institute (EPRI) reports that 4% of the USA's power generation is consumed by water supply infrastructure. In California the figure is 20%.

In the future, it is expected that there will be some significant developments affecting nuclear power water use. To begin with, the very efficiency of the nuclear reactors is expected to rise, prompting lower water requirements for cooling. Further on, new materials such as superconductive foams hold the potential to replace water in certain parts of the system inventory of a nuclear plant. Another essential development would be the use of tertiary coolants that will allow for the implementation of dry-cooling systems, with expected drastic reductions in water requirements for nuclear power plants. Spent fuel management and waste treatment are also developing in the direction of reduced water requirements.

This report concludes that today, nuclear power is capable of state of the art engineering solutions around the limitations of water availability. Case examples of nuclear and comparable fossil fuel power plants have been presented to support the conclusions made.
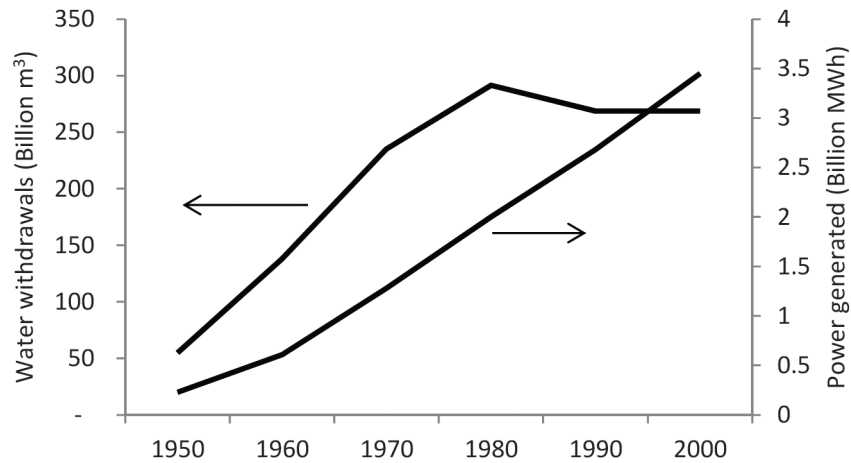
FIG. 1. Water withdrawal, power generated, and improvement in water withdrawal efficiency 1950–2000.

1.1.1. Development trends

Alternative cooling technologies must reduce the water use at power plants, improve its efficiency, broaden its applicability, and provide savings for the power industry. Despite the fact that power generated each year is steadily raising the water withdrawals of the thermal power stations has stayed steady since 1980. That means that efficiency on water use for power generation has increased (Fig. 1). In 1950, it took 240 m^3 meters of water to produce 1 MW·h(e) and in 2000 only 80 m^3 were needed to produce 1 MW·h(e) [5]. The efficient use of water is becoming a very important consideration as projections of future power needs are determined and different cooling technologies are being developed.

Applying new solutions to address water use in NPPs is crucial for their increased deployment. Lower water use and consumption have been given attention through different programmes considering:

— Higher plant efficiences to reduce heat rejection in nuclear power plants. Modern reactors have moved from the 33% to 36–39% efficiency, with new designs aiming at even higher efficiencies;
— Alternative cooling systems (air-cooling, hybrid cooling and closed loop water cooling). Alternatives to the traditional once-through cooling design are being implemented in conventional and nuclear power stations throughout the world;
— Alternative water sources (desalination and water reclamation). Desalination is already being used in several NPPs, while Palo Verde NPP is the only plant situated in a desert, using municipal wastewater as a source of cooling water;
— Alternative technologies that would replace water in some areas. For example: high thermal conductivity foams already in development for use in air-cooled condenser types. The foam could significantly decrease energy consumption while enhancing water conservation within the power industry;
— Cogeneration is one of the simplest ways to increase the efficiency and thus reduce cooling needs. Using the heat, rather than rejecting it in the environment, for thermal applications such as desalination or district heating, has so far not been widespread, but have a significant potential for future deployment.

Technological advances like these can have a positive impact on the attractiveness of nuclear power and its benefits. This is not just for developed countries that are already users of nuclear power, but also for developing countries.

1.1.2. Perspectives of countries with limited amounts water intending to build new or more NPPs

In the developing world, high rates of economic growth require the rapid expansion of electrical generating capacity and thus the rapid development of water resources. Nuclear power plants have environmental advantages
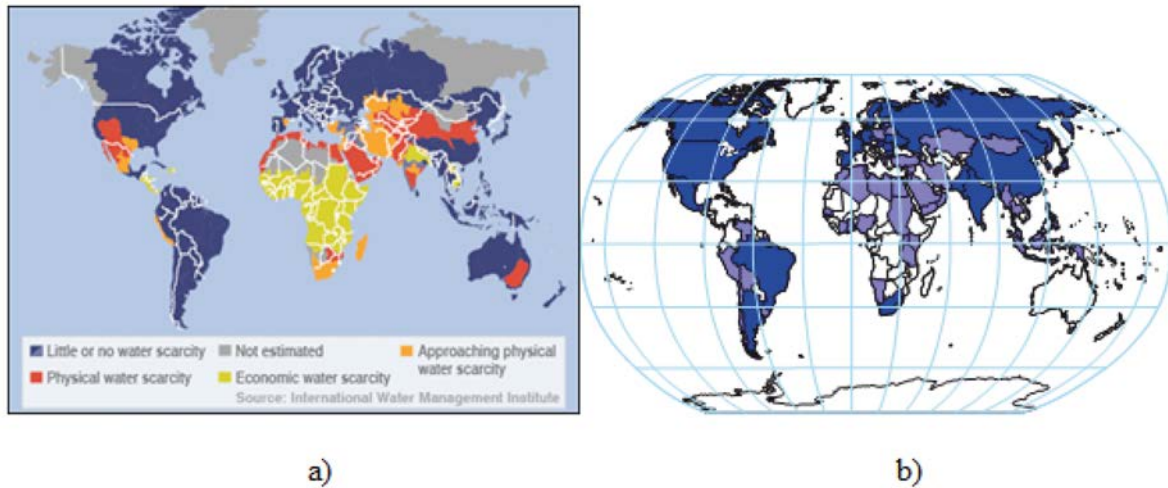
FIG. 2. (a) Growing water scarcity (b) countries considering the introduction/expansion of nuclear energy.

since they have practically zero CO_2 emissions. However, due to the lower efficiency, nuclear power plants require greater water withdrawal than other types of thermal power stations and therefore are considered a less attractive option for the major additions to capacity these nations require.

Yet there are several main perspectives on nuclear power in the developing countries. First of all, although economic development was historically achieved at the expense of the environment, this is no longer conceived as an acceptable practice. New global mechanisms, such as the Kyoto Protocol, have imposed a very different set of conditions for further development. Further on, the issue of energy independence and security for developing countries is of high importance, just as it is for the developed countries. Finally, developing countries with their growing populations show a sharp growth in energy demand. For these reasons, nuclear power seems a viable option for developing countries.

Additionally, economic growth also involves development of other industries, including agriculture, which may be very water intensive. Thus water resources can become economically scarce and affect development. Reducing water use for nuclear power is likely to help developing countries in introducing nuclear power in their energy supply mix.

As seen in Fig. 2, many countries considering the introduction of nuclear power, or increasing its share in the energy mix, are in regions with water shortage. At the moment it certainly limits the possibility for deployment of nuclear power plants, hindering development and energy security in those countries. That is a huge incentive to enhance the efforts for introducing innovative water use, management practices and technologies.

But as indicated earlier, developing and newcomer countries are not the only ones with water issues that affect the deployment of nuclear power. Countries already using nuclear power face a number of those problems as growth in water users and diminishing water resources.

As an example of a future water-related impact on the industry that may come in the form of regulation, the case of the US Environmental Protection Agency (EPA) is presented, even though it is not actually connected to the unavailability of water. The US EPA is developing regulations under §316(b) of the clean water act that will require that the location, design, construction and capacity of cooling water intake structures reflect the best technology available for minimizing adverse environmental impact, namely entrainment and impingement, and thermal discharge impacts. As these impacts are proportional to the water withdrawal rate, the EPA regulations have pressed nearly all new thermal power plants in the USA into building closed loop cooling systems as wet cooling towers and cooling ponds [6, 7].

Cumulative impacts have a large role in the development of nuclear power. The development of the NPP project in Tricastin for instance, where Suez is considering building an EPR™ reactor, was based on advanced cooling methods from the beginning. Though located on the powerful river Rhône, it will have cooling towers because there are already the following units upstream:

4

— 4 Bugey units 4·900 MW(e);
— 2 Saint Alban units 2·1300 MW(e);
— 4 Tricastin units for Eurodif gaseous diffusion enrichment plant 4·900 MW(e).

1.2. OBJECTIVES AND SCOPE

So far there have not been any comprehensive reports that discuss water management in nuclear power plants. In an effort to illustrate the sustainability of nuclear power, the main objective of this report is to present current water requirements in NPPs, the technologies employed, best practices and strategies for lower water withdrawal rates, as well as the trends that are likely to be of interest in the future. The report aims at enhancing the understanding of the issues and possibilities regarding nuclear power and water availability. The objectives of this publication are to disseminate information, share experiences through lessons learned from practical examples, and set guidance that will help countries planning to construct nuclear power plants, but which have worries about water availability to support such plants to:

— Identify key issues of current technologies of water use in NPPs including technology of turbine island and cooling systems (once-through, closed loop: wet, dry, and hybrid);
— Evaluate water requirements for the construction, operation, and commissioning of new nuclear power plants that affect decisions on the suitability of water resources with design of NPPs;
— Assess promising technologies to optimize water use in the design of new NPPs, and innovative approaches for more efficient water resources to support NPPs.

As water and power are inseparably related, it becomes clear that the availability of one will affect the availability of the other. The optimal choice will require knowledge of the available options. Therefore, this report is intended primarily for decision makers, project managers or coordinators, energy and/or water planners, and environmental experts.

The scope of the report will encompass, wherever possible through a generic case, the water requirements throughout the lifetime of a nuclear power plant, including construction, operation, decommissioning and spent fuel storage.

1.3. STRUCTURE

Section 2 of this report lays out the current practices on water usage, and typical water quantities needed throughout the life cycle of a nuclear power plant.

Section 3 describes the current technologies applicable for cooling in nuclear power plants, along with their advantages and disadvantages.

Section 4 provides an overview of the technologies for the production or reclamation of water for industrial and potable water, depending on the water source available. It will also present the rationale and economics that affect the technological choice.

Section 5 present the various strategies in nuclear power plants for reducing water use and consumption that are currently available or feasible, the efficiency-related improvements and their associated effect on the specific cooling water demand.

Section 6 reflects the new designs, processes and materials that may be implemented in the future, making the technology less water intensive.

Section 7 summarizes the report and lists some of the recommendations that are likely to achieve a significant decrease in water use and consumption by nuclear power plants.

2. CURRENT PRACTICES OF WATER USE AND CONSUMPTION IN MAJOR PHASES OF A NUCLEAR POWER PLANT

Water cooled reactors, depending on their size, capacity and type, require different quantities of water during the various phases of construction and operation. However, the use and consumption of water in a nuclear power plant can be categorized into two main areas.

— Water used in cooling systems for the dissipation of heat generated: represents the majority of water use and consumption in the nuclear power plant lifetime.
— Use of industrial and potable water for plant service and operation: as for production of demineralized water for circuit make-up, sanitary water, fire fighting, irrigation, etc.

The concepts of water withdrawal and water consumption are shown in Figs 3 and 4. Open loop cooling systems (once-through) withdraw water from the sea, rivers or lakes to remove heat from the power plant. Once the cooling water is heated up, it is returned to its natural source. In comparison, closed loop cooling systems as wet cooling towers recirculate the cooling water, but evaporation and other losses need to be supplemented by make-up which leads to water consumption from its natural source.

This section discusses current practices for water management in nuclear power plants, including water withdrawal and consumption during the major phases in the plant's lifetime (construction, commissioning, operation and decommissioning). Reasoning for the use of water will be given and typical quantitative values on specific water requirements will be provided.

2.1. WATER USE AND CONSUMPTION DURING CONSTRUCTION

In general, water needs during the construction phase of a NPP are mostly satisfied by drinking water. Water is needed for concrete mixing, backfill moisture adjustment, dust control, potable water for construction personnel, initial fill of circulating water reservoirs, and pre-operational flushing and testing. Typical values of water consumption during construction (approximately 4–5 years) in total are:
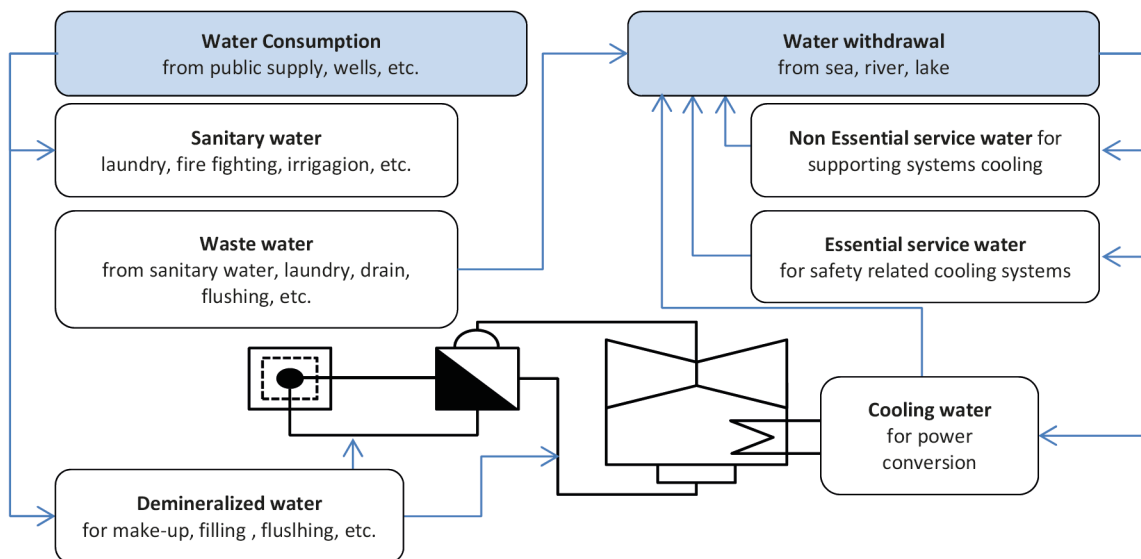
FIG. 3. Water streams in an NPP regarding consumption and withdrawal for open loop cooling systems.
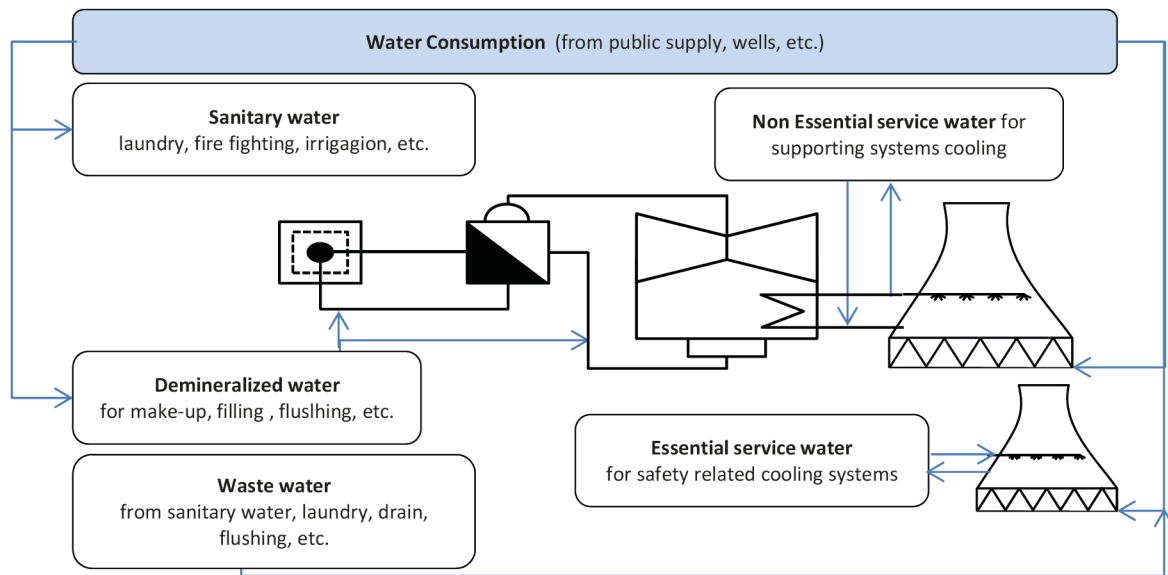
FIG. 4. Water streams in an NPP regarding consumption and withdrawal for closed loop cooling systems.

— 10 000 to 40 000 m^3 during excavation depending on site characteristics;
— 70 000 to 120 000 m^3 for concrete mixing;
— 300 000 to 600 000 m^3 supply for the construction staff depending on the site.

One study for the phased construction of two 1520 MW(e) economic simplified boiling water reactors (ESBWR) in the southwestern USA concluded that water use during construction would be 2700 m^3/h (6500 m^3/d) peak value, excluding initial reservoir fill.

2.2. WATER USE AND CONSUMPTION DURING COMMISSIONING

Starting with commissioning and pre-operational tests, water consumption is mainly determined by cleaning, flushing and initial filling of the plant's operating circuits.

The cooling water circuits will be cleaned, flushed and filled with sea or river water from the same source that is planned to be used during plant operation. This can be considered as water withdrawal without significant heat introduction. The values to be considered are determined by the related pump capacities and are the same as for normal operation as these systems typically run at full flow. So one day of operation during commissioning exceeds the needs for filling and flushing.

Closed loop systems on the primary and secondary sides as the primary circuit, water/steam cycle in the turbine island, component cooling water, etc. require demineralized water, produced generally from drinking water, for cleaning, flushing and filling. The common practice in today's plants is to discharge the cleaning and flushing waters, as they contain impurities. The consumption of demineralized water (produced with drinking water) during commissioning can be estimated in a range of 20 000 to 30 000 m^3. In addition drinking and potable water is needed for the plant staff use. The consumption will be similar to that during the plant outage period, as the number of workers is similar. Typical values would be approximately 200 to 400 m^3/d.

Cooling water consumption starts as soon as hot functional tests are performed until the provisional takeover of the plant by the client.

2.3. WATER USE AND CONSUMPTION DURING OPERATION

With the start of the power operation, cooling needs of the plant arise from the required heat dissipation due to the power conversion process: turbine condenser cooling and plant supporting systems cooling (Table 2).

Cooling requirements related to decay heat removal from fuel elements (spent fuel pool, reactor cooling, etc.) which exist continuously as long as fuel elements are present on the NPP site and require safety design features will be treated in Sub-section 2.4. Industrial water and potable water consumption, described in Sub-section 2.3.3, is reduced to plant service and operation needs.

2.3.1. Water use for cooling power conversion system

The predominant water use at a nuclear power plant is in the cooling system required to remove the heat rejected in the condenser after the power conversion process (Fig. 5). The quantity of water used for condenser cooling is a function of several factors, including the capacity rating of the plant and the increase in cooling water temperature from the intake to the discharge [8]. Additionally, the necessity to clean the cooling water before being used in the plant increases the total water use, as a portion of it is used for discharging the debris and cannot be used for cooling.

The larger the plant, the greater the quantity of waste heat to be dissipated, and the greater the quantity of cooling water required. A power plant with a 33% thermal efficiency will need to reject about 14% more heat than one of the same capacity with 36% efficiency. Nuclear power plants currently being built have about 34–36% thermal efficiency, depending on site (especially water temperature) [9]. One of the new nuclear reactors claims an

TABLE 2. TYPICAL VALUES FOR TURBINE CONDENSER COOLING AND SERVICE COOLING WATER FLOW RATES USING IN CLOSED LOOP FOR A 1000 MW(e) NPP

	Turbine condenser cooling (m^3/s)	Supporting systems cooling (m^3/s)
Recirculating cooling water[1]	46	1.2
Evaporation losses[2]	0.63	0.016
Blow-down losses[3]	0.4	0.011
Make-up water to compensate losses	1.03	0.027

[1] For a cooling water temperature increase of 10°C.
[2] At 20°C dry air and 60% rel. humidity. The evaporation losses depend on the ambient conditions.
[3] Blow-down depends on the water quality and the cycles of concentration.
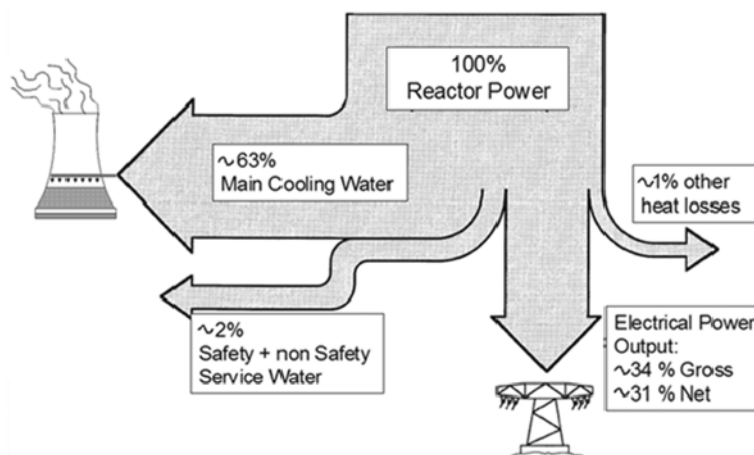
FIG. 5. Energy conversion and heat dissipation during operation at full load.

efficiency of 39% [10]. Older ones are often only 32–33% efficient (Table 3). Lower thermal efficiency of nuclear power plants when compared to fossil fueled plants is translated to higher specific steam flows (kg/kW·h(e)) through the secondary cycle and therefore higher cooling requirements. A typical PWR power plant has a specific steam flow of 5.5 kg/kW·h(e) while a conventional coal power plant uses only 3 kg/kW·h(e).

The water needs for cooling the turbine condenser depend strongly on the site conditions and location of the plant. To achieve a high performance, the site selection considers cooling water sources with the lowest possible water temperatures, which also might allow a higher heat up range (respecting local aquatic life). The more heating up of the cooling water is allowed, the less cooling water flow is required. Further reduction of water withdrawal from the river/lake is possible, if hybrid cooling systems are used. Specific water consumption and withdrawal depend on the cooling system design which is subject to water availability, technoeconomical factors and applicable regulations. The different cooling options and the selection considerations are described in Section 3.

2.3.2.   Water use for cooling non-safety supporting systems

The non-safety grade component cooling water systems supply all systems in the turbine island which require cooling during normal plant operation. The water source can be shared with the main cooling water for the turbine condenser cooling as the same operational aspects apply. Main sources for heat dissipation during normal plant operation are:

— Spent fuel pool: the heat dissipated from the spent fuel elements is highest after beginning a new cycle and decreases overtime. It is independent from the daily load operation of the plant;
— Cooling of components: the heat dissipated from the components depends on the plant operating status (e.g. number of pumps in operation) and reaches a maximum at full load operation;
— Coolant treatment: the heat dissipated during coolant treatment depends on the frequency of load follow operations of the plant. A minimum is reached at base load operation;
— Chillers and ventilation: the heat dissipated from chillers and ventilation depends on the plant operating status (when a maximum number of components are in operation) and on the ambient temperature (summer period).

The volume of water required for these systems is usually less than 10 percent of the volume required for condenser cooling. Some of these systems are augmented with auxiliary cooling towers to reduce the temperature of the effluent released to the adjacent body of water [8].

During plant operation, the heat to be transported varies but the water withdrawal remains constant as service water pumps are usually operated at constant flow rates. Specific influence on the design comes from safety considerations which lead to functional separation between safety and non-safety component cooling water systems (see Sub-section 2.4.1.) but the water withdrawal remains unaffected, as this is determined by the dissipated heat.

Typical water needs values for service water systems related to a 1000 MW(e) plant are given in Table 2. These values vary according to the concept of consumer distribution in the different plants. For more details on existing plants please refer to Annex I. Depending on the site conditions service water systems can be designed as open loop or closed loop following similar criteria as for turbine condenser cooling.

TABLE 3. COMPARISON OF HEAT DISSIPATION FOR DIFFERENT EFFICIENCIES FOR A TYPICAL 1000 MW(e) POWER PLANT

	Plant 1	Plant 2	Plant 3
Electrical output (MW(e))	1000	1000	1000
Thermal power (MW(th))	3030	2778	2564
Efficiency (%)	33%	36%	39%
Dissipated heat via turbine condenser (MW(th))	2030	1778	1564

If wet cooling towers are used, make-up water is required to be provided to replace the water loss through evaporation. Evaporation losses depend on the local daily ambient conditions, determined by the relative air humidity and the saturated air state (see Sub-section 3.2.1.2). Dry cooling towers have not yet been used for service water for technical reasons such as the higher cooling water temperature during peak summer months.

2.3.2.1. Spent fuel cooling

Spent fuel management has always been one of the most important stages in the nuclear fuel cycle. It is still a vital question to all countries with electricity producing reactors and an important issue to be resolved for the sustainable utilization of nuclear power. Spent fuel management begins with the discharge of spent fuel from the reactor and ends with the final disposal of the spent fuel or the residues from reprocessing.

In the last few decades, spent fuel management policies have shown diverging tendencies among the nuclear power production countries. Two main options for closing the fuel cycle exist, the open once-through cycle with direct disposal of the spent fuel and a closed cycle with reprocessing of the spent fuel and recycling of the Pu and U in new fuel assemblies. There are also many countries which have not taken a decision yet, taking up a position called 'wait and see', reflecting a tendency not to rush towards any solution and to wait and see if technology provides a better alternative in the future.

Spent fuel from power reactors is currently stored either in at-reactor pools (fuel pools in the fuel building) or in independent spent fuel storage installations (ISFSI) using wet or dry technology. During the past 15 to 20 years, storage capacity of fuel pools was increased using high density spent fuel storage technology. To achieve maximum capacity, storage racks were replaced in many of the power reactors in operation, some of them went through various re-racking cycles.

Nevertheless, the amount of accumulated spent fuel to be stored is growing. For now, nuclear power plants have to keep their growing supplies of spent fuel on site in fuel pools that were never intended to double as long term storage bins. Besides the current storage of spent fuel in the fuel building pools in nuclear power plants there is a remarkable need for additional storage capacity.

Therefore, out of pool storage facilities (also known as independent spent fuel storage installations, ISFSI) have to be established, either at the sites of power reactors or away from them, as is the case for a couple of years. These independent spent fuel storage installations use either wet or dry storage technology, the latter in the form of metal casks and concrete silos or vaults.

Spent fuel, using the wet storage technology, is stored in an ISFSI in pools, well known from the power plant operation. Water storage of spent fuel does not impose problems related to safety and performance. Having adequately chosen the kind of structural materials, handling and storage can be performed without any limitations. If wet storage is selected, also interim and long term storage is applicable without principal concern, e.g. it is demonstrated over more than two decades in Sweden's CLAB facility or Finland's KPA store.

The wet storage requires a fuel pool cooling system to remove continually all the heat generated by the stored fuel assemblies and thus to maintain a certain pool water temperature. The decay heat is transferred safely from the fuel pool water under all normal and credible abnormal operating conditions to the heat sink. For safety and availability reasons, the cooling system consists of series connected cooling circuits designed on a multiply redundant basis. Each train forms a cooling chain which consists of the fuel pool cooling circuit with heat exchangers, an intermediate cooling circuit with pure water and a heat sink, for example sea water or dry cooling towers.

The second technology is the dry storage technology (in concrete/metal storage casks, concrete silos or vaults). Today, storage in metal storage casks is the most common dry storage technology. The casks are typically steel cylinders, have a double lid closure system and are either welded or bolted closed. The steel cylinder provides a leak-tight containment of the spent fuel. Each cylinder is surrounded by additional steel, concrete or other material to provide radiation shielding to workers and members of the public. Some of the cask designs can be used for both storage and transportation to and from a storage facility without any rehandling of fuel assemblies (dual purpose casks). Dry storage provides passive safety, does not generate radioactive wastes during the storage/operation period and has the potential of a better economy. Typically, fuel is transferred to an ISFSI after the fuel has cooled for 5 years.
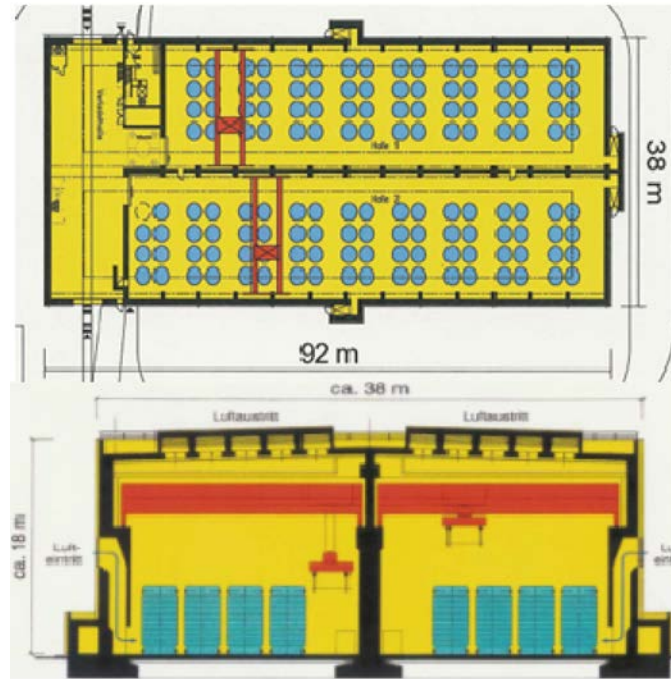
FIG. 6. Dry storage facility in Biblis, Germany.

FIG. 7. ISFSI Site in Haddam, Connecticut with 43 dry storage dual purpose casks.

There are several examples of dry storage ISFSI:

— Dry spent fuel storage facility for German NPP Biblis. This site provides a capacity for 135 casks with a total power dissipation of 7.1 MW. The 135 casks are placed inside a concrete shield building. The dimensions of the building are 38 m by 92 m by 18 m high with passive cooling (Fig. 6). The primary purpose of the shield building is to protect the casks from potential attacks including aircraft crashes;
— Connecticut Yankee ISFSI site in Haddam, Connecticut, with 43 dry storage dual purpose casks (Fig. 7).

2.3.3. Water use for industrial and potable uses

In addition to the use of water for heat dissipation, a nuclear power plant also needs water for plant service and operation. Industrial quality and potable water is required for these purposes. Nuclear power plants withdraw water from rivers, lakes, groundwater and the public water supply system. The available source of water normally does not fulfill the quality requirements for use (Table 4) in the nuclear power plant [11]. Impurities in water are present in several forms: ionic, nonionic, dissolved, suspended, colloidal and gaseous. To be used as make-up water, treatment systems apply various combinations of processes as needed to remove impurities and render the water

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TABLE 4. TYPICAL WATER CHEMISTRY PARAMETERS

Parameter	PWR		BWR
	Primary	Secondary	
pH	6.8–7.4[1]	8.8–10[2]	5.6–8.6
Conductivity (μS/cm)	~1[3]	3–5[4]	<1
Boron (ppm)	100–2000	—	—
Lithium (ppm)	<3.5	—	—
Hydrazine (ppb)	—	0.1–0.6[4]	—
Oxygen (ppb)	<5	<5	200 (<10)[5]
Hydrogen (ppm)	2–3	—	10 (50)[5]

[1] pH at high temperature.
[2] pH at room temperature.
[3] Control with correlating Band Li according to burnup.
[4] Depend on plant.
[5] In case of hydrogen injection.
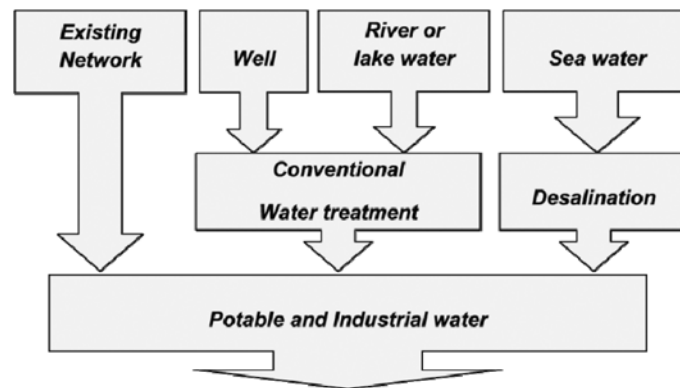
FIG. 8. Sources for industrial/demineralized water.

suitable for use in the cycle. Demineralized water is used for primary and secondary system make-up in order to minimize corrosion.

Ion exchange equipment is typically an integral part of make-up water treatment systems regardless of the water supply source. The sources, depending on the site location, are shown schematically in Fig. 8.

As an operating plant example, Florida Power and Light Co. obtains about 160 m³/h of water from the Miami-Dade public water supply system's Newton water-treatment plant for uses related to PWR Turkey Point Units 3 and 4. Most of this water is used as demineralized make-up water for use in the primary and secondary cooling loops. A small fraction of the water is used as potable water and for fire protection. FPL does not withdraw either groundwater or surface water for make-up or potable water uses. Make-up water for the canal system comes from used process water (which is treated and released to the canal system), incident rainfall, storm water runoff, and possibly groundwater infiltration. Sanitary wastewater is treated and then released to the groundwater through an injection well [12].

Kori Units 3 and 4 in KHNP Korea Hydro and Nuclear Power Co., Ltd obtains potable water from municipal water (Busan Water Authority) and Industrial water from K-water (government agency). Kori Units 3 and 4, pressurized light water reactors with three steam generators are capable of 950 MW(e). In 2008 for example, the quantity of water used in Kori units 3 and 4 during normal operation was about 192 000 m³/year. Another example

is the Neckarwestheim, Germany, Units 1 and 2 which obtain approximately 110 000 m^3/year fresh water from the local community. Between 50% and 60% of this water is used to produce demineralized water for use in the plants.

EDF reports for the 900 MW(e) French plants a yearly consumption per plant of the order of 100 000 m^3 as necessary make-up for primary and secondary circuits.

The use of industrial and potable water in a NPP includes production of demineralized water for primary and secondary circuit make-up water as well as for private households like shower, laundry or irrigation. Wastewater, as shown in Fig. 9, is collected, treated and reused or given back to the environment.

The industrial and potable water quantities used in nuclear power plants depend on several factors such as replenishment of systems, regeneration of ion exchange resins, quantity of persons and water chemistry policy. The following chart (Fig. 10) shows the distribution of water consumption for the different uses used by a 1000 MW(e) plant.

Depending on the technology and operational practices, the daily consumption of the plant varies and the following values are just indicative numbers:

— Demineralized water as make-up for primary and secondary circuits approximately 50–150 m^3/d;
— Flushing, cleaning etc. approximately 30 m^3/d;
— Waste treatment including tritium dilution approximately 20–40 m^3/d. For related data to PHWR, see Section 5;
— Condensate polishing plant make-up and flushing approximately 30–60 m^3/d;
— Potable water for showers, toilets, laundry approx. 15–70 m^3/d (typically approx. 200–400 person at site);
— Potable water for air wash plant make-up including filter backwash in tropical regions 200 to 600 m^3/d. Variation in the range is due to inlet air dry bulb temperature and relative humidity variations.

Consumption and water use do not usually depend significantly on the types of reactor (pressurized heavy water reactor (PHWR), pressurized water reactors (PWR), boiling water reactors (BWR), etc.) it varies more with the plant size and the number of employees.
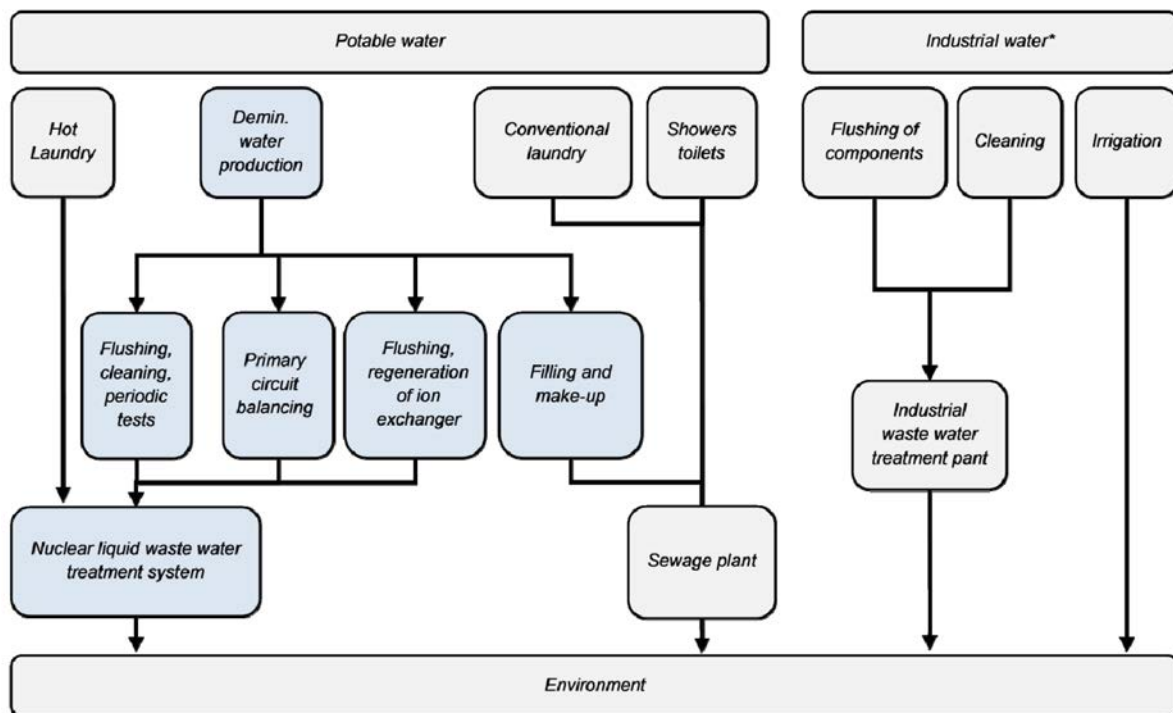
* Usage limited by the chemical parameters

FIG. 9. Typical water treatment scheme.
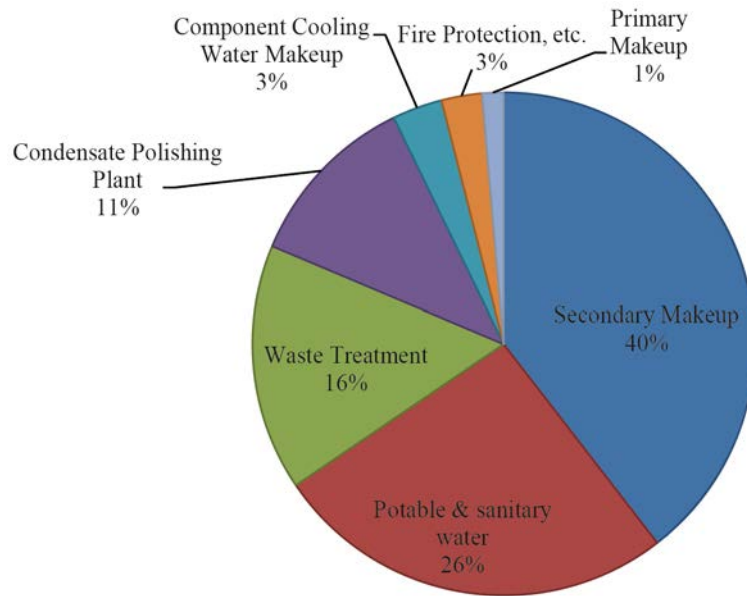
FIG. 10. Distribution of industrial and potable water consumption.

2.3.3.1. Water use and consumption due to air wash plants

Water sprays are extensively used in several engineering applications, such as, dust control, air scrubbing and evaporative cooling. In hot and dry climates, such as the summer season in India and other parts of the world, evaporative cooling of air is an attractive energy efficient technique for producing a comfortable indoor environment. Air washers employed in large air-conditioning systems for dust removal can also be optimized for evaporative cooling with appropriate design modifications which can result in energy savings.

In typical air washers, pressurized water travels through the air during which most drops fall to the floor although some drops drift with the air. This drop motion in air causes heat and mass transfer due to evaporation and some sensible cooling.

Evaporative cooling operates using induced processes of heat and mass transfer, where water and air are the working fluids. It consists of water evaporation, induced by the passage of air flow, thus decreasing the air temperature. When water evaporates into the air to be cooled, simultaneously cooling and humidifying it, it is called direct evaporative cooling (DEC) and the thermal process is adiabatic saturation. With direct evaporative cooling, outside air is blown through a water spray and cooled by evaporation. The cooled air is circulated by a blower. DEC adds moisture to the air stream until the air stream is close to saturation. The dry bulb temperature is reduced, while the wet bulb temperature stays the same. The main characteristic of this process is the fact that it is more efficient when the temperatures are higher, that means, when more cooling is necessary for thermal comfort. It has the additional attractiveness of low energy consumption and easy maintenance.

2.3.4. Wastewater disposal

Liquid wastes resulting from light water reactor (LWR) operation may be placed into the following categories: clean wastes, dirty wastes, detergent wastes, turbine building floor-drain water, and steam generator blow-down (PWRs only). Clean wastes include all liquid wastes with a normally low conductivity and variable radioactivity content. They consist of reactor grade water, which is amenable to processing for reuse as reactor coolant make-up water. Clean wastes are collected from equipment leaks and drains, certain valve and pump seal leaks not collected in the reactor coolant drain tank, and other aerated leakage sources. These wastes also include primary coolant. Dirty wastes include all liquid wastes with a moderate conductivity and variable radioactivity content that, after processing, may be used as reactor coolant make-up water. Dirty wastes consist of liquid wastes collected in the containment building sump, auxiliary building sumps and drains, laboratory drains, sample station drains, and other miscellaneous floor drains. Detergent wastes consist principally of laundry wastes and personnel

and equipment decontamination wastes and normally have low radioactivity content. Turbine building floor-drain wastes usually have high conductivity and low radionuclide content. In PWRs, steam generator blow-down can have relatively high concentrations of radionuclides depending on the amount of primary-to-secondary leakage. Following processing, the water may be reused or discharged [8].

Wastewater from operating systems such as:

— Leakages;
— Drains, vents;
— Sampling;
— Blow-down;
— Cleaning, washing, regeneration

which is collected in open cycles like floor drains, pools, etc. might be polluted with minerals, oils and detergents and it needs to be cleaned and conditioned before being discharged to the sea or river. The cleaning process depends on the pollution and can be oil separator, neutralization, etc. (see Section 4).

Wastewater from radioactive fluids such as:

— Coolant treatment;
— Drainage, venting;
— Sampling;
— Cleaning, flushing for decontamination

is collected as far as possible in closed cycles and reprocessed. The main goal is to concentrate the radioactive waste mainly with evaporators; a typical process is shown below in Fig. 11.

Specific attention needs to be paid to the fact that the operation of PWRs and PHWRs produces tritium in the primary circuit. As in current plant designs tritium cannot be removed by coolant treatment processing, the only way to decrease its concentration is to dilute it. One possibility is to discharge a certain portion via the coolant
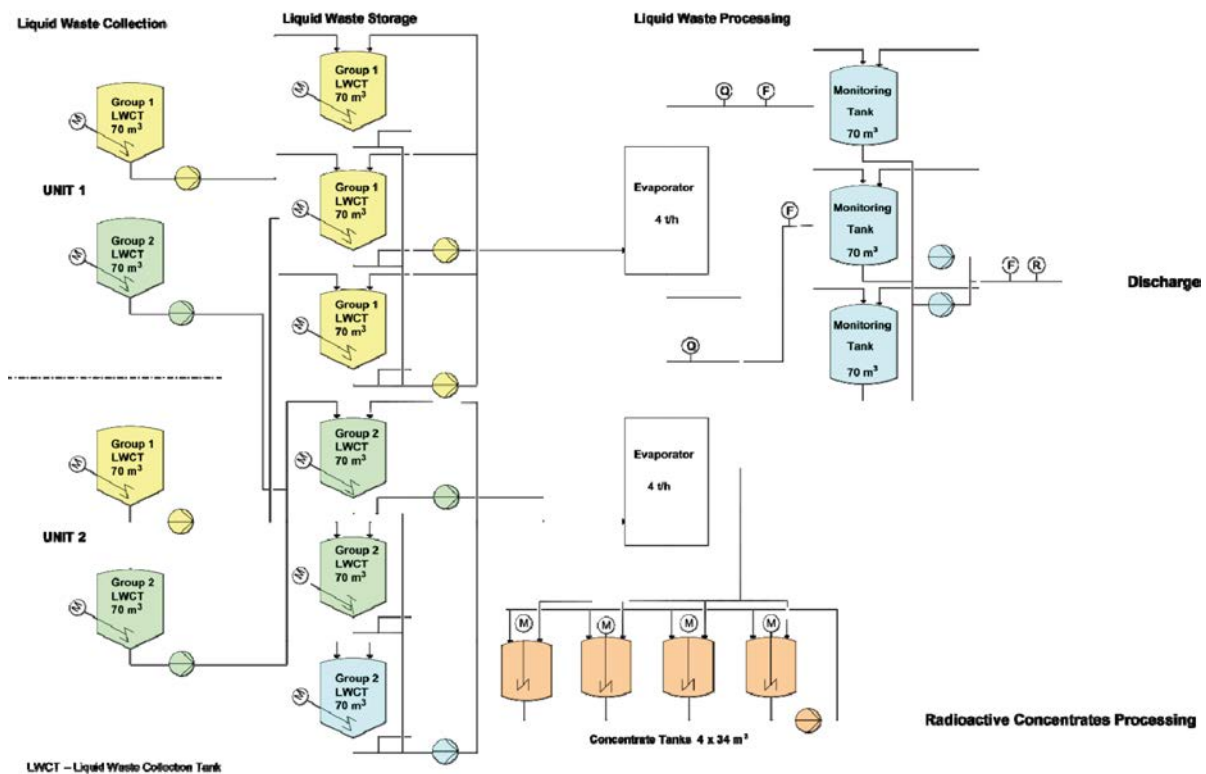
FIG. 11. Radioactive waste concentration (mainly with evaporators).

treatment systems and replace it with clean demineralized water. Another possibility is to dilute the wastewater at the outlet of the waste treatment systems using fresh potable or sea water, depending on the site location. The need for dilution depends on the local limits for tritium concentration discharge. In the case of tritium dilution during coolant treatment the amount will be between 2000 and 12 000 m^3/a of demineralized water.

Applying a tritium dilution in the coolant treatment process, the evaporator condensate after liquid waste treatment contains very low radioactivity and can be discharged.

2.4. WATER USE AND CONSUMPTION DURING SHUTDOWN STATE

In the case of shutdown, water consumption for condenser cooling is usually reduced to zero as long as the turbine is out of operation.

Service water is still in operation to:

— Supply heating, ventilation and air conditioning systems;
— Remove the residual heat from the fuel elements in the reactor and the spent fuel pool.

During the cool down of the plant to cold shutdown state, the dissipated heat transported by the nuclear service water reaches a maximum, as the stored heat and the residual heat from the primary circuit will be transferred to the ultimate heat sink. The service water withdrawal increases during that time (<1 day) as all cooling trains are in operation. On reaching the cold shutdown state the withdrawal for service water comes back to normal plant operating values. For typical values refer to Section 2.3.2.

The use of industrial and potable water during plant shutdown phase is similar to power operation. If it is a planned or unplanned shutdown for specific repair/maintenance without refueling the water consumption rises according to the increase in staff.

2.4.1. Water use for cooling safety related systems

The safety grade component cooling water systems supply all systems in the nuclear island which take over operational functions as well as safety functions during accidents. Typical systems (Table 5) of that kind are:

— Residual heat removal system (see Sub-section 2.4.1.1.): it cools down the reactor during operational plant shutdown as well as during accidents and ensures a long term reactor cooling if required;
— Spent fuel pool cooling system (see Sub-section 2.3.2.1.): transfers the heat dissipated from the spent fuel elements to the ultimate heat sink during operation of the plant as well as during accidents;
— Cooling of components: transfers the heat dissipated from the components working during load operation (e.g. reactor coolant pumps, cooling treatment, etc.), shutdown and accidents (e.g. residual heat removal system, safety injection system, etc.);
— Chillers and ventilation cooling: the heat dissipated from pipes, components, switchgear, I&C cabinets to the rooms needs to be removed to ensure safe environmental conditions for the related systems during plant operations as well as during accidents.

TABLE 5. TYPICAL VALUES FOR SAFETY RELATED SERVICE COOLING WATER FLOW RATES IN OPEN LOOP

	Safety related cooling flow rate (m^3/s)
Safety related service cooling water flow rate during normal operation[1]	0.8–1.6
Safety related service cooling water flow rate during plant cool down[2]	1.6–3.2

[1] At normal plant operation the flow rate is adapted to the required heat transport by switching off trains not required.
[2] At plant cool down operation the maximum flow rate is operated by switching on all available trains to save time for refueling.

This requires a heat sink which is available during normal operation as well as under all postulated accident conditions e.g.:

— External hazards: (earthquake, aircraft crash, explosion blast wave, external flooding, strong wind, extreme temperatures, etc.);
— Internal hazards: (fire, internal flooding, internal explosion, pipe leaks and breaks, etc.).

Typical is a system design has separated redundant trains, including an alternative water source or reservoir. If cooling towers are used, they need to be protected by geographical separation or civil constructive measures.

The alternative water source can be an additional geographically separated cooling water channel to an available water source or ponds with a reservoir of water for a certain grace period. These alternative water sources, even if they are not used during normal plant operation, need to be kept in perfect standby condition (without biofouling, free of dust and mud, etc.), to have them always available during accidents. The typical size for a pond guaranteeing a 30 day grace period is in the range of 30 000 to 50 000 m^3.

2.4.1.1. Water use for residual heat removal systems

During normal plant operation heat generated by the fuel elements produces steam that expands in the turbine producing electricity. Dissipated heat (not used for electric power conversion) is transferred via the main cooling water to the environment.

In the short term after reactor shutdown the turbine condenser can stay as a residual heat sink as long as the cooling water is available. The cooling need is determined by the decay heat produced in the fuel after power shutdown. The decay heat decreases rapidly and reaches approximately 2% of the nominal thermal power after 30 min. As with reactor shutdown also the turbine is shut off, the steam generated by the decay heat is in the short term usually routed via the turbine bypass to the condenser, cooled by main cooling water. For the long term it is required to bring the reactor to cold shutdown state (<60°C) which requires cooling via service water systems.

Residual heat removal is also necessary in the case of accidents; this means the reactor residual heat sink must be safety grade. As turbine condenser and cooling water are designed as operational systems a substitute for the short term phase is heat transfer via the steam generator steam dump to the atmosphere. This results in a loss of water to the environment, which need to be stored on site. Typical storage for 10h–72h is available on site, some 1000–3000 m^3. In the long term the residual heat removal is taken over by the safety grade service water system. Hence the heat sink (sea, river, ponds, cooling towers, etc.) is to be designed to withstand the postulated events and to provide a sufficient grace period for post-accident actions.

To support normal and emergency shutdowns of the nuclear unit, essential cooling water systems are engineered to provide a heat removal path for the decay heat of the nuclear fuel and energy stored in the primary coolant system. The systems that provide the residual heat removal path support other essential cooling functions such as containment cooling, control room air conditioning, compartment and room cooling, and emergency core cooling pump oil and seal cooling.

The residual heat removal path typically comprises a residual heat removal system (RHR), a closed component cooling water system, and an open service water system. RHR systems comprise low pressure reactor coolant injection pumps, drop line(s) for pump suction from the primary coolant system, containment sump or containment suppression pool suction strainers and suction lines, heat exchangers, and coolant injection lines back to the primary system. Heat is rejected via the RHR heat exchanger, the essential closed cooling water system heat exchangers, to the essential open service water system.

From the essential service water system, heat is rejected to the atmosphere using one of several types of ultimate heat sink (UHS) designs: a passive cooling pond, a spray pond, or a cooling tower. In essential service water systems that provide for a once-through cooling alignment, residual heat can also be rejected directly to a large body of water such as a river, a lake, or an ocean. The UHS is an essential system that is partially or totally independent of the main cooling system heat sink. Independent UHS designs have water withdrawal requirements to support make-up and blow-down and water loss rates due to evaporation that are separate from those for the main cooling system heat sink. Water withdrawal and loss rates for the UHS during normal power production and shut down operations can be 2–5% of those for the main cooling system.
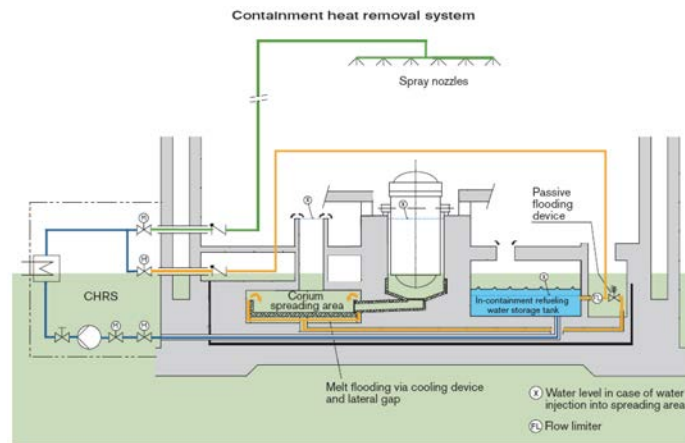
FIG. 12. Containment heat removal system.

RHR systems are typically sized for 2–3% of rated core thermal power and they are required to support a specified primary system cool-down and containment system cool-down time.

2.4.1.2. Water use for containment cooling

Containment cooling maintains containment atmosphere and wet containment suppression pools at temperatures low enough to assure that components, coatings, and structures are adequately protected against degradation due to exposure to a high temperature environment. Containment cooling (Fig. 12) is also a part of the residual heat removal path. The RHR system and containment air coolers provide containment cooling during normal and accident operation. Containment spray supports containment cooling for postulated accidents.

For a postulated loss of coolant accident (LOCA), a pipeline or a valve in the primary coolant system is assumed to fail, releasing primary coolant, and primary system energy into the containment atmosphere and containment sump/containment suppression pool. If the water level in the containment is sufficient to support pump suction, the RHR system is aligned to recirculate this hot coolant through the RHR heat exchangers to provide containment cooling. Containment spray systems can also be aligned to the containment sump/containment suppression pool, to recirculate coolant through the RHR heat exchanger, and to spray the cooled discharge into the containment atmosphere. The heat is transferred to the ultimate heat sink via safety grade essential service water.

Containment air coolers augment the heat removal capability of the RHR system. They remove heat from the containment atmosphere by rejecting it either to a closed cooling water system or to an open service water system. For dry containments, the containment air coolers are the only mechanism for removing heat from the containment during the initial phase of a postulated LOCA when the emergency core cooling and containment spray systems are aligned for injection. (In this alignment pumps draw water from a coolant storage tank and inject it into the primary system and spray it into the containment atmosphere until the storage tank is empty). The containment air coolers provide a better capability than the RHR system to draw the temperature of the containment down to levels close to those of the UHS. For this reason, they play an important role in long term accident recovery.

2.4.2. Water use during refueling

A typical outage for refueling with currently operating light water reactor plants lasts about 2–4 weeks. The plant is in cold shutdown state with only service water in operation (see Sub-section 2.3.3). During that period the industrial and potable water consumption reaches a maximum as the number of workers increases notably (200–900 additional workers [8]) and many systems are drained, flushed and refilled.

— Demineralized water for refilling primary and secondary circuits approx. 100 m^3/d;
— Potable water for showers, toilets, laundry approx. 250 m^3/d;
— Flushing, cleaning approx. 300–500 m^3/d.

One study for the operation of two 1520 MW(e) ESBWRs in the southwestern USA concluded that, excluding make-up to support heat rejection in the circulating water cooling reservoir and plant service water cooling towers, water use for the two-unit station could be as high as 3550 m^3/d during normal operation. The study found that during a single unit outage, water use could rise up to 7100 m^3/d, excluding make-up to the circulating water cooling reservoir and plant service water cooling towers.

2.5. WATER USE AND CONSUMPTION DURING DECOMMISSIONING

The final goal of decommissioning is to remove all nuclear and contaminated material from the facility and prepare the site for new industrial use or unrestricted use; i.e. green field. Cessation of plant operations will result in a significant decrease in water consumption because reactor cooling is no longer required. Although water will still be required for spent fuel cooling, this demand will decrease as the fuel ages. Dewatering systems may remain active during decommissioning of a nuclear facility to control the water pathway for the release of radioactive material. Decommissioning activities that may influence water use include fuel removal, staffing changes, large component removal, decontamination and dismantlement (using high-pressure water sprays), structure dismantlement, and entombment.

Most of the impacts to water resources likely to occur during the decommissioning of a nuclear facility are also typical of the impacts that would occur during decommissioning or construction of any large industrial facility. For example, providing water for dust abatement is a concern for any large construction project, as is potable water usage. However, the quantities of water required are trivial compared to the quantity used during operation. There are some activities affecting water resources and decommissioning nuclear facilities that are different from other industrial non-nuclear activities. The demand for water for spent fuel maintenance (approximately 0.2–2.0 m^3/d of water, depending on the size and location of the pool), for wet decontamination methods (such as a full flush of the primary system) or for hydrolising (i.e. cutting with a water jet) embedded piping in situ, although not large, are unique to nuclear facilities.

One facility reported using approximately 9.5–11.0 m^3/d of water for spent fuel pool spray-cooling during the summer months until the fuel was removed from the plant. Additionally, water in some of the systems or piping may continue to be used during decontamination and dismantlement to provide shielding from radiation for workers who are dismantling structures, systems, and components (SSCs) in the vicinity. For example, 912 m^3 of water were used at one site to fill the reactor cavity in preparation for the segmentation of the reactor vessel. Common engineering practices, such as water reuse, are used to limit water use impacts at most construction or industrial sites. However, use of some of these practices may be limited by radiological exposure considerations at decommissioning sites. Current or anticipated decommissioning activities at the fast breeder reactors (FBR) or high temperature gas reactors (HTGR) have not and are not expected to result in water-quality impacts that are different from those found at other nuclear reactor facilities.

2.6. CONCLUSION

Typically, the use of water in NPPs is for water withdrawal for heat dissipation and water consumption for plant operation and staff supply.

The water withdrawal is mainly dominated by the turbine condenser cooling and is therefore independent of the type of reactor. The main influence here is the efficiency of power conversion, which is the factor defining the dissipated heat. High efficiency plants can notably reduce the cooling water demand. Water withdrawal reaches maximum values for open loop cooling, where the cooling water flow represents often more than 95% of the total water usage. The use of cooling towers in closed loop cooling reduces the water withdrawal to the evaporation, blow-down losses, and drift losses which are about 1% to 4% of the water flow rate of open loop cooling, but this increases investment and operation costs.

Current nuclear power plants are usually located on sites where a sufficient water source was available at an economically reasonable price and at sufficient low temperatures to make the NPP comparable with coal/gas fired plants. The water source differs for each NPP and depends on site specific conditions and on the geographical

location. The most economical solution is direct cooling, as this allows the use of the coldest water source available and generates the lowest condenser vacuum. In Table 6, the current practice of cooling systems is listed.

Cooling primary and secondary components often follows the principle of condenser cooling in open or closed loop. Special arrangements are required for nuclear safety if alternative cooling to the ultimate heat sink is required.

Industrial and potable water is used for plant service and operation to satisfy the needs for demineralized water production, flushing, cleaning and sanitary use. The amount of water used is less than 1% of the water withdrawal for cooling purposes in open loop. Compared to the evaporation losses if wet cooling towers are used, the water consumption of industrial and potable water is about 5%.

Considering the lifetime of NPPs (30–60 years) the water consumption during erection, commissioning and decommissioning is negligible. But the water needs at these phases exceeds the industrial and potable water needs during normal operation.

3. TECHNOLOGIES AVAILABLE FOR COOLING SYSTEMS

The electric power industry requires reliable access to large amounts of water, primarily for cooling. Steam condenser cooling is normally the largest consumptive use of water at an electric power plant. In many situations, the desire to save water leads to the consideration of dry or wet/dry cooling in order to reduce plant water requirements.

The most common types of nuclear power plants use water for cooling in two ways: to convey heat from the reactor core to the steam turbines, and to remove and reject surplus heat from this steam circuit. (In any steam cycle plant there is a loss of about two thirds of the energy due to the intrinsic limitations of turning heat into mechanical energy).

If the power plant is next to the sea, a big river or large inland water body the cooling may be achieved simply with a once-through cooling system, where large amounts of water are circulated through the condensers in a single pass and discharged back into the sea, lake or river a few degrees warmer and without much loss from the amount withdrawn. The water may be salt or fresh. Some small amount of evaporation will occur off-site due to the water being a few degrees warmer (about 1%).

If the power plant does not have such abundant water, the cooling may be carried out by passing water through the condenser and then using a cooling tower, where an updraught of air through water droplets cools the water. Occasionally an on-site pond may be sufficient for this. Normally the cooling is chiefly through evaporation, with simple heat transfer to the air being of less significance. Wet cooling towers evaporate up to 5% of the flow to cool down the recirculating water that is returned to the condenser. The 3 to 5% or so is effectively consumed, and must be continually replaced. This is the main type of recirculating cooling. Increasingly popular are dry cooling towers that rely on a closed water cooling loop that rejects heat to the atmosphere via a mechanical water-air radiator.

This section will discuss current technologies applicable for nuclear power plant cooling, with advantages and disadvantages of their use. Water withdrawal rates and water consumption rates for various cooling system technologies will also be discussed. Several real-world cases will be presented as examples. Available technologies that have not yet been widely used but are readily available will be discussed.

TABLE 6. DISTRIBUTION OF COOLING SYSTEMS IN CURRENT OPERATING NPPs

Once-through cooling			Closed cycle
Sea	Lake	River	Cooling tower
45%	15%	14%	26%

Cooling systems are classified based on the following criteria:

— Cooling type: Wet cooling systems recirculate water after cooling into a tower or pond where it is cooled down by direct contact with air, mainly due to evaporation. In dry cooling systems heat from the cooling water is transferred indirectly to the ultimate heat sink through heat exchangers without evaporation losses (Table 7);
— Cooling loop: Indirect cooling systems include an intermediate water circuit between the steam turbine condenser and the heat sink, as for direct cooling heat is transferred directly from the condenser to the ultimate heat sink;
— Heat sink type: Refers to the equipment used for rejecting waste heat to the ultimate heat sink;
— Tower draft type: Defines the type of air circulation trhough the tower;
— Mechanical draft type: Forced types the air is forced into the tower while induced type pull the air through the towerby a fan located at the discharge of the tower.

Any possible combination of the above can be used in hybrid systems. This section is structured on the classification of all cooling system types shown in Fig. 13.

TABLE 7. HEAT EXCHANGER PHASES FOR DIFFERENT COOLING SYSTEMS

Cooling type	Turbine condenser heat transfer	Ultimate heat sink heat transfer
Wet cooling tower	Steam/water HX	Water/air (direct contact)
Indirect dry cooling tower	Steam/water HX	Water/air HX
Direct dry cooling tower	—	Steam/air HX
Heller system	Steam /water (direct contact)	Steam/air HX
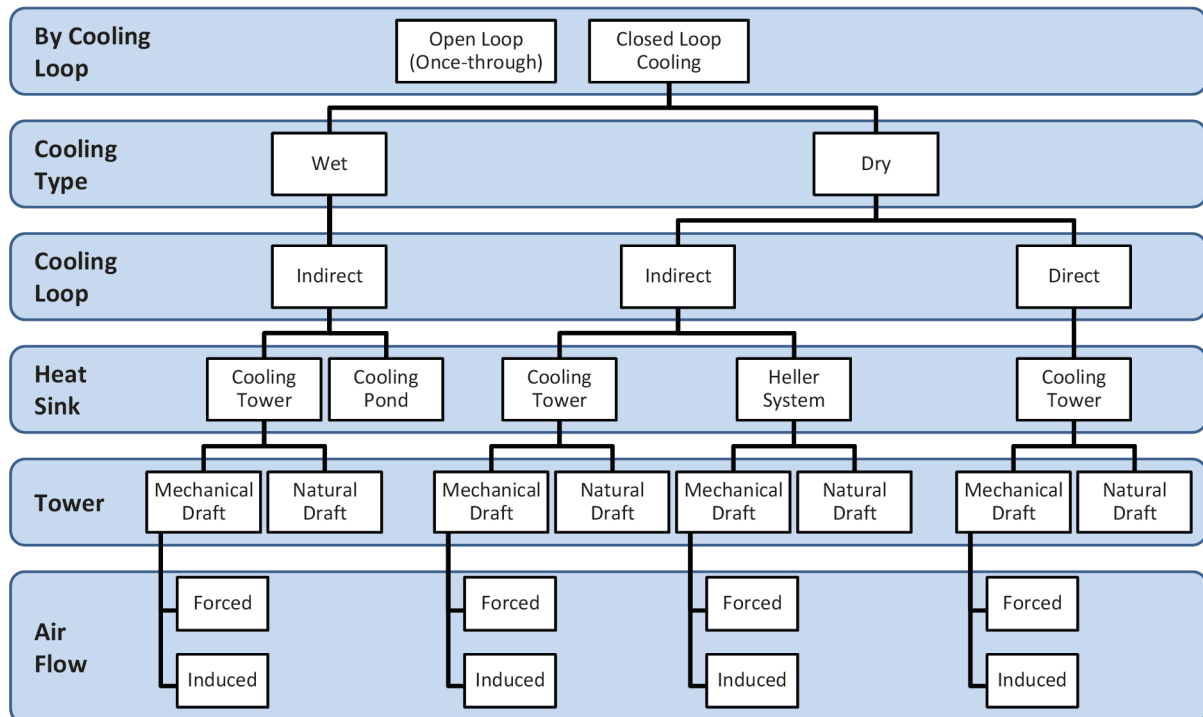
FIG. 13. Classification of cooling systems.

3.1. OPEN LOOP COOLING

Plants located in coastal areas mostly use the cooling water in open cycle; this means the cooling water is taken from the sea, pumped through the turbine condenser and returned directly to the sea. Once-through plants withdraw large quantities of water from a source body, but virtually all of that water is returned to its source at a quality similar to that removed, albeit a little warmer and sometimes with a trace of residual chemicals. Only a small quantity is consumed via increased evaporation to the atmosphere from the warm discharge water plume. In the USA, where most of the NPPs were constructed more than 30 years ago, 60% of them utilize a once-through cooling system.

An example of an open cycle cooling system is shown in Fig. 14.

Nuclear power plants withdraw large amounts of mainly surface water to meet a variety of plant needs. Water withdrawal rates are large from adjacent bodies of water for plants with once-through cooling systems. Flow through the condenser for a typical 1000 MW(e) plant may be 45–65 m^3/s [8]. However, the design cooling water flow rate is usually set on the basis of a maximum allowable temperature increase above ambient water (to respect aquatic life) or an absolute maximum discharge water temperature, as determined by water quality regulatory agencies.

Plants located at river or lakes are usually more restricted when using the cooling water in an open cycle. As shown in Fig. 15, the lower the allowed temperature water heat up, the higher the required cooling water withdrawal.

Mechanical filters are installed in every cooling water system using natural water to remove debris and marine life (fishes, mussels, etc.) from the mass flow. Therefore, some part of the water flow is needed to clean or flush the filters in order to ensure their operability. This part of the mass flow is not available for cooling purposes. The flushing water needs for cleaning screening devices are approximately 0.4% of the overall mass flow.

In some cases, to meet the environmental consideration; e.g. to limit the return temperature to the river, cooling of the outlet water (using the so called outlet cooling) before discharging to the river, lake or reservoirs by using wither cooling ponds or wet cooling towers either in series or in parallel is utilized.

3.2. CLOSED COOLING SYSTEMS

In a closed-cycle (recirculating) system cooling water is pumped from the condenser to a cooling source where the heat of the water transfers to the ambient air. The resulting lower temperature cooling water is then returned back to the condenser. Closed cycle cooling systems may use wet cooling, dry cooling or hybrid of both wet and dry. These alternatives are described later in this section.
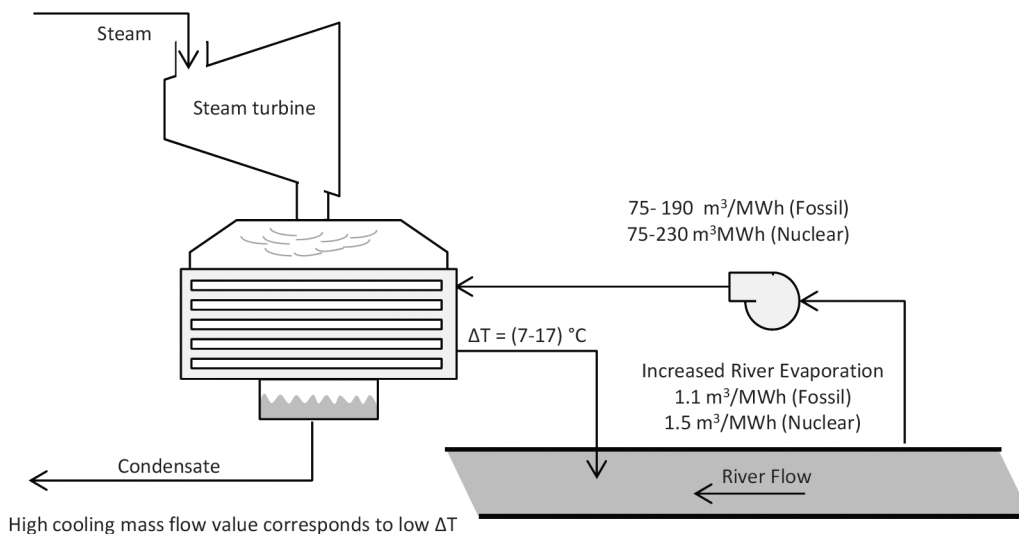
FIG. 14. Once-through cooling.
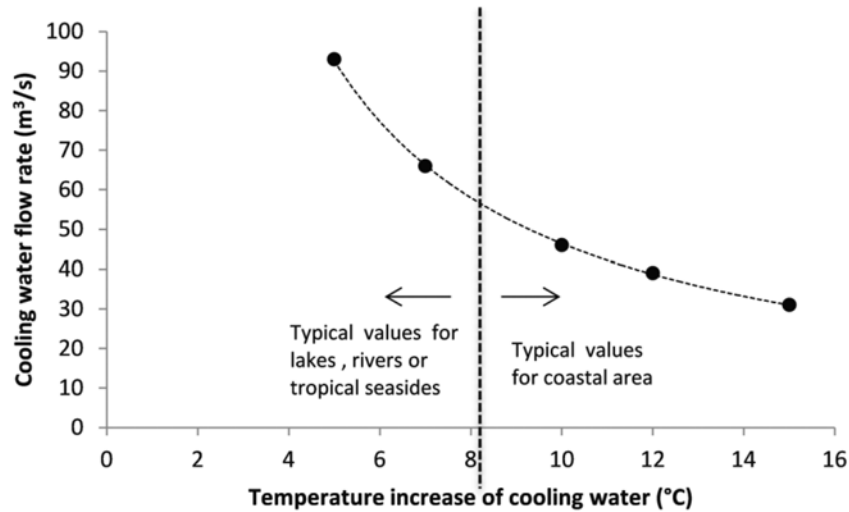
FIG. 15. Cooling water withdrawal for a typical 1000 MW(e) plant in different areas.

TABLE 8. TYPICAL VALUES FOR WATER SURFACE FOR CONDENSER COOLING

Plant	Nominal power MW(e)	Dissipated thermal power MW(th)	Available pond surface (km^2)	Specific cooling area m^2/MW(th)
Dresden 2+3	1734	3321	5.16	1554
La Salle 1+2	2238	4756	8.33	1752
Braidwood 1+2	2330	4929	10.28	2086
Trawsfynydd 1+2	390	1306	4.42	3385
Turkey Point 1 to 5	2196	4392	15.6	3552

3.2.1. Wet cooling

3.2.1.1. Cooling pond

Cooling ponds are used as the means for the final transfer of heat rejected from the steam condenser to the atmosphere in lieu of cooling towers in some recirculating wet cooling systems. Cooling ponds are either human-made bodies or natural bodies. Heat transfer from the pond to atmosphere is accomplished by radiation, convection, conduction and evaporation of water from the pond surface. This requires a large surface to allow the heat exchange, which for some designs is combined with spray equipment, increasing the effective surface area for heat exchange by generating water droplets. Cooling ponds with spray equipment enable the pond surface to be reduced to approximately 5% of the area of a simple pond but it still occupies 10–20% more area than for wet cooling towers.

Heat transfer is mainly influenced by local topography, air humidity, solar radiation and wind speed. Looking at some installed facilities the specific water surface for heat transfer is in a range of 1500 to 3500 m^2/MW(th) and a volume of about 10 km^3 per 1000 MW(e) considering one degree Celsius the average vertical temperature increase at the most unfavourable time of the year (Table 8).

Cold water is pumped from the pond and passed through condenser and returned to the pond for heat dissipation. Make-up is provided to the pond from a river to meet evaporation losses, blow-down and system leaks. The water balance of the circuit is indicated in Fig. 16.

An example for cooling ponds is the Florida Power & Light's Turkey Point NPP in the USA uses a system of canals approximately 270 km long for cooling giving an effective surface area of some 1560 ha. The average
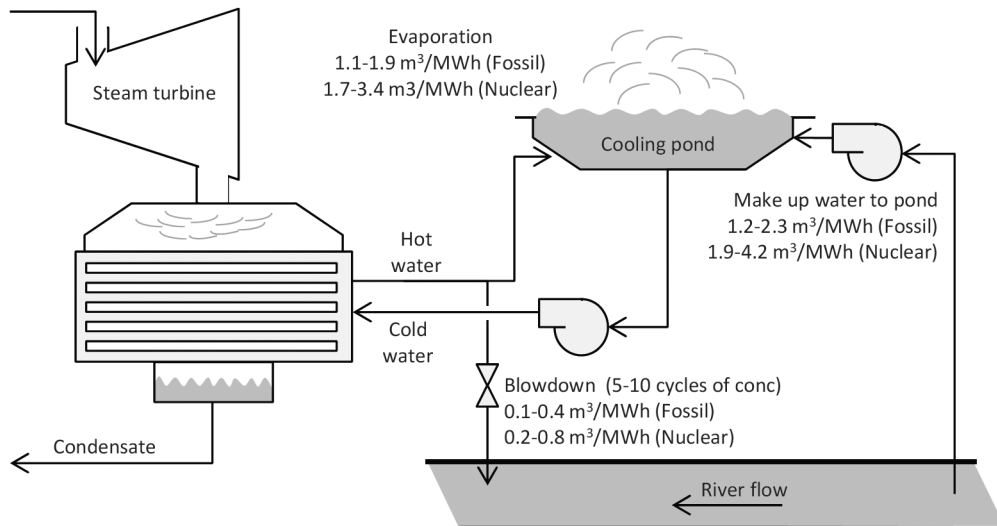
FIG. 16. Recirculating cooling pond.
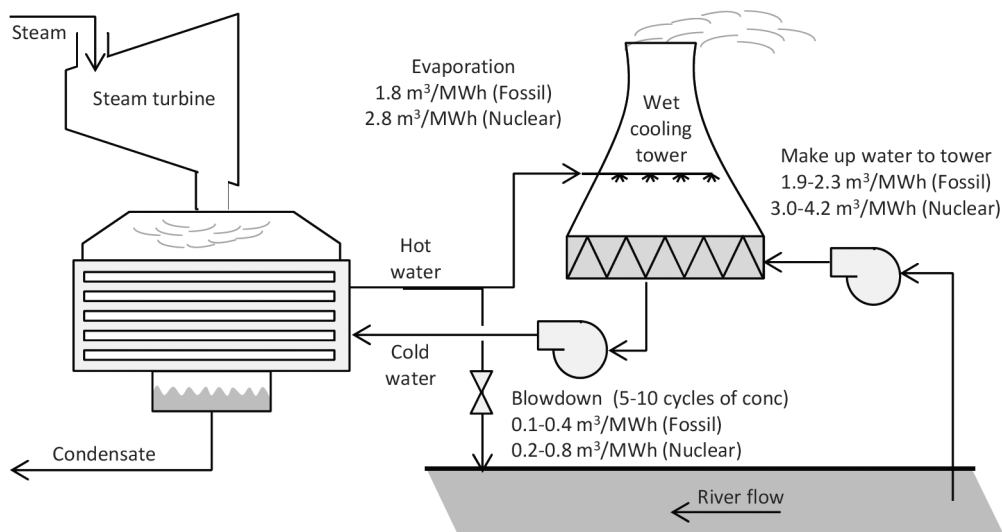
FIG. 17. Schematic of recirculating wet cooling tower (natural draft).

residence time of the water in the pond is 40 hours [2] (for more details see Annex I). Evaporative losses from the cooling canal system are replenished by rainfall, plant storm water runoff, and treated process wastewater, which ultimately comes from the municipal supply.

3.2.1.2. Cooling tower

Wet cooling towers (Fig. 17) reduce the total volume of water withdrawal from the environment by nearly 95% compared to once-through cooling. Although water withdrawal is significantly less, it is still a significant quantity, up to 1 m^3/s for a 1000 MW(e) power plant [8]. Thus, these NPPs still need to be located near a body of water.

In wet cooling towers, water is cascaded through the cooling tower and put into contact with air that is pushed or pulled through the fill by mechanical draft fans or natural draft. As water passes through the tower it transfers its heat to the air by convection and mainly by evaporation. The cooled water is collected at the bottom of the tower and pumped back to the condenser for reuse. The water balance of a wet cooling tower circuit is shown in [6, 13].
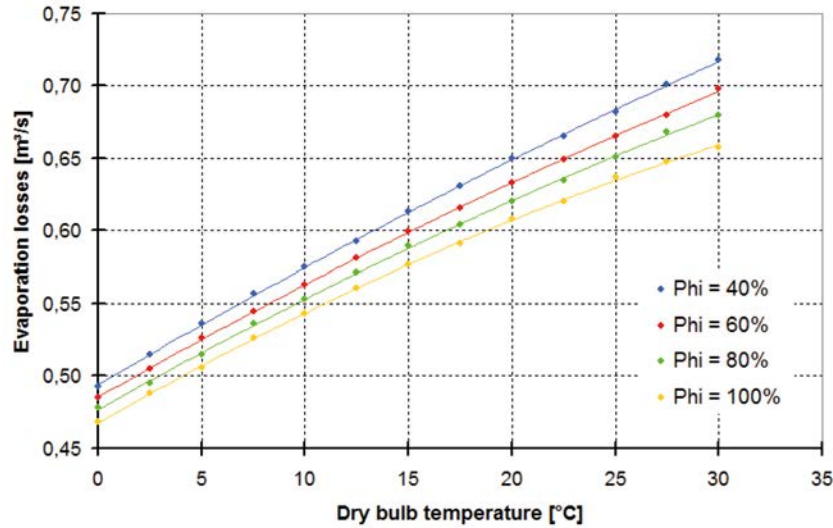
FIG. 18. Evaporation in a natural draft weet cooling tower (Phi = relative air humidity).

TABLE 9. MINIMUM POSSIBLE APPROACHES FOR VARIOUS COOLING TOWERS

	Minimum approach (compared to wet bulb) (°C)	
	Technical	Economical
Mechanical draft cooling towers	2.8	4
Natural draft wet cooling towers	5.6	10–15

Evaporation in a wet cooling tower depends on the local daily ambient conditions, determined by the relative air humidity (RH) and the dry bulb temperature (temperature of dry air measured with a conventional thermometer). The heat transfer capability of a wet cooling tower, directly related with the evaporation, increases with decreasing relative humidity at a given dry bulb temperature. Evaporation is estimated by the following empirical equation:

$$E = F \cdot CR \frac{\Delta T}{5.6}$$

where E (m³/s) is the evaporation flow, F (–) a factor that depends on site conditions, CR (m³/s) the circulation rate of the cooling water through the tower and ΔT (°C) is the temperature differential across the tower [14]. This empirical equation implies that for a cooling water temperature drop of 5.6°C, 0.8% of the total recirculating cooling water will be lost through evaporation in high humidity areas (F = 0.008) and up to 1.2% in low humidity areas (F = 0.012). For a typical 1000 MW(e) nuclear power plant, Fig. 18 shows the evaporation absolute flow as a function of relative humidity and dry bulb temperature.

Theoretically the lowest possible cooling water outlet temperature is the wet bulb temperature of the air entering the tower. However, this limit is not achievable technically (Table 9) because an infinite heat exchange surface would be needed. In practice, a temperature difference between the wet bulb temperature and the cooling water outlet temperature is applied. This temperature difference is called the approach of the cooling tower, which is a very important design factor. Larger approaches would reduce the cooling capacity of the tower, while lower approaches would increase the investment costs.

In addition to the evaporated water leaving the cooling tower also drift losses occur as small water droplet are carried out by the air flow.

The water that is evaporated from the tower is pure; that is, it doesn't contain any of the mineral solids that are dissolved in the cooling water. Evaporation has the effect of concentrating these dissolved minerals in the remainder of the tower water. If this were to occur without restriction, however, the solubility limit of the dissolved minerals would soon be reached. When the solubility limit is reached, dissolved minerals (most commonly calcium and magnesium salts) precipitate as an insoluble scale or sludge. This is the off-white, mineral scale that is frequently found in heat exchangers, in the tower fill, or deposited in the sump.

To prevent the tower from over concentrating minerals, a percentage of the cooling water is discharged to drain. The bleed or blow-down rate is adjusted to control the concentration of dissolved minerals to just below their solubility limit. This limit is commonly set and controlled by specific conductance (micro ohms/cm) or total dissolved solids (mg/L) measurements. The water that is lost by evaporation and bleed must be replaced by fresh make-up to maintain a constant system volume. Hence, the amount of water lost by evaporation, drift and blow-down bleed must be replaced by fresh make-up to maintain a constant system volume (Fig. 19).

One indicator of cooling tower efficiency is cycles of concentration, or concentration ratio (COC). This is the ratio of the make-up rate to the blow-down rate, assuming drift losses are negligible. The better the quality of available water, the less blow-down is needed to be extracted in order to maintain acceptable water concentration in the cooling loop and the higher values of COC can be achieved. Table 10 presents some typical values for different water conditions. Strategies for increasing COC are described in Sub-section 5.1.2.3.

There are two common types of wet cooling towers: natural draft towers and mechanical draft towers. They are further classified depending on whether air and hot water flow directions are cross flow or counter flow. In a cross flow tower the air flows perpendicular to the water flow and in a counter flow tower the air flows counter current to the water flow. Figure 20 indicates the arrangement of cross flow and counter flow type mechanical draft and natural draft cooling towers.

In natural draft towers the airflow through the tower is induced by density differences in a 'chimney effect'. Natural draft towers are either hyperbolic, reinforced concrete structures resting on X legs, or consist of a cylindrical steel structure on top of a conical skirt, with corrugated aluminium cladding. In both cases the ring
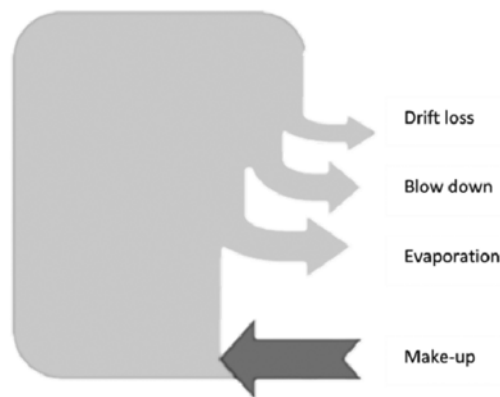
FIG. 19. Make-up needs for cooling water in nuclear power plants.

TABLE 10. COOLING WATER BALANCE FOR DIFFERENT MAKE-UP QUALITIES

	Make-up	Blow-down	COC	Evaporation	Drift
Specific pre-treated water[1]	1.25%	0.05%	Up to 25	1.20%	
City water	1.50%	0.30%	5	1.20%	
					0.01%
Treated sewage effluent	2.00%	0.80%	2.5	1.20%	
Seawater	4.20%	3.00%	1.4	1.20%	

[1] The values given in this row are related to Palo Verde nuclear power plant, where specific water management of 'zero discharge' is applied. This requires the installation of advanced water cleaning facilities. For more details see Annex I.
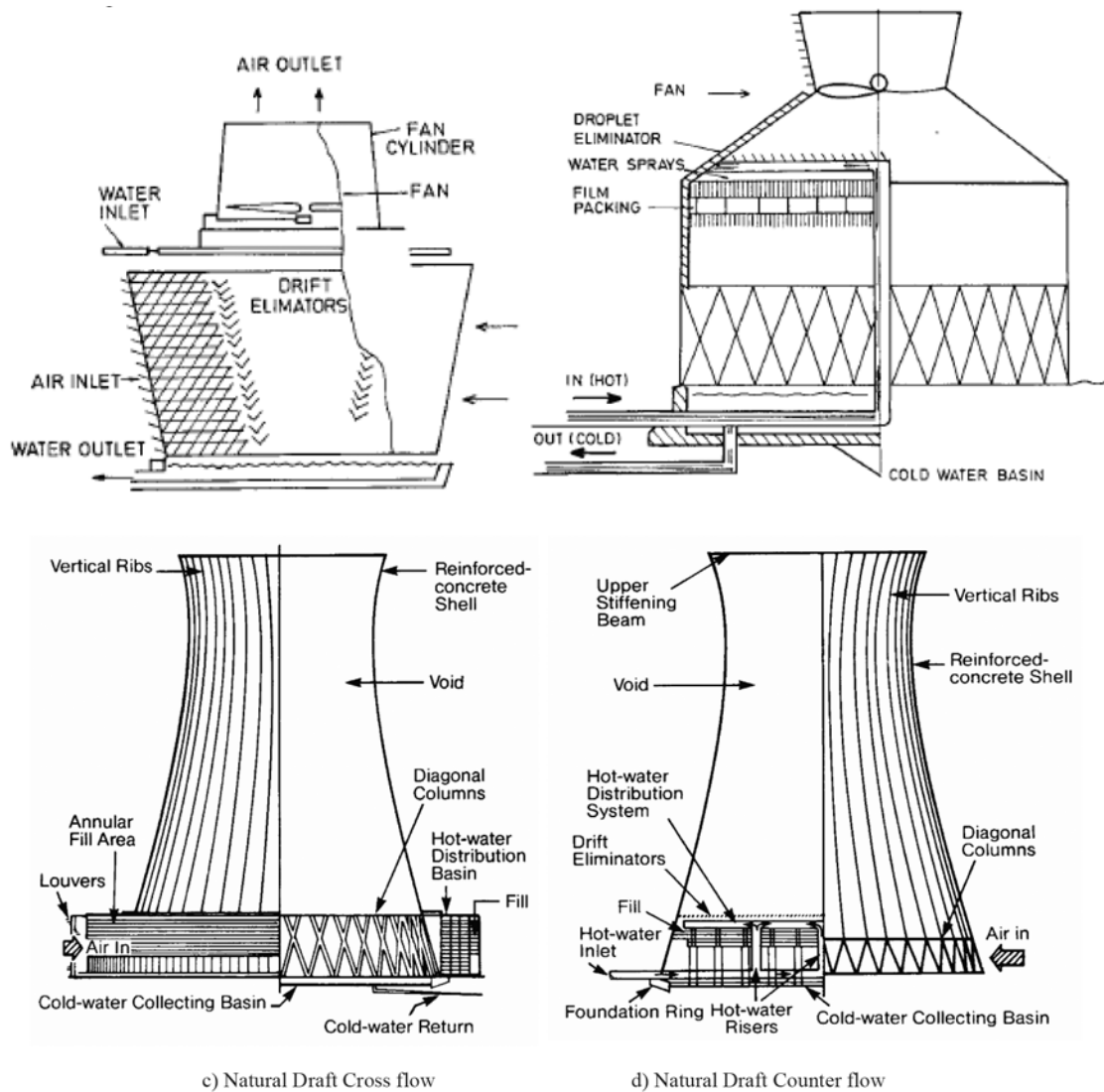
FIG. 20. Schematic diagrams of various types of wet cooling towers (courtesy of Gulf Coast Chemical Commercial Inc. 1995).

shaped concrete foundations surround buried tanks to accommodate water from the heat exchangers when they need to be drained.

Mechanical draft towers are built in both forced draft and induced draft with cross-flow or counter-flow designs. Hot water from the condenser is introduced at the top of the fill and flows down through a 'fill' section where it is brought into intimate contact with ambient air flowing across, or counter to, the direction of the falling water flow. Both sensible and latent heat transfer to the air cools the bulk of the water, which is then collected in a basin and returned to the condenser. The air leaving the tower is heated and humidified to an essentially saturated plume. Figures 20 and 21 show schematic diagrams of natural draft and mechanically induced draft tower circuits.

3.2.2. Dry cooling

The need for power plant cooling water can come into conflict with agricultural, residential, industrial, and environmental requirements. To reduce water consumption in thermoelectric plants a design approach is to replace the evaporative wet cooling towers in closed-loop systems with dry cooling towers cooled only by air. However, dry cooling systems are more costly than comparable wet systems and their use can reduce plant efficiency and limit plant output during the hottest hours of the year. This is particularly important to tropical countries (Example: India, UAE) where the hottest summertime hours are those when power is most needed by the grid. Capacity shortfalls of several megawatts because of increased turbine backpressure could create both a potential system reliability

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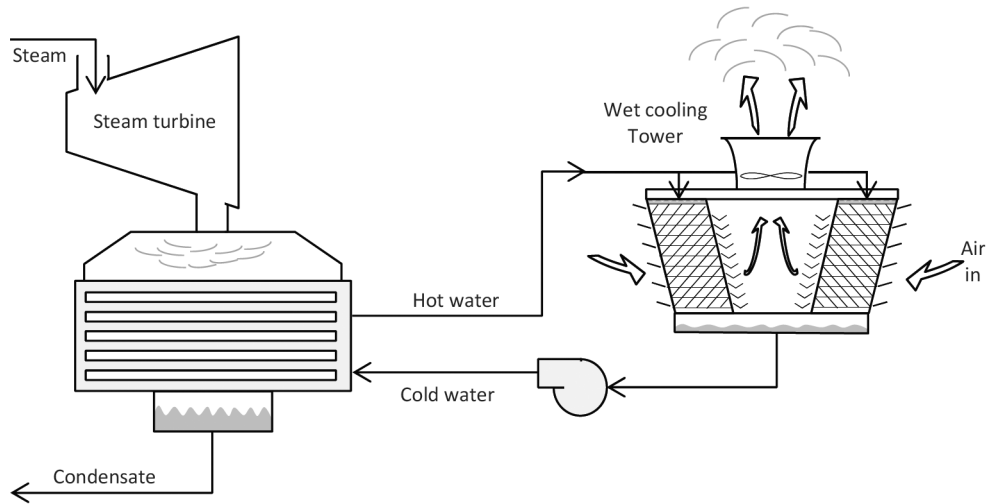
FIG. 21. Schematic diagram of re-circulating mechanical (induced) draft, cross flow wet cooling tower.
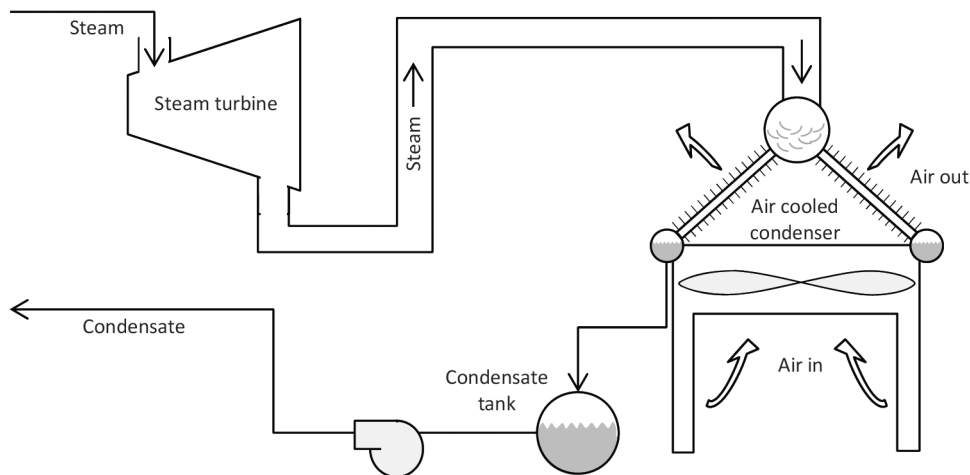
FIG. 22.   Schematic diagram of direct dry cooling — air cooled condenser.

problem and a substantial revenue loss to plant owners. Dry cooled systems impose a lost generation penalty of about 2% on an annual basis [15] compared to wet cooling. Evaporative closed-loop cooling provides cooling that approaches the dew point temperature. Dry cooling can approach only the ambient air temperature. Unless the relative humidity is 100%, the air temperature is always higher than the dew point, so the outlet temperature of a dry-cooling system will almost always be higher than for an evaporative wet cooling system. As the cooling system outlet temperature increases, plant efficiency decreases. In other words, plant efficiency is higher for plants using evaporative wet cooling than for plants using dry cooling, especially in a hot, arid climate. In the hottest weather, when power demands are highest, plant efficiency may decrease by up to 25% [16] in pure dry cooling towers. This could provide greater incentives for other efficiency and water use technology improvements.

Dry cooling systems can be categorized as direct and indirect.

3.2.2.1. Direct

In a direct dry cooling system, turbine exhaust steam is delivered directly to an air cooled condenser (ACC) as shown in Fig. 22. Steam is condensed within the condenser tubes, which are finned on the air side, by air directed over the tubes. The dry cooling tower can be either mechanical or natural draft. This system will have a footprint about 2.2 times larger than for a wet cooling tower and a height about 1.9 times greater.
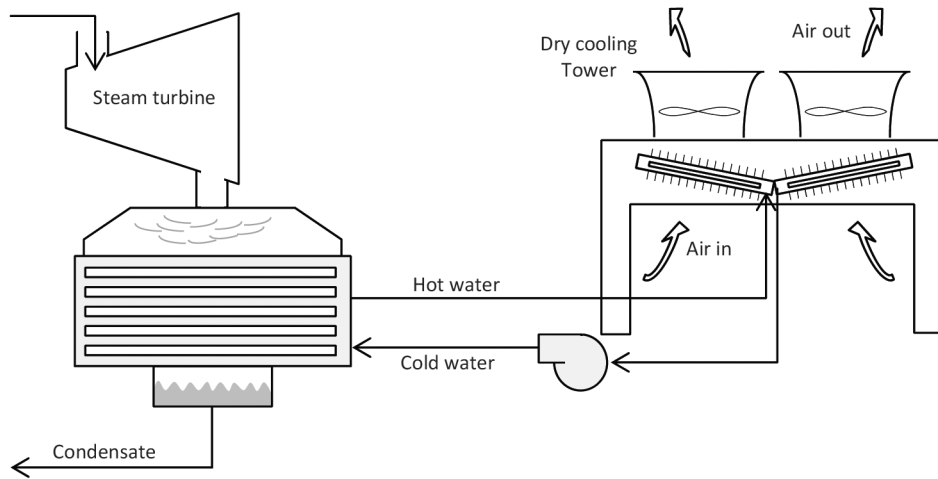
FIG. 23. Indirect dry cooling with mechanical draft tower.

3.2.2.2. Indirect

Dry cooling tower

Indirect dry cooling systems have a separate surface condenser of the conventional shell and tube type. The turbine exhaust is condensed over water circulating in condenser tubes (shell side). The water circulating through the condenser tubes is cooled in dry cooling towers passing air over finned tube heat exchangers. Either mechanical draft or natural draft towers are used to pass air through the heat exchanger. Figure 23 indicates an indirect dry cooling system with a mechanical (induced) draft tower.

Indirect dry cooling systems use an intermediate loop between the condenser and the environment, decreasing efficiency but increasing the operator's control over the process. This allows for rapid corrections to achieve optimal condensation rates and generator back pressure by simply adjusting the flow in the intermediate loop, making indirect dry cooling more suitable for larger applications. Due to decreased thermal efficiencies, however, the overall cost of these systems is even higher.

Indirect dry cooling has another advantage, however, in that the cooling system can be moved farther from the generator building. In direct dry cooling, the system must be immediately adjacent to the generator building, due to the difficulty in transporting high temperature exhaust steam without leakage. The secondary loop in indirect dry cooling, however, is at atmospheric pressure, and can easily be stretched away from the main body of the power plant. This allows indirect dry cooling to use natural draft towers, where the natural forces of convection create airflow without using expensive fans. The massive cooling towers used to create the draft needed for dry cooling are expensive compared to similar wet systems [17].

Around the lower circumference of the natural draft towers are vertical plate-fin all-aluminium heat exchangers housed in galvanised steel frames. Each pair of heat exchangers forms a V, with the opening of the V facing outwards, and they are in parallel connected sectors. The heat exchangers are usually of the cross-counter-flow type, with the inlet/outlet header at the bottom and the return header at the top. They are built up from tube arrays joined by common rectangular plate fins, with spring-type contact between tubes and fins ensured by mechanical expansion of the tubes during array manufacture. The fins have a protruding pattern to intensify air-side heat transfer. Sector ring pipes distribute and collect heat exchanger cooling water close to the ground, while vent ring pipes with tall standpipes protruding inside the tower ensure that the heat exchangers stay pressurised, or if necessary, can be quickly drained. The natural draft towers are equipped with louvers for air flow control. The system has no minimum steam flow requirement.

Heller system

An alternative approach to dry cooling is represented by the Heller system, named after its developer, H. Heller in Hungary in the 1940s. The system is similar in approach to the indirect dry cooling system, which uses
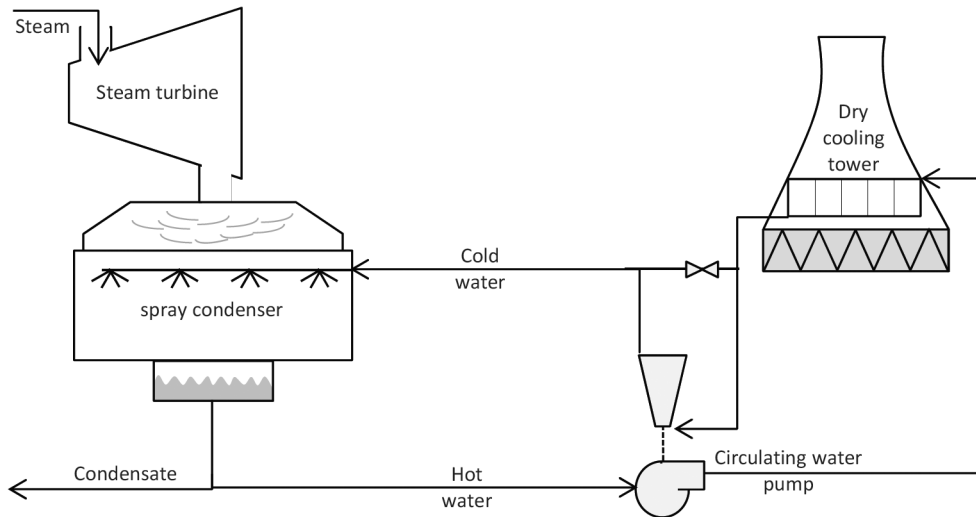
FIG. 24. Schematic diagram of Heller cooling system with natural draft cooling tower.

an intermediate water circuit between the steam turbine condenser and the dry cooling tower, with notable differences. The steam condenser is a direct contact (DC) jet or spray or barometric condenser in which the exhaust steam condenses on the surfaces of sprayed droplets and films of cool water thus virtually eliminating any terminal temperature difference between condensing steam and cooling water. The resulting mixture of condensate and heated cooling water is then pumped to an air-cooled heat exchanger where it is cooled and returned to the condenser. The system is shown schematically in Fig. 24. A portion (~3%) of the circulating water is drawn off from the hot side of the loop and returned to the power cycle as boiler feed water. With the Heller system the cooling water flow rate is roughly 50 times that of the condensate. This is comparable with that of a once-through or evaporative system. In the Heller system this cooling water, which is of condensate quality, circulates in an intermediate circuit between the point where condensation takes place and the heat sink where its enthalpy gain is transferred to the ambient air via water to air heat exchangers. A key benefit of the Heller approach is that it widens the applicability of dry cooling. This is important with the ever increasing pressure to reduce water consumption, while at the same time keeping power plants competitive.

The air cooled heat exchanger is normally designed as a natural draft unit in order to reduce auxiliary power requirements, although systems with mechanical draft or fan assisted natural draft units exist. Additionally, the process side of the air cooled exchangers is operated slightly above atmospheric pressure in order to eliminate the risk of air in-leakage so the water from the condenser must be pumped up through a head of approximately one atmosphere. To reduce the auxiliary power required, the cooled water is returned to the condenser through a work-recovery turbine. The system is shown schematically in Fig. 24. Generally, 30–35% of the circulating power is provided by the recovery turbine. It is usually needed on Heller systems employing the DC jet condenser, but its use also depends on the difference in elevation between the site of the cooling tower and the turbine hall.

Cooling water enters the condenser through a side-mounted distribution header. Rows of nozzles mounted on the sides of an array of A-shaped distribution chambers serve to produce the water films. The widening neckpiece usually accommodates a number of devices such as bypass spargers, the bleeding train of the first low pressure (LP) heater, and a curtain spray (for bypass operation). Below is the integrated hot well, with large water volume, from which the circulating water (CW) pumps — in certain cases also the condensate booster pumps — take suction.

The condenser is of simple carbon steel construction and has a volume under vacuum comparable with surface condensers. This makes hogging (initial air evacuation) fast and holding of the vacuum easy. The air evacuation devices employed are conventional, either steam jet ejectors or water ring mechanical vacuum pumps. The condenser is available in several versions for all kinds of turbine exhausts: vertical (downward, or even upward); lateral; and axial.

Depending on unit size, two or three identical circulating machine groups are located in a pit close to the condenser. A circulating machine group consists of three machines with their shafts coupled together: medium voltage electric motor; CW pump; and a pressure head recovery hydro-turbine. The pump is usually double suction,

low speed, since it takes suction from vacuum, and the turbine can be of either the Francis or Kaplan type, with, in recent installations, electric inlet vane control.

The cooling tower may be either natural draft or mechanical draft, the latter being applied in the case of smaller plants, unusual and/or restricted plot shapes, sites where visual impact must be minimal or locations with extreme (arctic) weather conditions.

3.2.3. Hybrid cooling

Dry and wet cooling systems have been developed to save water in arid regions while avoiding the high cost of full dry cooling systems and ensuring low process fluid temperatures where necessary. This system is also used to maintain turbine output close to design even under peak ambient air temperatures during summer months. There are a variety of ways to use a modest amount of water to enhance the performance of air cooled condensers for those limited periods of the year during which the ambient temperature and the power demand are simultaneously high.

Conventional approaches use hybrid systems (i.e. single cooling towers having wet and dry sections) or independent dry and wet cooling tower systems where the heat is rejected through two separate cooling systems. A dry system will dissipate most or the entire condenser heat load during non-peak summer months. The wet system will dissipate a portion of the heat load during the peak summer months, when the performance of the dry system is limited. These hybrid systems or dry and wet cooling systems come in many different arrangements and designs.

The performance of dry cooling towers (for both normal dry and Heller cooling systems) can be further enhanced by using either deluge cooling or inlet air cooling.

Deluge cooling is used for performance enhancement in conjunction with all-dry, direct systems in which all the steam is condensed in an air cooled condenser. The hot-day performance is enhanced by the use of water either to increase the heat transfer rates from the finned tube bundles (known as deluge cooling) or to pre-cool the inlet air. The performance of a dry cooled system is enhanced during periods of high ambient temperature and/or high cooling demand by deluging the air side of the heat transfer surface with water. The rate of heat transfer can be increased by a factor up to five by deluging the air –side surface of the heat exchanger compared to a dry-cooling system, 60 m^3/h deluging water will increase the output of a 100 MW(e) unit by more than 2 MW(e) compared to dry operation for an ambient temp of 38°C.

In deluge cooling systems, water is introduced onto the finned side of the air cooled condenser tubes. In this arrangement, the tubes are horizontal and the fin surfaces are vertical. The water runs down the fins in a film with the air moving in cross-flow across the outer surface of the film. It transfers heat from the fin surface to the water film, conducting it through the film and rejecting it to the atmosphere through evaporation of the water at the outer surface of the film. It derives enhanced performance from both the higher heat transfer coefficient at the fin surface (compared to a dry fin rejecting heat to flowing air) and the temperature of the water in the film being lower than the ambient air.

Another option to enhance the performance is by pre-cooling air. In these systems water is introduced into the inlet air stream of the air cooled condenser. The water evaporates, reducing the air temperature to the finned tube bundles. The greatest temperature reduction theoretically achievable with this method is equal to the wet bulb depression, defined as the ambient temperature minus the ambient wet bulb temperature ($T_{amb} - T_{amb \; wb}$). In practice, only some fraction of that amount of cooling will be realized. There are two approaches for the design of these systems:

— The first is to use inlet matrix or packaging, where the opening around the perimeter of the air cooled condenser is fitted with panels of a mesh or matrix material through which the air can pass with minimum resistance and which can hold water in contact with the air stream. In some designs, the water enters at the upper edge of the panel and trickles down through the material while the air flows through the panel in cross-flow with the water. The system collects any un-evaporated water at the bottom of the panel and re-circulates it. Alternatively, the system can spray water on the upstream face of the panel and retain it in the matrix as the air flows past it. Systems of this type have been used for inlet air cooling on gas turbines and in agricultural applications, such as maintaining cool conditions in poultry sheds.

— The second option is to use inlet spray cooling. This approach involves the spraying of a small amount of water into the inlet air stream where it evaporates and cools the air. Gas turbine inlet cooling and some process air cooling applications have used spray systems [18].
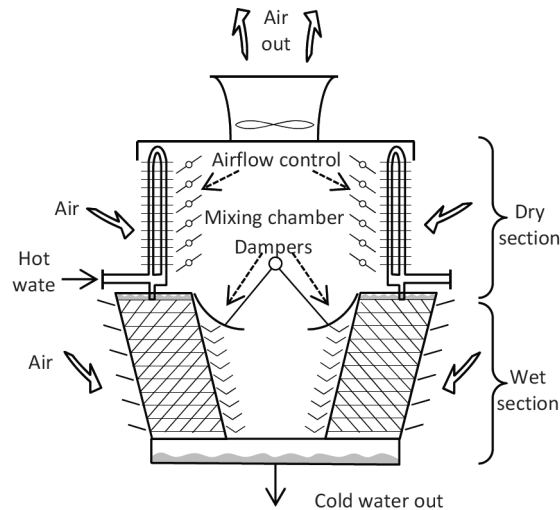
FIG. 25. Schematic diagram of plume abatement hybrid (wet and dry) cooling tower.
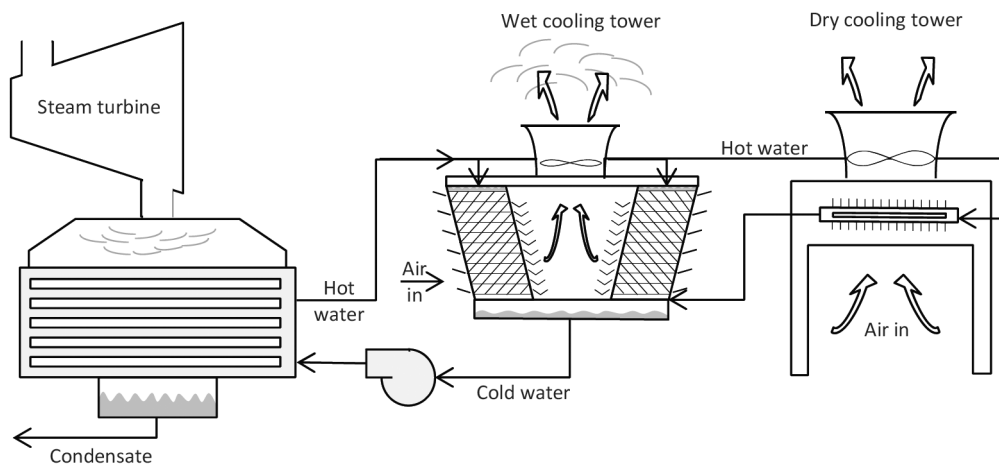
FIG. 26. Parallel connected dry and wet cooling systems employing a combined indirect cooled surface condenser.

While these systems can achieve significant water conservation and still maintain good hot-day performance, they can have high initial costs as a result of the need for two cooling towers (or a more complex integrated single structure), parallel circulating water loop components, more complex controls, and other requirements associated with providing two, nearly independent cooling systems.

Hybrid dry and wet cooling has also been used for plume abatement, reducing the vapor exhaust to avoid potential foggy or icy conditions on nearby roadways, but these systems do not emphasize water conservation. It is a mainly wet system, with just enough dry cooling added to reduce the relative humidity of leaving air from the cooling tower. A schematic diagram of plume abatement hybrid (dry and wet) cooling tower is shown in Fig. 25.

Dry and wet cooling systems are commercially used in power industry to conserve water by maintaining turbine back pressure within specified limits even under peak summer months. Some typical examples are described in the following sections.

3.2.3.1. Parallel connected dry and wet system with indirect cooled condenser; i.e. surface condenser

Parallel connected dry and wet cooling systems employing a combined indirect cooled surface condenser is shown in Fig. 26. In this circuit, a single surface condenser is cooled by dry and wet cooling systems in parallel. The dry cooling tower can be either natural draft or mechanical draft. Dry and wet cooling towers are sized considering technoeconomics in terms of saving of water consumption, capital and operating costs so that turbine output is maintained at rated capacity even under summer month atmospheric conditions. Normally the wet cooling tower is
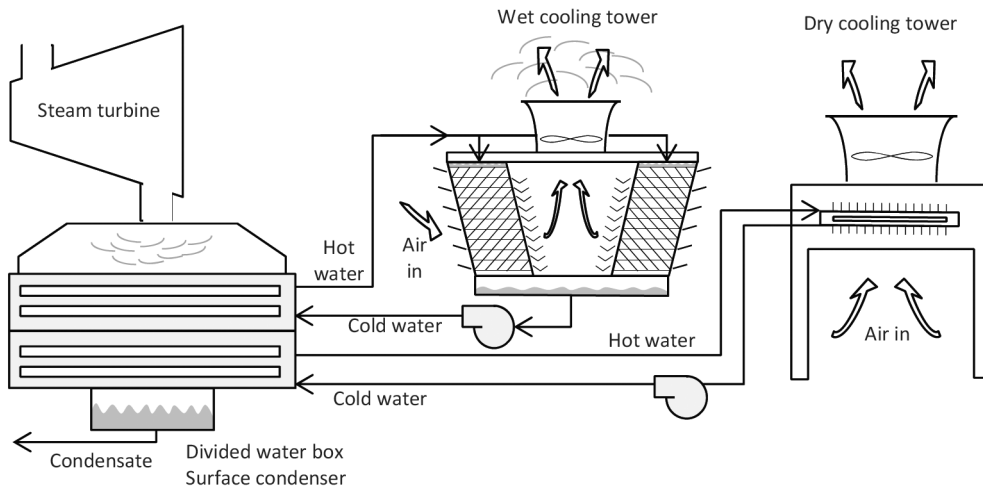
FIG. 27. *Schematic diagram of parallel connected dry and wet cooling systems.*
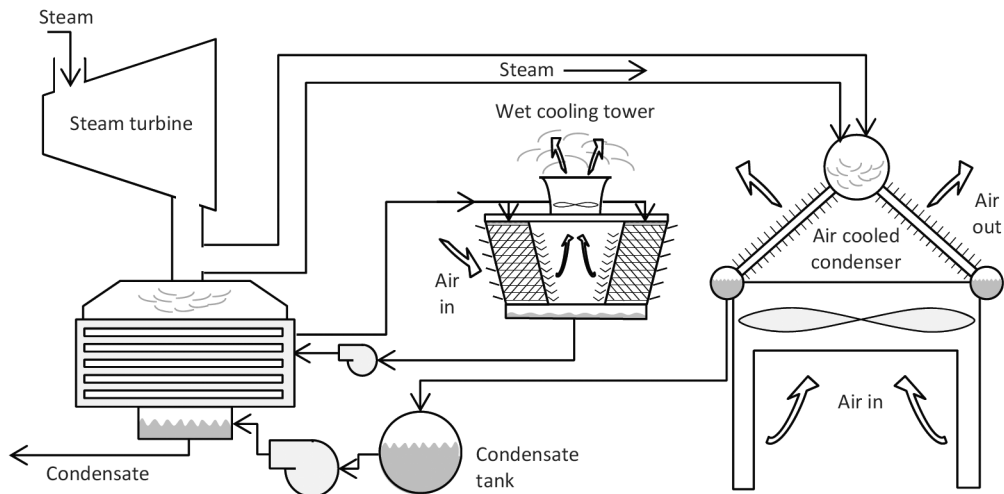
FIG. 28. *Schematic diagram of parallel connected dry and wet system with direct cooled air condenser and indirect cooled surface condenser.*

designed to meet additional heat sink requirements during summer months, and so during other seasons the wet tower will not be operating.

A parallel connected dry and wet cooling system employing an indirect cooled split surface condenser is shown in Fig. 27. In this system, both dry and wet cooling circuits are independent.

3.2.3.2. *Parallel connected dry and wet system with direct air cooled condenser and indirect cooled surface condenser*

A parallel connected dry and wet system with direct air cooled condenser (ACC) and indirect cooled surface condenser (SC) scheme is shown in Fig. 28. In this system turbine the exhaust steam is bifurcated into two streams, one stream is sent to the air cooled condenser and the other stream is sent to the surface condenser. The air cooled condenser is cooled by dry cooling using either a natural draft tower or a mechanical draft tower. The surface condenser is cooled by wet cooling using a mechanical draft tower. The ratio of dry and wet cooling is derived from technology-informed economics so that plant output can be maintained the same with minimum water consumption during summer months.
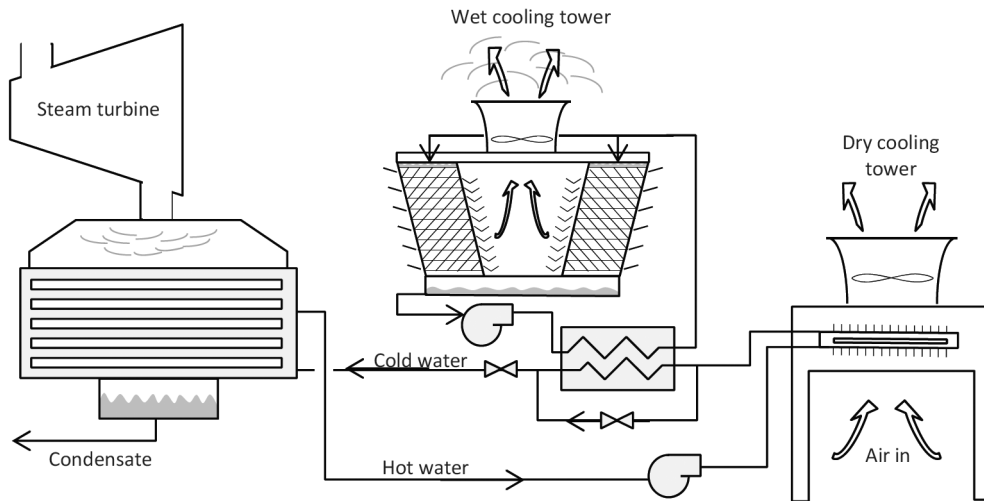
FIG. 29. Schematic diagram of serially connected dry and wet system with surface condenser.
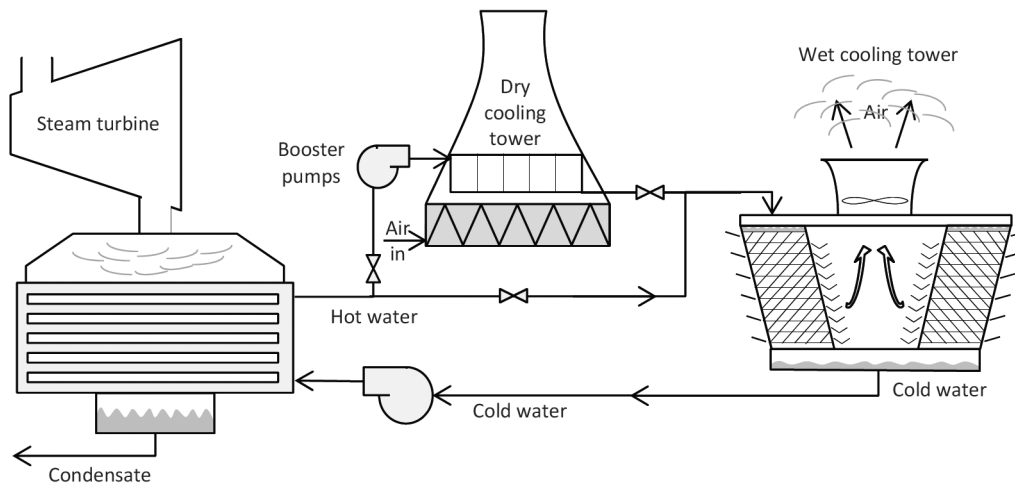
FIG. 30. Schematic diagram of single circuit serially connected dry and wet system.

3.2.3.3. Serially connected independent dry and wet systems with surface condenser

A serially connected dry and wet system with a surface condenser scheme is shown in Fig. 29.

In this system hot water drawn from the surface condenser is first cooled in a mechanical draft dry cooling tower and subsequently the same water is passed through heat exchangers to be cooled further using a wet cooling tower. Whenever the dry cooling tower outlet water temperature is within the operating range of the condenser then the wet cooling tower will not be operated. During summer months by operating the wet cooling tower, the condenser inlet water temperature is brought down so that turbine output can be maintained as designed or can be operated with minimum reduction in output.

3.2.3.4. Single circuit serially connected dry and wet system with surface condenser

To reduce the plant efficiency loss with a dry cooling circuit and an indirect cooled surface condenser, a wet cooling circuit is provided in series. The schematic diagram of the circuit is shown in Fig. 30. Hot water from the condenser is first cooled in a dry cooling tower and then it is further cooled in a wet cooling tower to achieve the desired re cooled water temperature at condenser inlet. In this system both dry and wet systems require large towers. An example of this type of system is found operating at the 500 MW(e) San Juan power plant in New
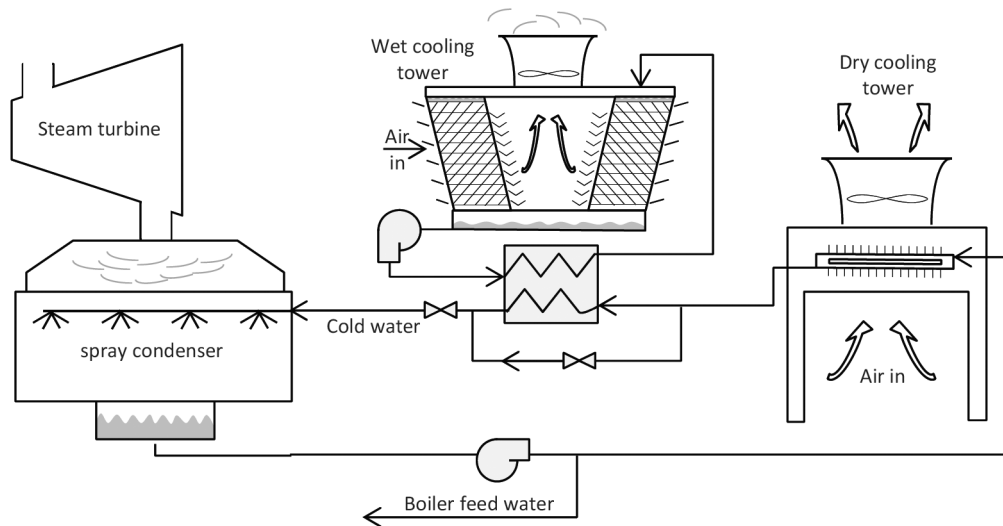
FIG. 31. Schematic diagram of serially connected dry and wet system with direct cooled jet condenser.
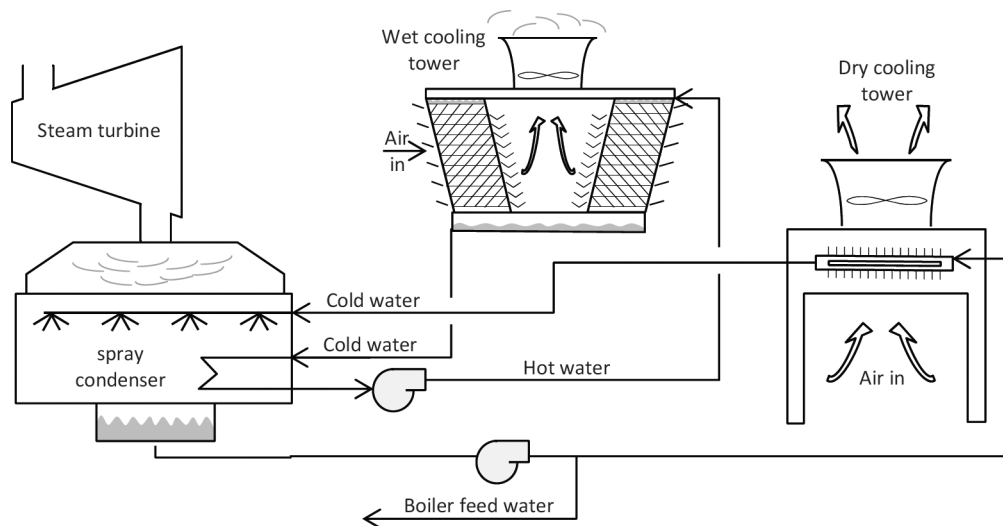
FIG. 32. Schematic diagram of parallel connected dry and wet system with combined condenser.

Mexico, consisting of two induced draft cooling towers. Each tower consists of five cells and each cell contains sixteen air cooled heat exchanger modules and two evaporative sections.

3.2.3.5. Serially connected dry and wet system with direct cooled jet condenser

The schematic diagram for this system is shown in Fig. 31. Part of the demineralized water drawn from the direct cooled jet condenser is pumped through a dry cooling tower and cooled further in series through a heat exchanger using a wet cooling tower before returning to the direct condensing (DC) jet condenser. This method eliminates or reduces power loss during summer months due to dry cooling. Water consumption can also be reduced 95–98% of the requirement of a total wet cooling system.

3.2.3.6. Parallel connected dry and wet system with combined condenser

To reduce the plant efficiency loss with a dry cooling circuit, a direct cooled jet condenser and a surface condenser can be combined together in a single condenser and they are provided with independent dry cooling and wet cooling respectively. In both dry and wet sections either mechanical draft or natural draft cooling towers are used. The schematic diagram of this system is shown in Fig. 32.
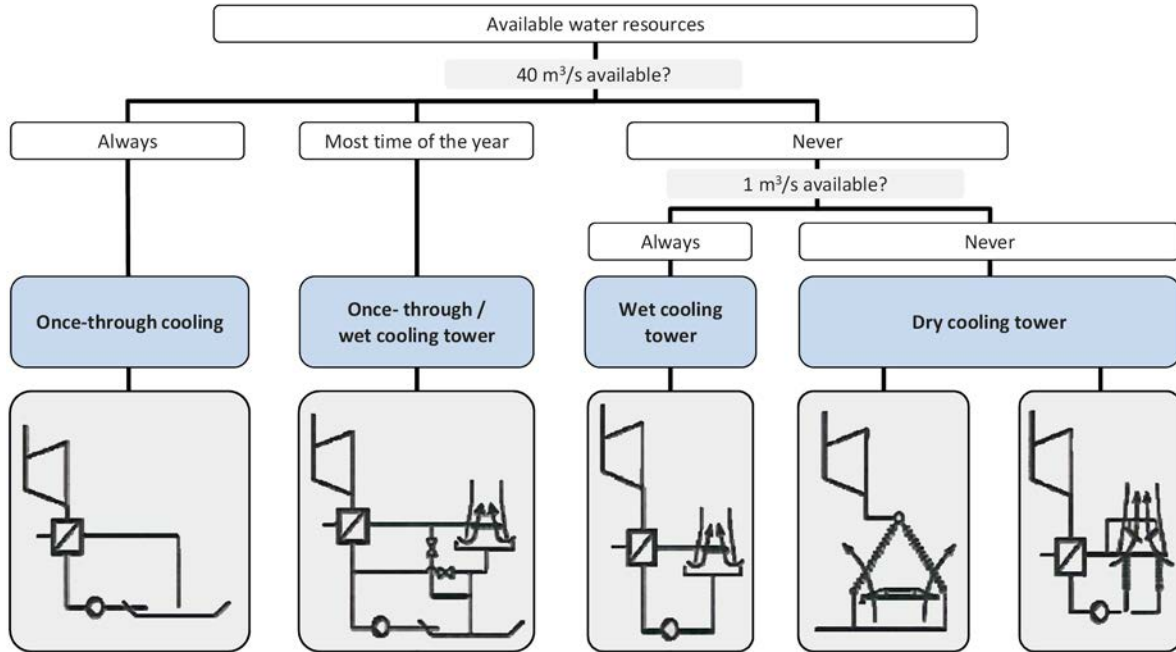
FIG. 33. Cooling system selection based on available water resources.

3.3. BASIS FOR SELECTION OF COOLING SYSTEMS

Cooling system selection is controlled by a number of factors — some physical/economical and some legal/political.

3.3.1. Physical and economic factors

To reach the best plant efficiency, the turbine condenser vacuum should be as low as possible. As an optimum, the cooling water temperature remains constantly low year round. This requirement can best be fulfilled by using sea water, which offers low temperature variations between winter and summer time and a very large reservoir for water withdrawal. Therefore, conceptually once-through cooling is the preferred cooling approach for thermoelectric power plants. It uses the least amount of equipment, is simple, has low capital and operating costs, consumes the least water and offers the greatest thermal efficiency. However cooling water is often limited by the capacity of possible water withdrawal and the allowed heat-up gradient.

In the cases that water resources are not abundant, alternatives such as partly or totally closed loop cycles with cooling towers need to be applied. Closed cycle cooling results in reduced water withdrawal and reduced heat rejection to water bodies associated with the power plant. Water is required to replace evaporation and drift losses as well as for blow-down for impurity control. Water withdrawal from adjacent bodies of water for plants with closed cycle cooling systems is 5–10% of that for plants with once-through cooling systems [8]. Plant efficiency is reduced because the heat sink temperature is higher and plant power is required to operate the cooling tower fans. In case of closed loop dry re-circulating cooling system, no water is used to cool the steam in the condenser back down to water. Instead, air blown by fans causes a transfer of heat from the condenser to the ambient air. Compared to wet cooling towers, however, dry cooling towers involve higher operating costs, require more electricity, occupy a larger footprint, have lower performance, and entail higher capital costs [6].

Example for decision making based on available site cooling water for a typical 1000 MW(e) plant with cooling water temperature rise of 12°C shown in Fig. 33.

The annual water consumption of all dry cooling systems is shown in Fig. 34, the Heller cooling system with deluge (water spray) system, Heller cooling system with dry and wet system and plume abatement wet and dry hybrid system, relative to an all wet system.
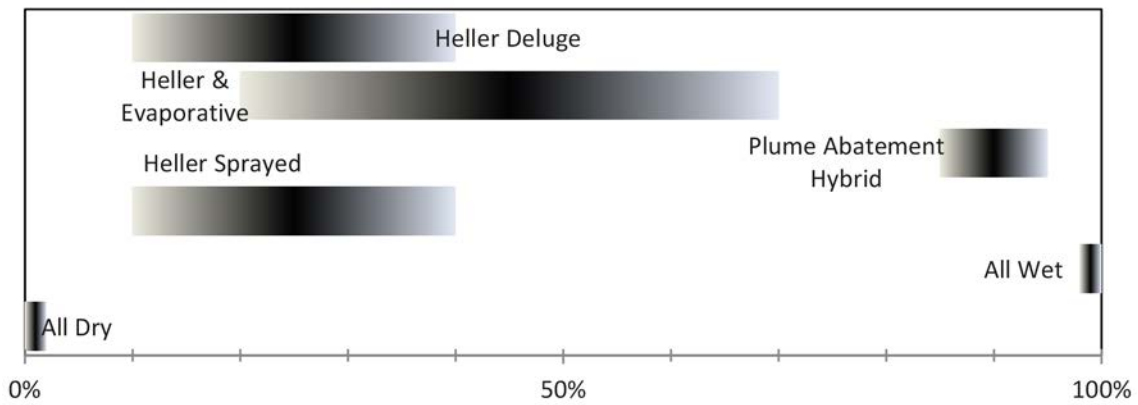
FIG. 34. Annual water consumption of dry and hybrid cooling systems relative to all wet system.

The achievable cooling water temperatures are somewhat higher for closed loop cooling tower systems as the evaporative process is restricted to the ambient air conditions. Furthermore cooling towers are directly exposed to the daily temperature variation influencing by that the turbine performance. These influences lead to a higher condenser pressure and hence to a slightly lower pressure difference at the turbine resulting in a lower electrical output.

From an economical point of view the selection of an appropriate cooling system comes from the comparison of different cooling systems such as closed loop wet system, closed loop dry system, Heller system and dry and wet system. For closed cooling systems, to achieve the highest efficiency for the plant, the operation usually tends to be as near as possible to the wet cooling principle as the environmental restrictions allow. So the water consumption is determined by the evaporation losses via the wet cooling section to the atmosphere, and depends on the operating performance. A series of calculations of life cycle costs is carried out, taking into account the investment costs, the difference in annual generation due to differences in technical features, operation and maintenance costs, replacement energy costs due differences in availability, and total water costs (sourcing, pumping, treatment, evaporation loss, blow-down disposal), assuming a given economic environment (plant economic lifetime, interest rate, inflation). A comparison of present values determines the viability of wet or dry (air cooled condenser) cooling options, resulting in an envelope diagram where areas divided by a border line represent viable cooling options, telling us which one to apply for different electricity and water prices. Basically, the application of the Heller indirect dry cooling system pushes the border line 'downwards' i.e. extends the viability of dry cooling to higher electricity prices at a given water price, or, looked at another way, at a given electricity price, makes dry cooling viable at lower water costs. As a rough estimate it can be assumed that initial capital costs requirements for dry cooling range from five to ten times those for wet cooling. Significant operating power penalties (four to six times greater for dry cooling) are also incurred [19].

3.3.2. Legal and political factors

From a regulatory point of view, the use of once-through cooling has been limited or prohibited on the basis of environmental issues including thermal discharge plumes, cooling water intake issues of entrainment and impingement and in-stream flow maintenance. Some governments place restrictions on the amount of heat that can be discharged to cooling water bodies and/or there are sensitive flora/fauna that need to be protected from the non-thermal effects of the power plant [20].

The Indian government has promulgated the following requirements for new generating facilities: "Temperature limit for discharge of condenser cooling water from thermal power plant:"

— New thermal power plants commissioned after June 1, 1999: New thermal power plants, which will be using water from rivers/lakes/reservoirs, shall install cooling towers irrespective of location and capacity. Thermal power plants which will use sea water for cooling purposes, the condition below will apply;

— New projects in coastal areas using sea water: The thermal power plants using sea water should adopt suitable system to reduce water temperature at the final discharge point so that the resultant rise in the temperature of receiving water does not exceed 7°C over and above the ambient temperature of the receiving water bodies;
— Existing thermal power plants: Rise in temperature of condenser cooling water from inlet to the outlet of condenser shall not be more than 10°C;
— Guidelines for discharge point: The discharge point shall preferably be located at the bottom of the water body at midstream for proper dispersion of thermal discharge;
— In case of discharge of cooling water into sea, proper marine outfall shall be designed to achieve the prescribed standards. The point of discharge may be selected in consultation with concerned state authorities/NIO;
— No cooling water discharge shall be permitted in estuaries or near ecologically sensitive areas such as mangroves, coral reefs/spawning and breeding grounds of aquatic flora and fauna [21].

Table 11 presents the European Union thermal regulations for rivers within the Union [22].

Similar restrictions were applied in the United States of America. Argonne National Laboratory (US-ANL) reports "virtually all new steam electric units built in the United States since the mid-1970s have used closed cycle cooling, and most of those have used cooling towers" [23]. Federal and local regulations in the USA make it highly unlikely that new NPPs will utilize once-through cooling.

Some of the NPPs in the USA, that are undergoing the license renewal process (where the original 40 year operating license is renewed for an additional 20 years), are being required to replace the existing once-through cooling system with cooling towers. No final decisions have been reached for those NPPs; the utilities contend that less expensive alternatives can be implemented [24].

The US Environmental Protection Agency (EPA) is currently developing revised regulations for power plant cooling water intake structures under 316(b) of the Clean Water Act which requires "the location, design, construction and capacity of cooling water intake structures shall reflect the best technology available (BTA) for minimizing adverse environmental impact". EPA is considering technology-based aquatic life protection performance standards that may require closed cycle cooling as BTA for existing thermoelectric facilities [7].

As an example, California (USA) has established a timetable for all existing power plants to come into compliance with the requirements of US EPA 316(b) (which basically prohibits once-through cooling systems). California Coastal Act requires the following to be considered when evaluating power plant cooling system options.

— The compatibility of the proposed site and related facilities with the goal of protecting coastal resources;
— The degree to which the proposed site and related facilities would conflict with other existing or planned coastal-dependent land uses at or near the site;
— The potential adverse effects that the proposed site and related facilities would have on aesthetic values;
— The potential adverse environmental effects on fish and wildlife and their habitats;
— The conformance of the proposed site and related facilities with certified local coastal programmes in those jurisdictions, which would be affected by any such development;
— The degree to which the proposed site and related facilities could reasonably be modified so as to mitigate potential adverse effects on coastal resources, minimize conflict with existing or planned coastal-dependent uses at or near the site, and promote the policies of this division;
— Such other matters as the Coastal Commission deems appropriate and necessary to carry out this division" [25].

TABLE 11. TEMPERATURE LIMITS FOR RIVER AND LAKES IN EUROPE

	Salmonidae water[1]	Cyprinidae water[2]
Allowed heat up (°C)	1.5 °C	3°C
Limit temperature (°C)	21.5	28

[1] Fish like salmon and trout.
[2] Fish like pike and eel.
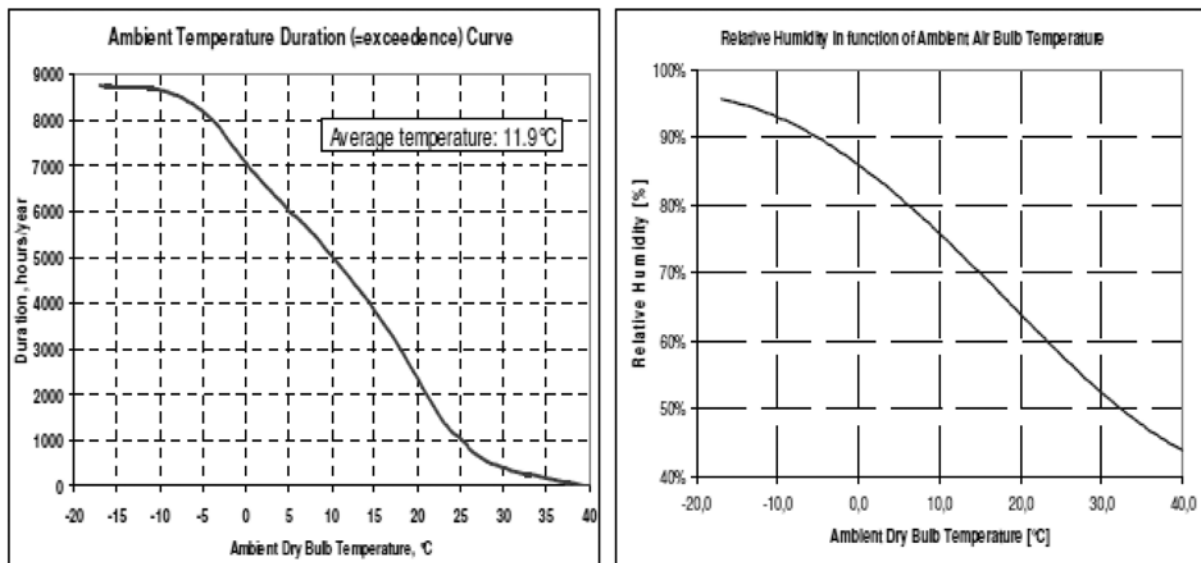
FIG. 35. Ambient DBT vs duration in a year and ambient DBT vs RH.

Special consideration is being given to the NPPs in California in recognition of their positive contribution to the reduction in greenhouse gases. Factors like energy cost, engineering constraints, space constraints, permitting constraints, and public safety considerations along with potential environmental impacts are examined [26].

The US-ANL report states: "Therefore, one must conclude that in those instances where dry cooling is selected — which has occurred with increasing frequency in the USA and worldwide in recent years — the choice is driven by other considerations such as severe water use limitations at otherwise preferred sites, environmental pressures, and the avoidance of licensing delays" [20].

3.3.3. Case studies

A comparison of different recirculation (closed loop) cooling systems made by GEA EGI Contracting/Engineering Co. Ltd is presented in the following case studies:

3.3.3.1. Case study 1: 800 MW(e) combined cycle gas turbine plant

The following site conditions were considered:

— Site elevation: 200 m;
— Annual mean dry bulb temperature (DBT): 11.9°C;
— Dry bulb temperature range: –17°C–40°C;
— Design point ambient dry bulb temperature: 15°C;
— Design point ambient relative humidity (RH): 70%.

DBT duration (exceedence) curve and assumed correlation between ambient dry bulb temperature and relative humidity are shown in Fig. 35.

Thermal evaluation of various dry, wet and wet and dry cooling systems considered for 800 MW(e) combined cycle gas turbine at design condition and net power output per year round operation considering ambient temperature variations are indicated in Table 12. This table also indicates water consumption at design condition and yearly consumption for various cooling systems.

TABLE 12. THERMAL PERFORMANCE AND MAKE-UP WATER CONSUMPTION OF VARIOUS COOLING SYSTEMS CONSIDERED FOR CASE STUDY (800 MW(e) CCGT PLANT)

Thermal data	Var. A	Var. B	Var. C	Var. D	Var. E	Remarks
	Heller dry	Heller sprayed. No spray at design temp.	Heller wet assisted only one coil at design temp.	Direct ACC	Wet cooling tower	
(a) At design point DBT 15 ^{0}C/RH 70%						
Turbine back pressure (mbar)	84.8	84.8	79.1	84.8	59.4	
Overall ITD at design point (^{0}K)	27.62	27.62	26.30	27.62	24.17 (refers to WBT)	ITD = Sat.steam temp. at turbine exhaust minus amb. air temp.
Gross turbine output (MW(e))	276	276	278.39	276	283.25	
Heat to be dissipated (MW(e))	455.5	455.5	453.11	455.5	448.25	
Cooling system auxiliary power MW(e))	2.4	2.4	2.83	4.9	5.7	Var C single cell operation
Net turbine output (MW(e))	273.6	273.6	275.56	271.1	277.55	Gross turbine output reduced by the aux. power of the cooling system
Make-up water consumption (m^3/hr)	n.a	n.a	41	n.a	656	
(b) Year round results for 7008 hours operation per year						
Annual net electricity generation (GW·h/year)	1911.324	1914.442	1930.045	1881.921	1956.283	Only cooling system auxiliary consumption deducted from gross electricity.
Average net output (MW(e))	272.3	273.18	275.41	268.54	279.15	
Annual make-up water consumption (m^3/year) and % of wet system	n.a	56007 (1.28%)	373206 (8.5%)	n.a	4388749	Var. C — single cell operation at DBT > 13°C & 2 cell operation at DBT > 16°C. Var. B — Spraying applied DBT > 30°C
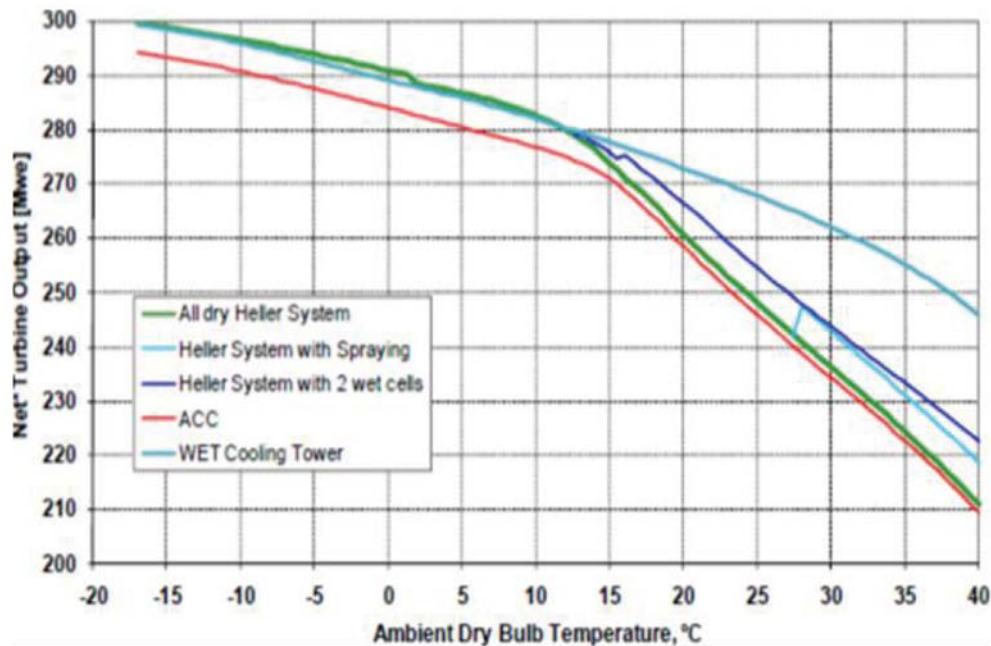
FIG. 36. Net turbine output vs ambient dry bulb temperature for various cooling systems in 800 MW(e) CCGT plant.

The various alternative cooling systems compared are:

— Heller cooling system consisting of direct cooled jet condenser, water to air cooled heat exchanger (HX) within/peripheral to natural draft cooling tower (Fig. 24);
— Heller cooling system consisting of direct cooled jet condenser, water to air cooled heat exchanger within/peripheral to natural draft cooling tower with provision of supplementary deluge system; i.e. water spraying on air cooled HX (Fig. 24);
— Heller cooling system consisting of direct cooled jet condenser, water to air cooled heat exchanger within/peripheral to natural draft cooling tower with provision of two parallel wet induced draft (mechanical) cooling tower two cells (Fig. 32);
— Direct air cooled condenser with forced draft fans (Fig. 22);
— Wet cooling system consisting of induced draft cooling tower (Fig. 23).

The net turbine output variation corresponding to ambient dry bulb temperature for each cooling circuit considered for the case study (800 MW(e) CCGT plant) is shown in Fig. 36.

Thermal and environmental impacts of various cooling systems considered in this case study (800 MW(e) CCGT plant) are summarized as follows:

— From Table 12 and the net turbine output graph (Fig. 36), it is observed that the best output is obtained with the all wet cooling system and the least water consumption and lowest output is obtained with the air cooled condenser system. On a yearly basis an air cooled condenser (ACC) system can generate 96.2% of wet system output without any consumption of water. By adopting the Heller system with 2 wet cells, the plant can achieve a net output of 98.66% of that for the wet system with 8.5% of wet system water consumption. There will be only 1.34% of net output loss with a reduction of 91.5% water consumption in comparison to the all wet cooling system.
— The power cycle equipped with an all-dry Heller system generates 1.56% more electricity on year-round basis than the same unit equipped with direct ACC.
— It corresponds to the same percentage reduction in pollutant emission (SO_2, NO_x and CO_2) in the case of equal electricity production.

— Compared to wet cooling, the annual electricity generation with dry Heller is smaller by 2.3%, which is reduced to 1.3% with a wet assisted Heller system at a cost of only 8.5% of the annual water consumption of the all wet system.

3.3.3.2. Case study 2: WWER-1000 nuclear power plant

WWER-1000 nuclear power plant was considered for comparison of plant performance with all dry cooling system and dry and wet cooling system. The main design data of the nuclear power plant are presented in Table 13.

A comparison for all-dry cooling system and dry and wet combined system is presented in Fig. 37 for condenser cooling water inlet temperature vs. ambient air temperature. From this graph it is clear there is a 5°C temperature reduction in condenser inlet water temperature when ambient air temperature exceeds 20°C by adapting dry and wet cooling system instead of pure dry cooling system. This difference reduces as ambient temperature becomes lower than 20°C.

TABLE 13. NUCLEAR POWER PLANT DESIGN DATA FOR CASE STUDY 2

Design parameters	Design type	
	All–dry cooling system	Dry–wet cooling system
Dry bulb inlet air temperature, °C	7	30
Relative humidity (assumed) %	80	46
Site elevation above sea level, m	745	745
Heat to be dissipated, MW(th)	1954	1954
CW flow rate, t/h	132 000	136 000
Warm water temperature, °C	34.1	52.68
Cold water temperature, °C	21.37	40.32
Pressure drop on towers, mbar	≈8	<8
Water evaporation, t/h	Practically zero	627
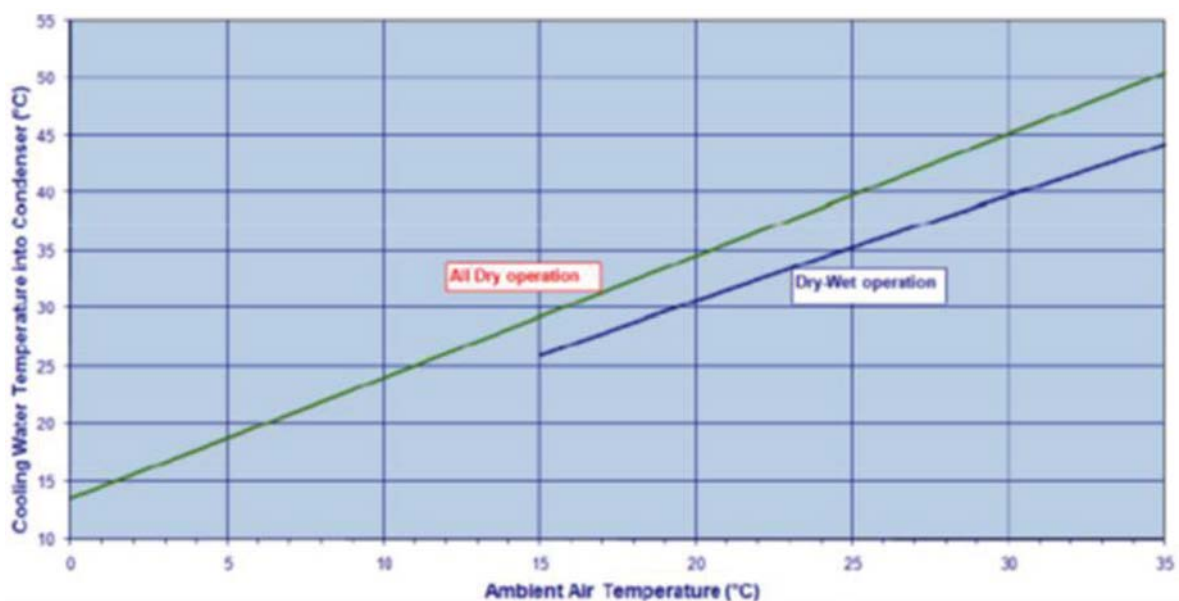
FIG. 37. Thermal characteristics of all dry and dry and wet cooling system.

Pressure in the turbine exhaust (condenser pressure) with respect to ambient air temperature is presented in Fig. 38 for all-dry cooling system and dry and wet cooling system. There will be an increase in turbine back pressure in all dry cooling system plant due to higher ambient temperature condition in summer months causing reduction in power generation. By adopting dry and wet cooling systems, the increase in turbine back pressure can be reduced to 0.05 bar at 35°C ambient air conditions compared to dry cooling system by utilizing nominal amount of make-up water. Correspondingly loss of power generation also can be minimized.
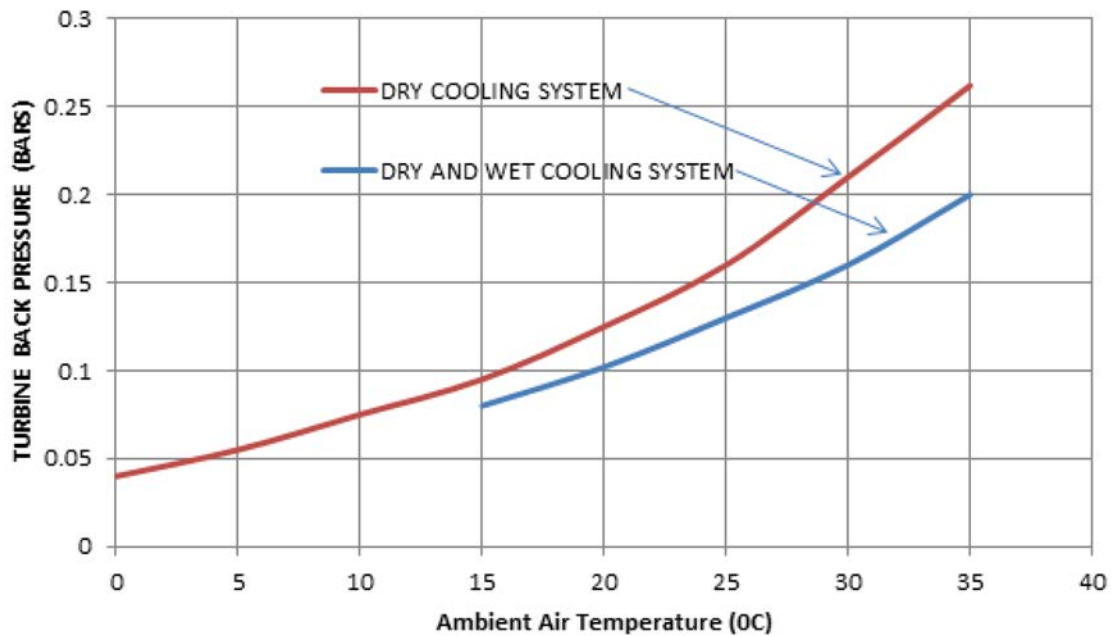
FIG. 38. Turbine back pressure vs ambient air temperature for dry and dry + wet cooling system.

FIG. 39. Bayswater power station (4 × 660 MW) New South Wales, featuring natural draft evaporative cooling tower.

3.4. EXAMPLES OF POWER PLANTS OPERATING WITH WET DRY OR HYBRID COOLING SYSTEMS

3.4.1. Wet cooling examples

As discussed before, wet cooling plants need to be close to a natural water body. The water lost via evaporation is visible in the form of plume. Figure 23 shows the actual four 660 MW(e) Bayswater power stations operating with natural draft evaporative cooling towers.

Table 14 shows the distribution of once-through, closed loop wet cooling systems and combination of both employed in some nuclear power plants.

A significant exception is the Palo Verde nuclear generating station in the USA which is currently the only NPP in the world not located on a natural water body. It uses reclaimed wastewater from the community sewage treatment system for the metropolitan Phoenix, Arizona area located approximately 65 km from the plant. Experience has shown that reclaimed water can be chemically aggressive. Reclaimed water is also high in suspended solids. Palo Verde experienced vent valve plugging from dissolved solids, resulting in pump trip water hammers. A report entitled Use of Degraded Water Sources as Cooling Water in Power Plants, commissioned by the state of California, is a useful resource for a user considering reclaimed water as a water source [27].

US-ANL reports with respect to the United States of America experience:

"Reclaimed water represents a valuable water resource with many potential applications. As the power industry sites new plants or expands capacity at existing sites, it must identify sufficient supplies of water to cool the steam. Reclaimed water can help meet that need. About 50 power plants are currently using reclaimed water for cooling. Several of these are also using reclaimed water for air pollution control equipment like scrubbers. As more plants add scrubbers, the need for additional water will rise, too".

TABLE 14. COOLING TOWERS USED IN NUCLEAR POWER PLANTS
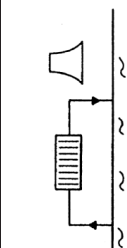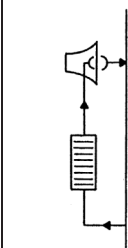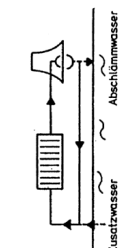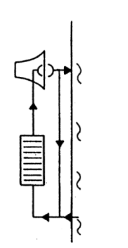
Plant	Reactor type	Cooling tower	Cooling tower operating modes			
			Once- through	Outlet cooling	Closed cycle	Mixed operation
Biblis A	LWR	X	X	Only at hot river temperature		
Biblis B	LWR	X	X	Only at hot river temperatures		
Grohnde	LWR	X			X	X
Philippsburg 2	LWR	X	X	X	X	X
Neckarwestheim 1	LWR	Cells	X	X	Short time	X
Philippsburg 1	BWR	X	X	X	Short time	X
Isar 1	BWR	X	X	X	Short time	X
Rajasthan 1and2 and Kaiga 1 to 4	PHWR		X-inland			
Madras 1and2 and Tarapour 3and4	PHWR		X-costal			
Kakrapara 1 and 2, Narora 1 and 2 Rajasthan –3 to 6	PHWR				X-inland	

FIG. 40. Actual picture of air cooled condenser with forced draft fan units at Pacific Corp Wyodak power plant, Gillette, Wyoming (Courtesy EPRI).

This report includes a database that identifies and describes power facilities in the USA that are using reclaimed water. Most of the examples are located in Florida, California, and Texas, all of which have dealt with freshwater shortages for many years. However, reclaimed water is being used throughout the country. Thirteen other states have facilities that are currently using reclaimed water. A few of the power plants have been using reclaimed water since the 1960s, although most began the practice since 1990 [23].

3.4.2. Dry cooling examples

Figure 40 shows an example of air cooled condensers that are used in direct dry cooling plants.

One illustrative example of the necessity to build a dry cooling system can be found in South Africa. The South African utility Eskom generates 95% of South Africa's electricity with a total generation capacity of 39 GW(e). This accounts for 45% of the continent's generation capacity. Eskom consumes approximately 2% of the country's freshwater resources [28]. Eskom uses dry cooling at many of its power plants and has two of the largest dry cooled power stations in the world. It is estimated that dry cooling saves 200 000 m^3/d that otherwise would have normally been lost through evaporation. Matimba coal power station, shown in Fig. 41 below, is the largest direct dry cooled station in the world (4000 MW(e)). Water consumption is about 0.1 L/kW·h of electricity compared to 1.9 litres on average for the wet cooled stations [29].

Kendall power station near Witbank in the Mpumalanga province is the largest indirect dry cooled power station worldwide, with a total of six 686 MW(e) turbines coupled with surface condensers (Fig. 42). Each unit is provided with natural draft cooling tower having 165 m height and 163 m base in diameter. It is equipped with 500 heat exchanger bundles arranged in concentric circles at the base of the tower. The total length of helically wound elliptical finned tubes is 2000 km per tower. It has a water consumption of about 0.08 L/kW·h of electricity sent out. Approximately 50 million cubic meters of water are saved annually in comparison to a wet cooling system. Visible steam emitted from the cooling towers is noticeably absent since with indirect dry cooling virtually no water is lost in the transfer of the waste heat [28, 30].

The amount of energy produced by Eskom's coal fired power stations over the period 1993 to 2004 has increased by 43%, while the corresponding increase in water consumption was only 27%. The commissioning of Kendal, Matimba and other dry cooled units since the late 1980s is the main reason for the organization's improved water efficiency. The cumulative saving is about 1 400 million m^3 of water over the period if compared to the quantity of water that would have been used if these power stations had been wet cooled [28].

FIG. 41. Matimba, 6 × 665 MW(e) coal power station.

FIG. 42. Kendall power plant, South Africa.

FIG. 43. Picture of Bilibino Nuclear power plant operating with dry cooling system.

The only dry cooled nuclear power station in operation in the world is Bilibino 4 × 12 MW(e) above the Arctic circle in Russian Federation (Fig. 43). In this plant dry cooling is provided to indirect cooled surface condensers to prevent any radioactivity release to atmosphere.

3.4.3. Hybrid (dry – wet) cooling example

Table 15 presents data from hybrid cooling system installations in world power plants.

3.5. CONCLUSION

Concerns over environmental impacts along with population growth in the more arid regions of the globe are driving the need for more water efficient cooling technologies. Until the last quarter of the twentieth century the traditional power plant cooling technology was generally once-through cooling. It resulted in a higher operating efficiency and lower construction and operating costs than alternative methods.

As the availability of cooling water has declined, either through regulatory restrictions or physical limitations, the trend has been to dry cooling towers.

Nuclear plant steam turbines needs efficient cooling as the maximum allowable turbine back pressure is lower than with thermal and combined cycle gas turbine plants. This restriction arises due to moderate live steam parameters, a large steam mass flow and wet turbine exhaust, large LP turbines and long last stage blades. Hence the application of all dry cooling systems for NPPs is not possible, only dry and wet cooling circuits in parallel or in series with indirect cooled surface condensers or direct cooled jet condensers are feasible. By using a wet cooling circuit, dry cooling circuit heat sink capacity can be augmented during high ambient dry bulb temperature conditions. With moderate use of make-up water, plant net output per year can be maintained very close to that for an all wet cooling circuit.

Table 16 summarizes the advantages and disadvantages of the major cooling technologies.

4. TECHNOLOGIES AVAILABLE FOR PRODUCTION OF INDUSTRIAL AND POTABLE WATER

This section presents some typical quantities of industrial/potable water required in nuclear power plants and provides an overview of the technologies available for production of water for industrial and potable water. The rationale that affects the technological choice in producing required water will be discussed. Desalination, another resource for supply of industrial and potable water is also presented.

TABLE 15. HYBRID COOLING SYSTEM INSTALLATIONS

Plant	Location	Capacity (steam) (MW(e))	Steam flow (tn/hr)	Turbine backpressure (bar)	Design T (°C)	Year installed
San Juan generating station, unit #3	New Mexico	550	1724	0.08	35 dry bulb 19 wet bulb	1978
Sempass WTE facility	New York	54	185	0.12	15	1986
Exeter energy L.P. Project	Connecticut	30	89	0.10	24	1989
Streeter generating station	Iowa	40	112	0.12	10	1993
Tucuman power station	Argentina	150	522	0.17	37	1997
Grumman TBG C0-Gen	New York	13	48	0.18	15	1997
Goldendale	Washington	110	307	0.15	32	Under construction

TABLE 16. SUMMARY OF DIFFERENT COOLING SYSTEMS

	ADVANTAGES	DISADVANTAGES
Once-through	Simple Uses least amount of equipment Low capital and operating costs Consumes the least water Greatest thermal efficiency	Thermal discharge plumes Cooling water intake Entrainment Impingement In-stream flow maintenance
Closed loop wet cooling	Reduced withdrawal rates Reduced entrainment/impingement Reduced thermal plumes	Decreased plant efficiency Higher capital cost Higher water consumption/evaporation Visible plume/drift emissions Wastewater treatment requirements Chemical treatment programmes Potential emissions of controlled air pollutants or pathogens Site space
Close loop dry cooling	Least water consumption No entrainment/impingement losses No aquatic impacts	Highest installation and operating costs Highest efficiency penalty Increased exhaust gas emissions/MCU Load limitations on hottest days Site space Possibility of increased unit trips Capital cost 5–10 times higher than wet cooling Power penalties 4–6 times greater than wet cooling

4.1. INDUSTRIAL AND POTABLE WATER USE IN NPPs

Raw water supply comes either from filtrated river water or from other source (desalination, waste, etc.). The capacity of the water supply and treatment system is determined based on a water supply plan relevant to the plant size. Approximately 1.2 m^3/d·MW(e) for typical multi-unit PWR plants is an adequate capacity for its water supply and treatment system. Raw water is stored in raw water storage tanks and sent to primary and secondary system make-up water storage tanks after treatment by a water treatment unit. As an example, the water consumption per month of Kori 3, 4 a coastal plant of KHNP of Republic of Korea, is shown in Fig. 44 and of an Indian power plant in Fig. 45.

The quantity of industrial and potable water used in NPPs depends on several factors such as the replenishment of systems, flushing and regeneration of ion exchange resins, the number of personnel and water chemistry policy. Typical quality standards for make-up water at the outlet of a water treatment unit were presented Table 4.

4.2. TECHNOLOGIES FOR RAW WATER TREATMENT

Water treatment consists of the processes used to make water more acceptable for a desired end use. These can include use as drinking water, industrial processes, medical and many other uses. The goal of all water treatment processes is to remove existing contaminants in the water, or reduce the concentration of such contaminants so the water becomes fit for its desired end use. One such use is returning water that has been used back into the natural environment without adverse ecological impact. A water treatment facility supplies high quality water to industrial plants, thermal and nuclear power plants.

The typical water treatment facility also consists of a pre-treatment system. Pretreatment is required to remove suspended solids and organics if they are present in significant amounts in the raw water. Pretreatment may take different forms of clarification, depending on the chemical composition of the raw water.
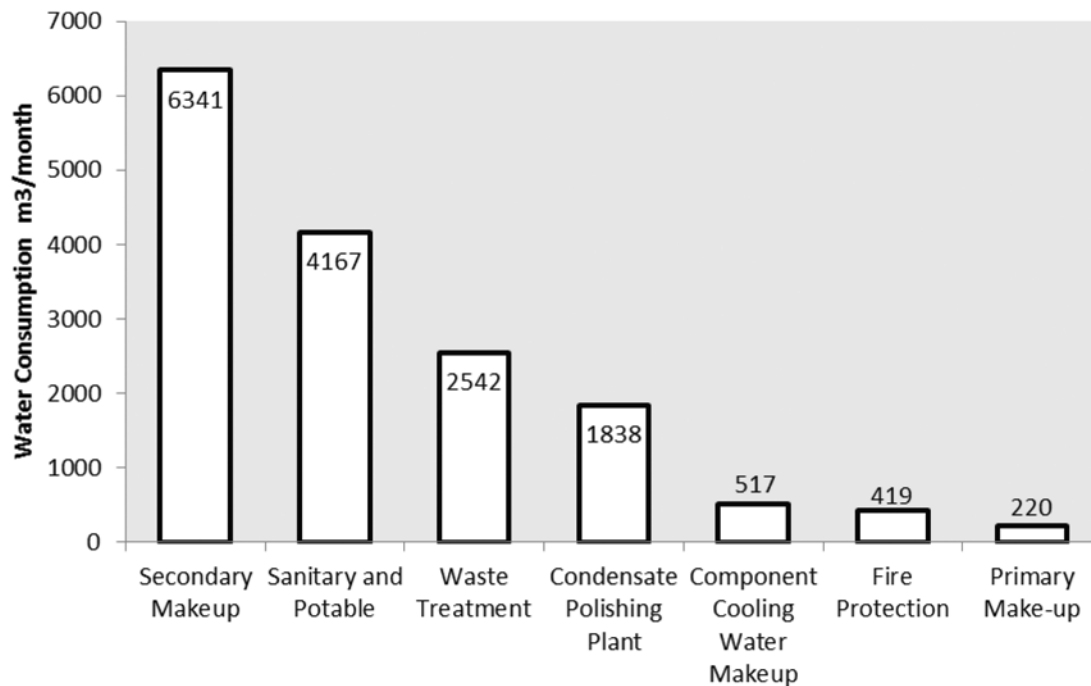
FIG. 44. Typical water consumption distribution for a Korean NPP (2 PWR units of 950MW(e)).
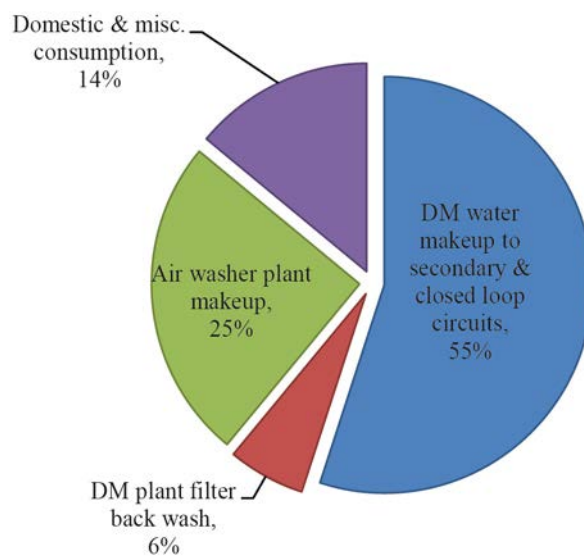
FIG. 45. Typical water consumption quantities for Indian nuclear power plants.

Water treatment technologies remove or neutralize impurities, making the water suitable for either consumption (freshwater) or discharge (wastewater effluent). Fundamental water treatment concerns are the same for most purposes, even though the quality requirements will vary. Standards for drinking water are quite high, but not as high as those for sensitive industrial processes like silicon chip manufacturing and NPP reactor make-up. Less stringent standards apply to non-sensitive industrial processes like cooling tower make-up water.

The most common treatment technologies are summarized in the following sections.

4.2.1. Separation

This is a very broad category that entails physically separating impurities from the treated water. Large particulate matter can be removed by screening, while fine suspended solids and dissolved compounds can be
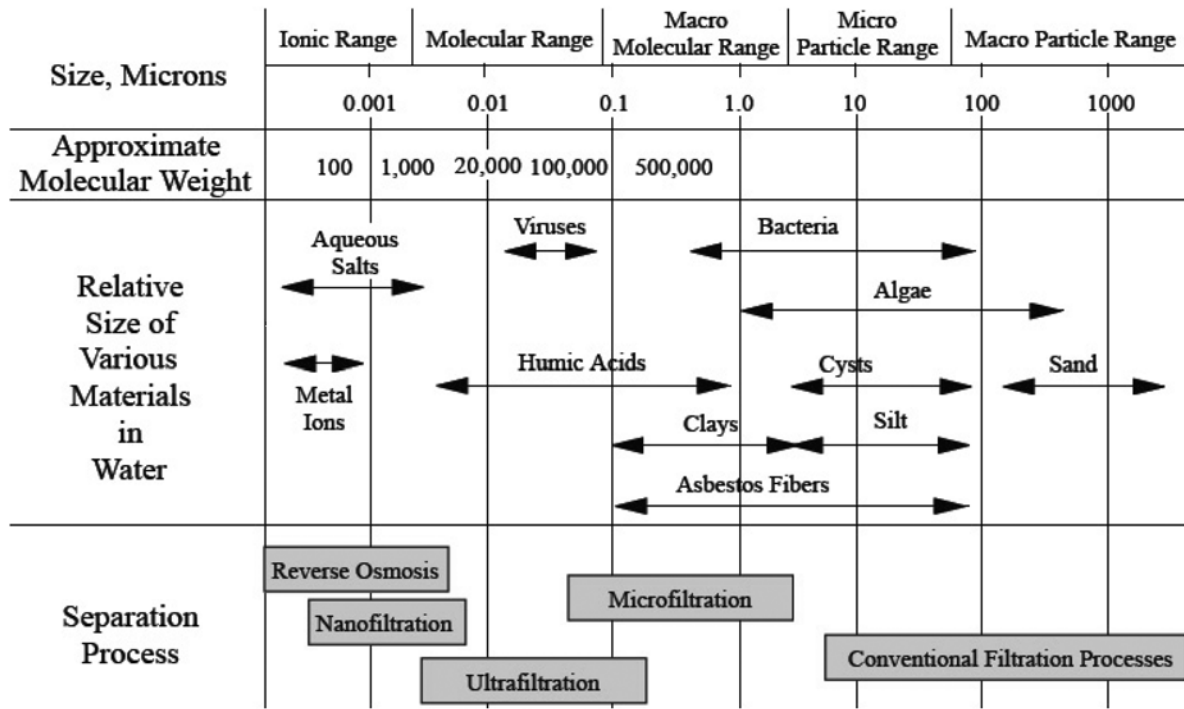
FIG. 46. Relative sizes of particles removed by membrane processes.

removed through chemical reaction that induces coagulation or precipitation. This category would also include flocculation, sedimentation, flotation, settling, skimming, and centrifuging. Separation is generally a first step in water treatment.

Separation processes are the primary means of reducing water turbidity. Oil and greases are generally removed early in the process via floatation and skimming techniques. Heavy metals and nitrates can also be addressed through chemical precipitation and settling.

4.2.2. Filtration

Filtration could be considered a very fine form of separation, since the filter media is intended to physically remove impurities. However, filtration is intended to remove very small impurities that remain after the separation process. Various filtration technologies can target very fine particles such as sand and silt, microscopic particles such as bacteria and algae, molecular constituents such as viruses and acids, and even ionic impurities such as salts and metals. The costs associated with filtration increase greatly as the targeted impurities decrease in size. Examples of the technology include sand filters, cartridge filtration, online filtration, and membrane filtration. As illustrated in Fig. 46 [31], filtration membranes are in turn classified by their pore size, placing them in the subcategories of micro-filtration, ultra-filtration, nano-filtration, and reverse osmosis. Filtration processes can remove virtually all water impurities when properly applied. Fouling is a common problem, so impurities usually need to be removed in stages such that any one filtration medium is not overwhelmed. Despite the impressive results achievable through filtration, there are large energy costs associated with pressurizing the water to the required process levels.

As depicted in Table 17, the pressure and energy requirements greatly increase with finer filtration. One of the main goals of membrane filtration research is to devise a means to achieve cost effective filtering [32].

TABLE 17. PRESSURE AND ENERGY REQUIREMENTS FOR MEMBRANE FILTRATION PROCESSES

Membrane process	Screens particles	Typical operating pressure [bar]	Typical energy use [kW·h/m^3]
Microfiltration (MF)	0.1–0.5 microns	0.2–2	0.4
Ultrafiltration (UF)	0.005–0.05 microns	0.35–5.15	3
Nanofiltration (NF)	0.0005–0.001 microns	3.5–10.5	5.3
Reverse osmosis (RO)	<10 MWCO	8.6–86	10-47

Reverse osmosis pressure depends on feed water quality; the greater the salt content, the higher the pressure.

All four membrane categories are commonly used in water treatment to achieve the goals of drinking water guidelines and standards, as well as to produce desalinated and/or ultra-pure water (UPW) for different industrial needs, such as make-up water [33].

4.2.3. Evaporation

Evaporating moisture from contaminated water and subsequently re-condensing the distilled water is a very old and generally inefficient technology. However, variations on thermal based distillation that utilize waste heat have received attention in recent years. Mechanical vapor compression has also been used to condense water, but has yet to be proven economically viable for large scale water reuse.

4.2.4. Adsorption

This technique traps organics that may escape other treatment processes by bonding them to an inert media. Activated carbon filters are the most common example of this technology, although other inorganic media are available. The arrangement of the media can vary, from simple granules in bulk volume, to filtration fibers coated with the media. Adsorption is often used as a final step to polish water prior to use. Over time the media loses its effectiveness as its surface area fills with bonded impurities. Adsorption systems require periodic replacement or regeneration of the media, which presents additional operating costs.

Adsorption is regularly used to remove volatile organic chemicals as well as pesticides and herbicides. Activated carbon is also an excellent means of reducing unpleasant odor and taste in drinking water.

4.2.5. Biological treatment

Utilizing the ability of naturally occurring microbes to degrade organic matter is a common practice for treating water and wastewater. Many inorganic compounds are also biodegradable.

Common techniques use aerobic digestion, anaerobic digestion, or a combination of the two.

Supplying adequate oxygen through aeration to support oxidation is the key for aerobic digestion. Anaerobic digestion occurs in the absence of oxygen and produces many by-product gases such as methane. Anaerobic digestion is often utilized for biogas production. Opportunities also exist to mimic natural microbes by engineering human-made custom enzymes for specific water treatment needs.

Nutrients such as nitrogen and phosphorus, while not organic material, can also be reacted in biological processes that convert them into separable solids. New processes are being developed to also treat nitrates and perchlorates in groundwater. Membrane bioreactors represent a hybrid treatment technique that combines the use of micro- or ultra-filtration within an aerobic process tank. In addition to the joint benefits of biological and membrane filtration treatment, membrane bioreactors are also effective at removing oil and grease.

Similar to aerobic digestion, advanced oxidation technique degrades organic material by encouraging the chemical oxidation of the target impurity's molecules. Unlike aerobic digestion, advanced oxidation generally entails injecting ozone or hydroxyl radicals into the water being treated. Conversely, ozone or hydroxyl radicals can be generated within the water by an external energy source such as ultraviolet (UV) light, electron beams, gamma

radiation, or soft X rays. A common technique is photocatalysis in which UV light is applied to a metal oxide catalyst, such as TiO_2, to produce the hydroxyl radicals. New technologies are being developed that will enable visible light to be used instead of UV.

Advanced oxidation techniques are generally used for treating target organics, and are not intended to remove all the biodegradable material in the water. The technique is often used as a means of disinfection when targeting specific pathogens after the water has already been treated to relatively high purity levels.

4.2.6. Disinfection

The goal of disinfection is to destroy, debilitate, or remove pathogenic microorganisms. This is achieved by killing the organism, preventing its development, or impeding its reproduction.

Water disinfection can be achieved through chemical or physical means. The most common form of chemical disinfection is the use of chlorine within municipal water systems. Physical means include heat, pressure, acoustics, electronic radiation, gamma rays, and ultraviolet light [34].

4.2.7. Demineralization

Demineralization is a process typically utilized to further treat water where additional purity is required or when hardness must be removed. Demineralization uses resins or membranes that have the ability to remove chemical ions.

With ion exchange, water for treatment is passed through a resin bed. The resin is initially charged with inert ions, generally salt, that exchange places with the target ions, often calcium and magnesium, in the water. The target ions are then retained on the resin. As with adsorption media, ion exchange resins must periodically be recharged or replaced.

Removal of ions can be achieved through electro-deionization wherein a combination of electric charge, selective membranes, and electrode surfaces drive the separation and capture of target cautions and anions. Electrodialysis is a mature technology that uses selective membranes that enable one-way passage respectively for anions and cations. Energy intensity and membrane costs tend to be high. Many electro-deionization technologies exist with variations on membrane and electrode design. Much research is currently being conducted in this field.

New technology eliminates the need for membranes and relies upon advanced electrode materials to attract and retain the ions.

In order for the ion exchanger to function properly (produce the desired effluent quality and quantity), potential contaminants should be controlled in the influent within limits presented in Table 18 [35]. In order to

TABLE 18. ION EXCHANGE INFLUENT WATER QUALITY LIMITATIONS

Parameter	Units	Influent water quality			
		Organic traps	Softener	Weak acid cation	Strong acid cation
Turbidity	NTU	<2– 5	<2–5	<2–5	<2–5
Oil	ppm	None detected	None detected	None detected	None detected
Chlorine, C_{l2}	ppm	<0.1–0.2	<0.1–0.2	<0.1–0.2	<0.1–0.2
Iron, Fe	ppm	Not applicable	<2	<0.1–0.3	<0.1–0.3
Manganese, Mn	ppm	Not applicable	<1	<0.1–0.3	<0.1–0.3
Barium[1], Ba	ppm	Not applicable	Not applicable	<0.2	<0.2
Nitrate[2], NO_3	ppm	No limit	No limit	<20	<20

[1] The limit on barium is only for action exchangers regenerated with sulfuric acid and is intended to prevent barium bisulfate precipitation.
[2] The limit on nitrate (weak acid and strong acid cations) is to minimize the amount of nitric acid in the cation exchanger effluent, which could degrade downstream anion exchange resins receiving decationized water.
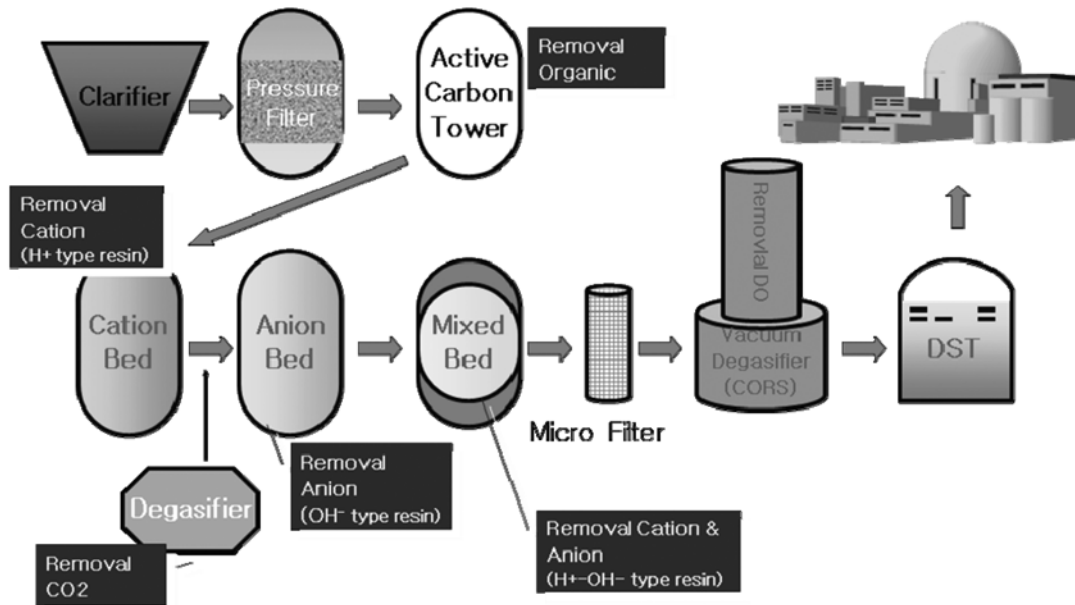
FIG. 47. Typical water treatment facility.

guarantee turbidity limits listed in the table, filtration is suggested ahead of the ion exchange equipment. Other water quality limits listed in the table can be achieved by conventional processes.

Ion exchange equipment is typically an integral part of make-up water treatment systems (Fig. 47) regardless of the water supply source. The proper ion exchange system may be selected and sized based on influent water quality, desired effluent quality, and flow rate. Ion exchange replaces undesirable ions in solution with more desirable ions. It is affected by passing water through a bed of synthetic beads of ion exchange resins. There are two basic types of ion exchangers. Cation exchangers typically employ a bed of sulfonated styrene divinylbenzene (SDVB) copolymer resin to remove undesirable cations. Anion exchangers are generally based on either an aminated SDVB copolymer or an aminated acrylic based resin to remove potentially troublesome anions. Removing all ionic impurities is called demineralization or deionization. In order to demineralize water, the cation impurities are exchanged for hydrogen (H+) in a hydrogen cycle cation exchanger and the anion impurities are exchanged for hydroxyl (OH–) ions in a hydroxide cycle anion exchanger.

The demineralization process which uses ion exchange resins has been utilized in power plants since the 1940s. Various techniques were introduced following much effort on the technical development of water treatment to allow efficient and economic systems to be applied. Recently the reverse osmosis (RO) system using membranes and the new technology, membrane deionization (MDI) which combines ion exchange resins, ion exchange membranes and direct current (DC) are considered to have economic superiority.

The MDI process is preferred in many water treatment systems primarily because of the environmental benefit of not requiring a hazardous chemical reagent for regenerating ion-exchange resins and the inherent superiority of continuous processes over conventional batch processes (Figs 48 and 49). This is a reasonable technical and economic alternative to the ion-exchange system, while providing significant environmental, safety and operational benefits. Other advantages of MDI include continuous operation, stable product quality, and the ability to produce high purity-water without the chemical regeneration.

Molecular resonance membrane (MRM) is particularly attractive for new facilities because it enables the design of an all membrane-based, chemical free water treatment system, thereby eliminating the need for acid and caustic storage, processing, and waste treatment.

Ultra-filtration/membrane-filtration (UF/MF) is a part of a physical separation process that can replace coagulation, sedimentation and filtration within the conventional water treatment scheme. Membranes are classified by the size of particulate matter that can pass through them, and include (in order of decreasing particle size) micro-filtration, ultra-filtration, nano-filtration and reverse osmosis. Reverse osmosis is capable of removing very small, ionic constituents, and thus is used for desalination. As particle size selectivity decreases, water feed
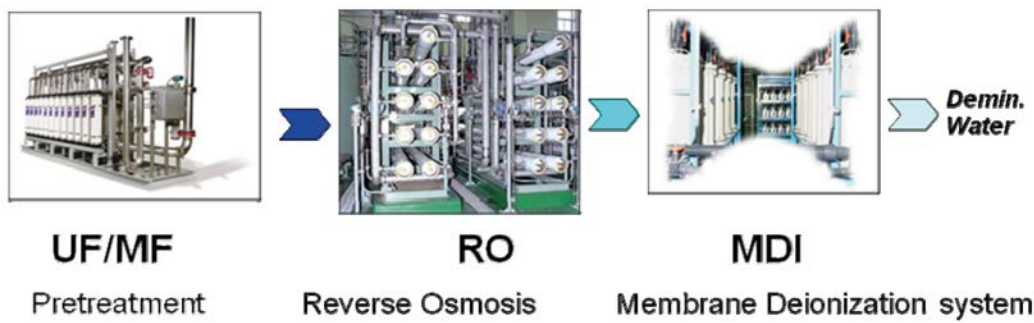
FIG. 48. *Photographic representation of the components of the MDI.*
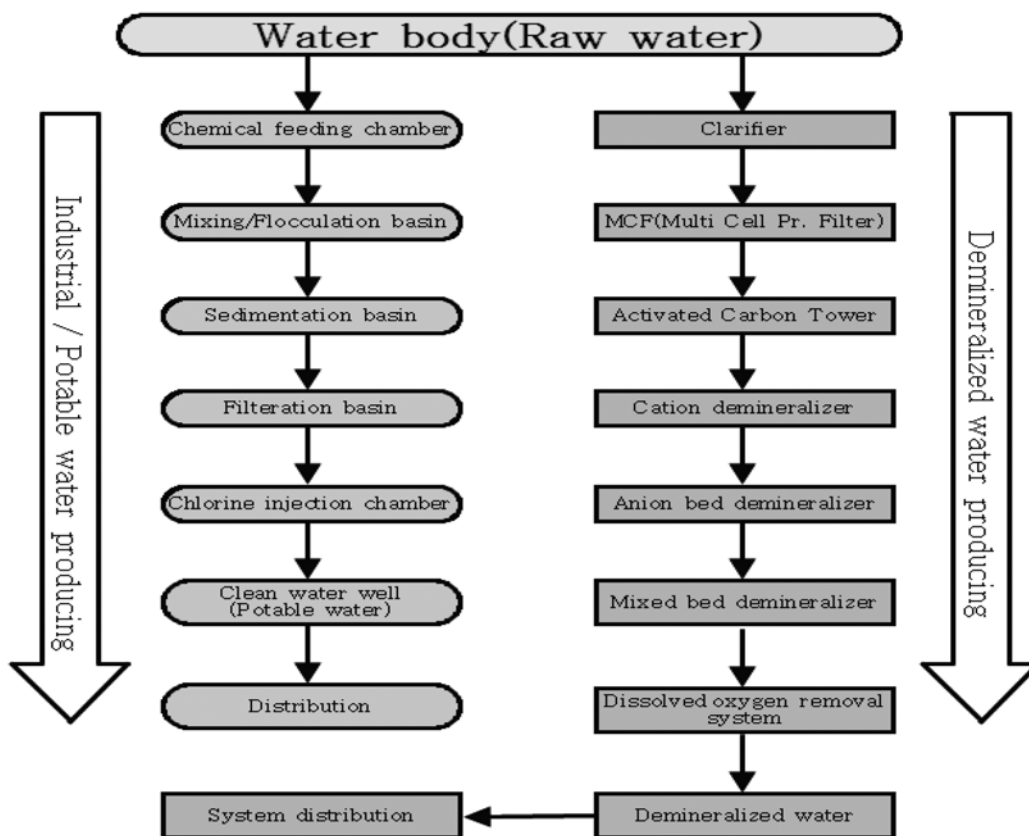
FIG. 49. *Process of producing demineralized water and potable/industrial water.*

pressure (and thus energy use) increases. The primary problem with membranes is fouling, which tends to increase with increasing feed water pressure. Thus, a major goal of advanced membranes research is to decrease operating pressures through improvements in membrane materials and multi-treatment configurations.

Reverse osmosis (RO) is a separation process based upon the natural osmotic pressure differential that exists between two solvent solutions with different levels of dissolved solute. When two different solutions, such as freshwater and saltwater, are separated by a semi-permeable membrane, freshwater molecules will be drawn to the higher salt concentration seawater through the membrane. The freshwater molecules will continue to pass through the membrane indefinitely until pressure is applied to the saltwater to produce equilibrium across the membrane. If excessive pressure is applied to the saltwater then water molecules will pass in a reverse manner back through the membrane, which is the essence of reverse osmosis water treatment.

With pressure being the driving force in a reverse osmosis process, significant amounts of pumping energy are required to produce meaningful volumes of treated water. The pressure requirements vary with the salinity level of the source water [36].

TABLE 19. COMPARISON BETWEEN MEMBRANE AND ION EXCHANGE RESIN

	MEMBRANE	ION EXCHANGE RESIN
Strength	— Low chemical — agent use — Low maintenance cost — Continuous operation	— Low cost to startup — Lots of experiences
Weakness	— High cost to startup — Limited experience — Membrane contamination	— Needed lots of regeneration — Low maintenance cost (chemicals, etc) — Total serviced water amounts depend on influx water quality — Much wastewater

TABLE 20. ATER SOURCES THAT CAN BE USED FOR NPP NEEDS BASED ON FOSSIL FUEL PLANT EXPERIENCE

Sources of water supply		Extent of utilization by fossil plants
Surface water	Rivers and streams	Widely used, especially in older plants.
	Lakes and ponds	Widely used — natural and man-made lakes.
	High-salinity waters	Limited usage at this time.
Groundwater	Shallow wells	Used mainly where surface supplies are unavailable.
	Deep wells	Used mainly where surface supplies are unavailable.
Municipal water	Treated surface water	Widely used, mainly at plants within a municipal distribution area.
	Treated groundwater	Widely used, mainly at plants within a municipal distribution area.
Wastewater	Internally generated	Practiced in some zero liquid discharge designs. (This approach requires an outside water supply for use elsewhere in the plant.)
	Externally generated	Minimal usage, but an important potential source for future plants.
Underground water	Mine pool water	Used in the area of coal field such as Pennsylvania or West Virginia

4.3. TECHNOLOGIES FOR PRODUCTION OF INDUSTRIAL AND POTABLE WATER

Raw water for the make-up plant may be obtained from a number of sources (where available in adequate amounts), although surface water supplies are most commonly utilized. Freshwater supplies from lakes, rivers and streams are generally considered, although in some instances high salinity waters — including seawater — have been used. Groundwater supplies are typically used in areas where insufficient quantities of surface water are available. At plants located in or near cities or towns, it is still common to use the treated municipal water supply as the input to the make-up water treatment plant. Municipal supplies generally originate as rivers but either surface water or groundwater (or a combination of the two) is also used. These supplies have received treatment which usually includes disinfection (most often by chlorine) and filtration, and for many supplies may also include coagulation, flocculation, settling and possibly softening and even reverse osmosis (RO). Available sources of water for power plant make-up treatment systems are summarized in Table 20.

Freshwater surface supplies, groundwater and municipal supplies have traditionally been the preferred sources. Limitations on the availability of water and a desire to conserve water have stimulated some interest in alternative sources of water for the make-up plant. Some generating plants presently employ high-salinity surface waters. We must make every effort to secure alternative water supply resources because the world will suffer from
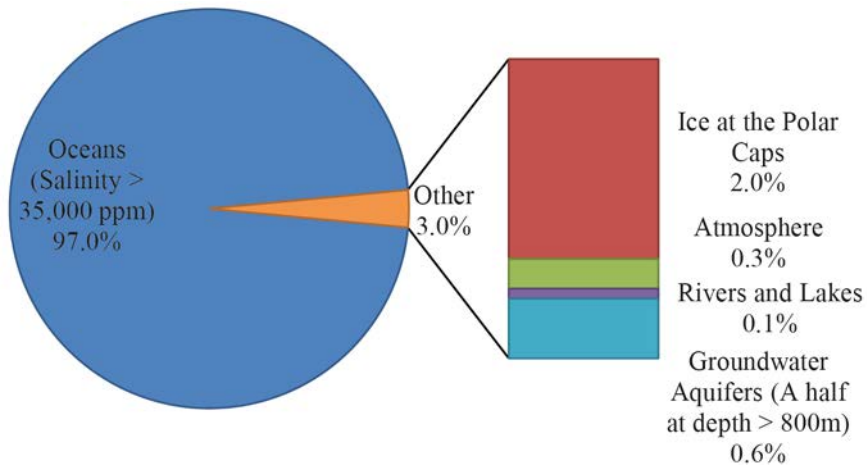
FIG. 50. Global water distribution.
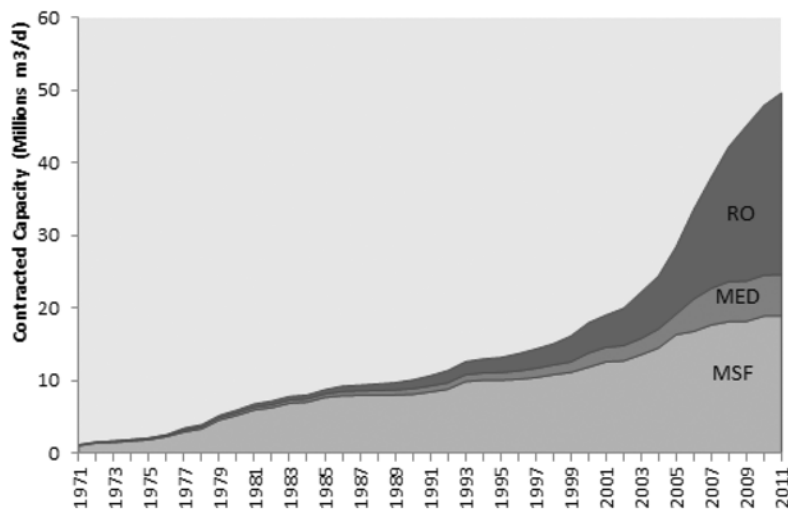
FIG. 51. Main seawater desalination technologies by capacity.

water shortages in the future. Desalinization and wastewater reclamation is another resource for alternative supply of industrial and potable water.

4.3.1. Desalination

Desalination technologies will become increasingly important in the future as marginal quality water supplies account for a growing share of total water supply. Worldwide, 6600 online seawater desalination plants produce more than 40 million cubic meters of water a day, according to the International Desalination Association [37]. Desalination though is more expensive than traditional sources, and critics say it harms the ocean. This planet's available water resources do not allow many alternatives for freshwater supply (Fig. 50). With 97% of available water represented by salty water with the salinity level >35 000 mg/L, the largest possible source of alternative water supply requires and will require desalination.

The oldest desalination methods are based on evaporating water and collecting the condensate. The best known thermal technologies are the multi stage flash (MSF), multi effect distillation (MED) and vapor ompression (VC). Electrodialysis reversal (EDR) uses high voltage current to remove cations and anions from the stream.

The newest and largest growing commercial technology for desalination is based on membrane treatment. Reverse osmosis (RO), whether brackish water reverse osmosis (BWRO) or seawater reverse osmosis (SWRO), has the greatest number of new installations around the globe. Desalination by RO is beginning to dominate the current and future desalination markets. As seen in Fig. 51, the capacity of RO desalination installations is above 25 million cubic meters, more than half of all desalination capacity [37].
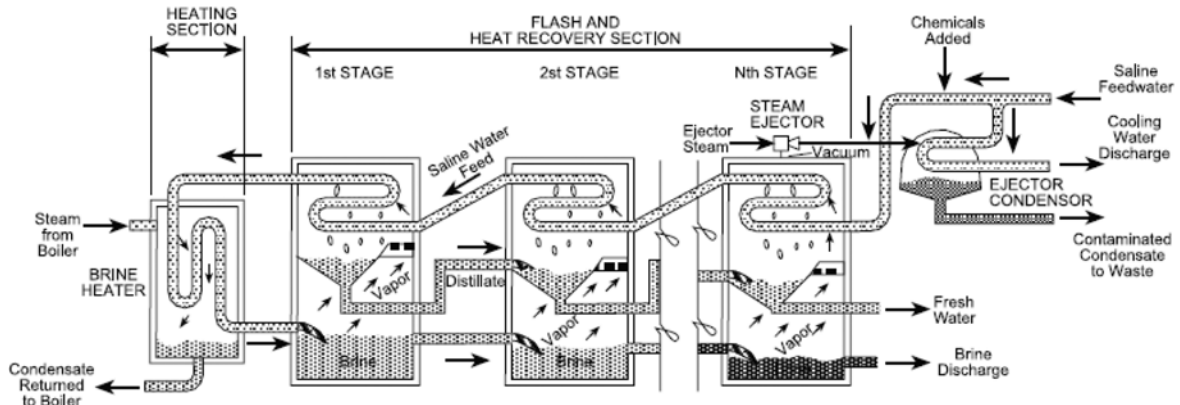
FIG. 52. Multi-stage flash thermal desalination plant.
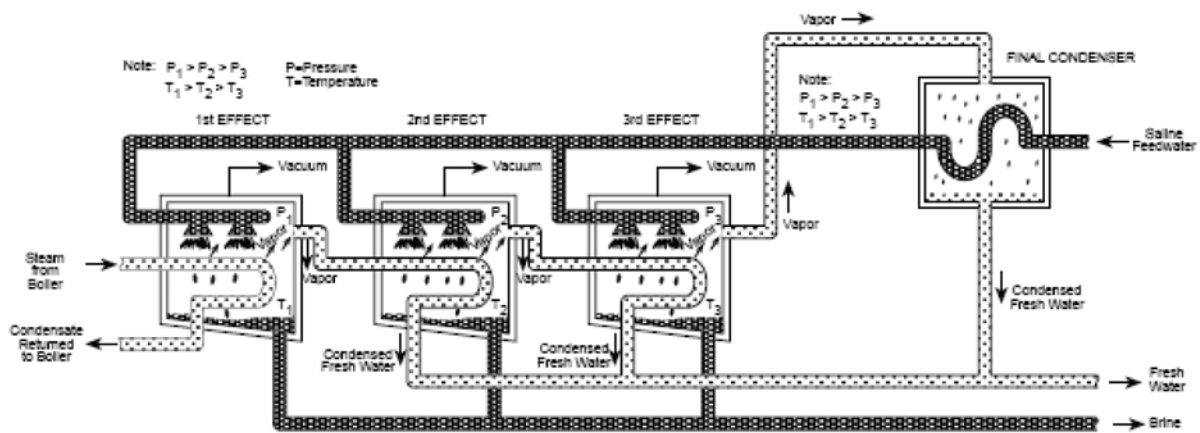
FIG. 53. Multi-effect thermal desalination plant with horizontal tubes.

Thermal processes have been on the market for more than five decades and most of them provide relatively high capacities. However, on a global level, this ratio is expected to change significantly because most of the desalination systems currently designed, constructed, and considered for construction are based on membrane technology. In a nuclear power plant though, it makes sense to utilize thermal desalination processes. Schematic diagrams of MSF and MED are presented in Figs 52 and 53, respectively [38].

For a given power rating, nuclear power plants, in general, have larger amounts of waste heat than conventional fossil fuel power plants. The enthalpy of the steam at the inlet to the high pressure (HP) turbine of a nuclear power plant is lower due to the lower pressure and temperature of the saturated steam, and thus, the specific steam consumption for nuclear power plants is higher. This leads to the availability of a higher amount of steam that could be utilized for thermal desalination. An additional benefit in using thermal desalination with NPPs is the lower thermal load that needs to be rejected, as heat is being used in a useful manner and thus reduced the cooling needs in the condenser. A nuclear plant depending on its type can provide steam or process heat from about 50–150°C for desalination.

So far no incidence of radioactive contamination of the product water has been reported from any of these nuclear desalination plants. Using nuclear energy for producing freshwater from seawater (nuclear desalination) has been drawing broad interest among Member States of IAEA due to acute water issues in many arid and semi-arid areas worldwide. Several demonstration programmes on nuclear desalination have been taken up to confirm its technical and economic viability under country specific conditions with the technical coordination or support of the IAEA. Desalination costs are highly site specific and range from US$0.40 to $1.90 per cubic meter of desalinated water produced.

As can be seen in Table 21 [39], the dominating desalination process in nuclear power plants until now has been thermal desalination. It can provide water with a solid content below 10 mg/L and in the case of BN-350 at Aktau, Kazakhstan, below 2 mg/L [40].

TABLE 21. EXPERIENCE IN NUCLEAR DESALINATION PLANTS

Type of reactors	Power (MW(e))	Desalination process	Capacity (m^3/d)
Ikata-1,2 (Japan) PWR	2×566	MSF	200
Ikata-3 (Japan) PWR	890	RO	2000
Ohi-1,2 (Japan) PWR	2×1175	MSF	3900
Ohi-3,4 (Japan) PWR	2×1180	RO	2600
Genkai-4 (Japan) PWR	1180	RO	1000
Genkai-3,4 (Japan) PWR	2×1180	MED	1000
Takahama-3,4 (Japan) PWR	2×870	MED	1000
Kashiwazaki (Japan) BWR	1100	MSF	1000
Diablo Canyon (USA)	2×1100	PWR/RO	2180
BN-350 (Kazakhstan) LMR (until 1999)	150	MED	80 000
MAPS (India) PHWR	2×170	Hybrid MSF-RO	6300
CIRUS (India) PHWR	40 MW(th)	LTE	30
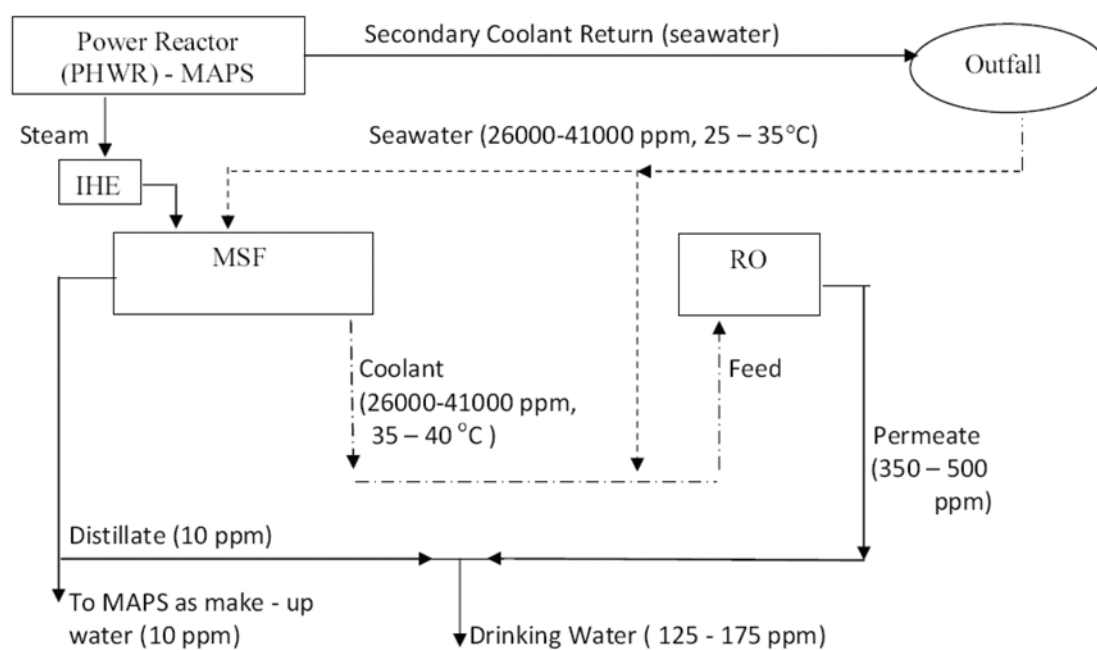
FIG. 54. Concept of hybrid nuclear desalination system.

The hybrid desalination plant combines the advantages of the main desalination processes, both RO and distillation. This design has already proven itself at the Kalpakkam nuclear desalination plant. It is based on hybrid desalination technology developed by BARC consisting of an MSF plant of 4500 m^3/d and an RO plant of 1800 m3/d capacity. It is coupled to 2×170 MW(e) PHWRs of Madras atomic power station (MAPS). The hybrid technology has provision for redundancy, utilization of streams from one another and production of two qualities of water. The desalinated water produced from MSF is of distilled quality, which is good for industrial process use. The product from RO is of potable quality. The two can also be blended for improving the quality of water produced from RO. The hybrid concept is shown in Fig. 54.
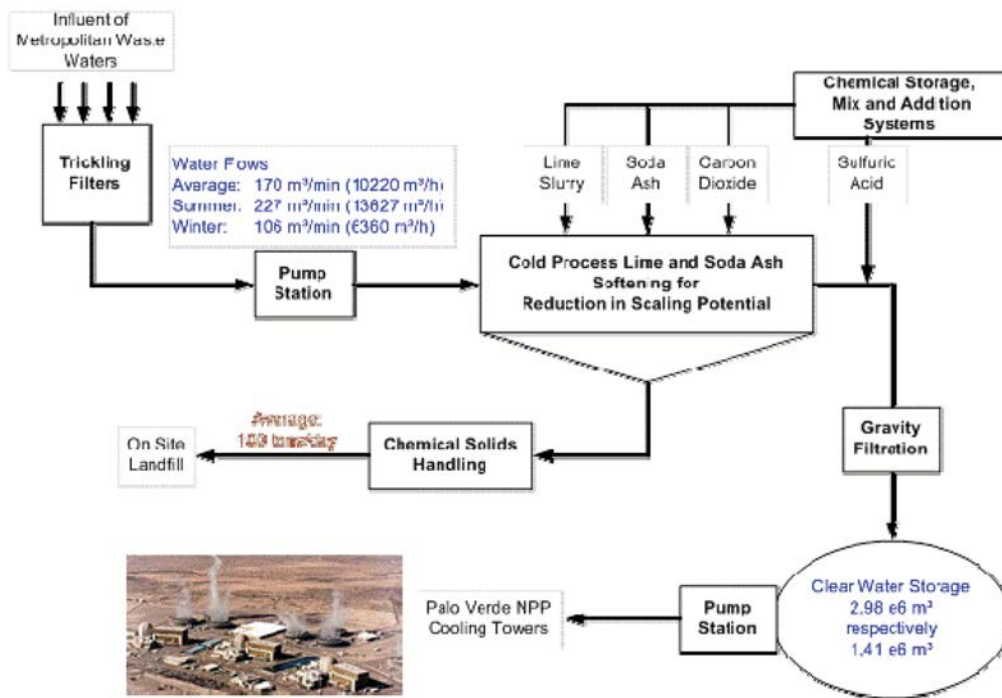
FIG. 55. Palo Verde nuclear generating station water reclamation facility.

4.3.2. Wastewater reclamation

Reclaimed water, sometimes called recycled water, is former wastewater (sewage) that has been treated to remove solids and certain impurities. In most locations it is only intended to be used for non-potable uses such as irrigation, dust control, and fire suppression, and there is controversy about possible health and environmental effects for those uses. In some places, including Singapore and California's Orange County, reclaimed water can be used indirectly for drinking when a more advanced treatment is made.

Although the cost of reclaimed water exceeds that of potable water in many regions of the world, where a fresh water supply is plentiful, throughout the world an increasing number of communities are utilizing reclaimed water. The uses for reclaimed water seem to grow on a daily basis, and demonstrate an international acceptance of reclaimed wastewater as a clean, safe product.

Palo Verde, because of its desert location, is the only NPP that uses 100% reclaimed water for cooling. The Palo Verde Water Reclamation Facility (WRF) is a 340 000 m^3/d tertiary plant. Palo Verde obtains all its cooling and plant water from the Phoenix 91st wastewater treatment facility through a 60 km combined gravity flow and pumped piping system. Reverse osmosis is used to obtain potable water. Mixed bed demineralizers are used to process water for station process needs. Cooling tower blow-down is pumped to settling/evaporation ponds; solids are buried on site. Palo Verde operates as a zero discharge facility. A flow diagram of the wastewater treatment system for the Palo Verde NPP in the USA is shown in Fig. 55.

The Limerick nuclear power plant in the United States (two 1134 MW(e) units) [6] obtains approximately 40% of its make-up water from polluted mine water sources from abandoned deep coal mines [27]. The Redhawk power station in the USA, located near the Palo Verde nuclear power plant, is a combined cycle gas power plant, with twin 530 MW power blocks [41]. Redhawk operates as a zero liquid discharge system (Fig. 56), reusing nearly 10 000 m^3/d water from the Phoenix wastewater treatment plants. Raw water is treated three times before entering a 17 hectare pond with 618 000 m^3 capacity. An additional water clarification system operates on standby for ground water treatment of when required.
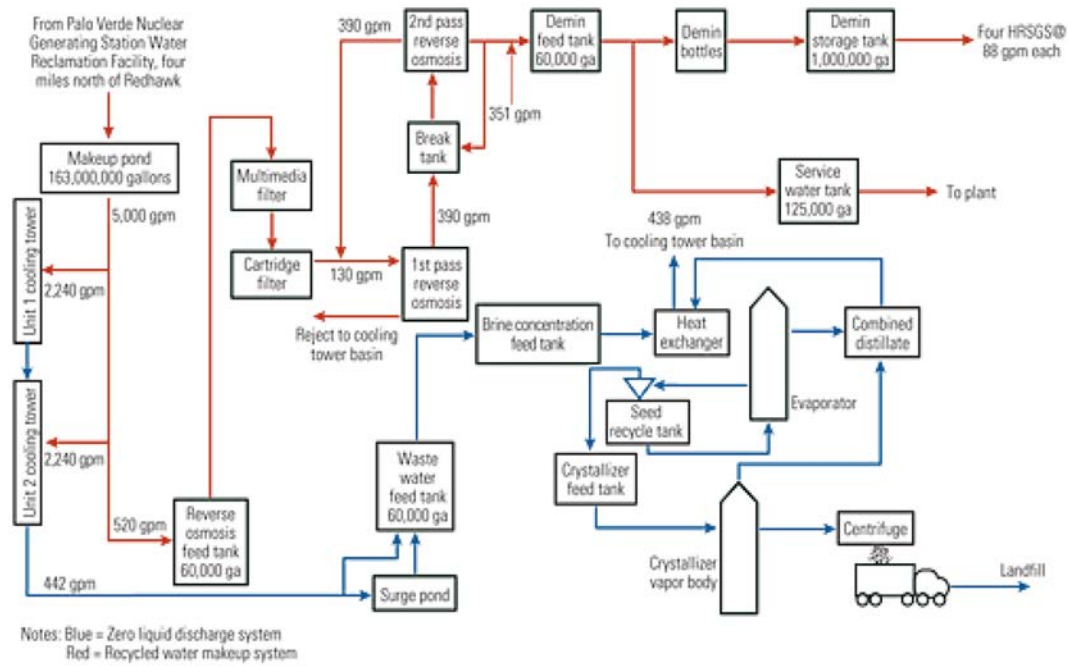
FIG. 56. Sources and uses of water at Redhawk power station.

4.4. CONCLUSION

The availability and use of water is a major concern in the electric power sector. There is a growing need in many countries around the world for new sources of fresh water. The processes of desalination, wastewater reclamation and wastewater treatment can be considered as new sources of freshwater.

It is very important to improve the efficient treatment and use of water. This could involve using less water via new conservation measures, reusing water for multiple purposes prior to disposal, or implementing innovative ways to reclaim usable water from non-traditional sources. In this section we have reviewed the water usage in NPPs, water quantities, and water treatment technologies — traditional methods using ion exchange resins as well as new technologies such as using membranes.

New technology for producing demineralized water using membranes needs no regeneration water and can improve the efficient use of water through water reuse and water use reduction.

There are numerous processes that can be used to clean up wastewaters depending on the type and extent of contamination. Most wastewater is treated in industrial scale wastewater treatment plants (WWTPs) which may include physical, chemical and biological treatment processes.

5. STRATEGIES FOR REDUCTION OF WATER USE AND CONSUMPTION IN NUCLEAR POWER PLANTS

As described in Section 2.3, water use and consumption in a nuclear power plant takes place in three main areas: water use for cooling systems, industrial and potable water and water for waste dilution. This section discusses various strategies and schemes in practice for optimizing and reducing fresh water use and consumption in each one of these areas, as well as the strategies that can be adopted in the future.

5.1. REDUCTION OF WATER USE AND CONSUMPTION IN COOLING SYSTEMS

This section addresses strategies for reduction of water use and consumption in the different cooling systems described in Section 3. Additional strategies for reduction in cooling water requirements as the reduction of rejected heat from the power plant or the use of non-conventional water sources (recycled municipal wastewater, agricultural runoff, brackish ground water, etc.) instead of fresh water are also analyzed.

5.1.1. Schemes for reducing water use in open loop cooling systems (once-through)

5.1.1.1. Variable speed cooling pumps for part load or load following operation

Variable speed drives can be used on pumps catering for various cooling systems involving the use of once-through circuits in order to reduce water withdrawal. The cooling water requirement will be less during part load operations as well as shutdown operations where there is only a decay heat load.

Under these conditions of low cooling water flow requirement, the variable speed drives will reduce the operating speed of the pumps. Consequently the operating capacity of the pumps can be reduced to only that required under such operating conditions (pump flow rate bears a linear relationship with pump speed as per affinity laws), thus reducing the excess water withdrawal under partial load conditions.

5.1.1.2. Variable speed drives on cooling pumps for temperature variations in the source of water

For seawater based cooling systems, the seasonal variation in sea water temperature will cause a variation in cooling water temperature. A process controller (along with temperature sensors and transducers (to convert the temperature signal to a 4–20 mA electrical signal) can be used to maintain a constant cooling water temperature at the outlet of process heat exchangers by comparing the measured cooling water temperature at the hot end of the heat exchangers and the set point cooling water temperature (design cooling water temperature at the hot end).

At certain times of the year, the cold water temperature at the inlet of process heat exchangers will be less than the design value. If the cold water temperature at outlet of the heat exchangers (i.e. at the hot end) can be kept constant as discussed above and meeting the hot discharge limits of the environmental stipulations, the temperature difference across the heat exchangers can be increased. For constant heat load, the cooling water requirement in process heat exchangers will be reduced taking the advantage of the higher DT. Thus by using variable speed drives on cooling water pumps, the operating capacity of the pumps can be reduced to only that required under such operating conditions thus reducing the excess water consumption under low ambient temperature conditions.

5.1.1.3. Variable speed drives on cooling pumps for tidal variations in the source of water

From the data available, the water level in the sea is seen to vary by few meters over the design basis low level during certain hours of a day (pumps are generally designed for the lowest low tide level). As the water level in the sump rises due to high tide effects, the pump discharge also increases. Due to variations in tidal level above the design basis low water level each day, a high flow would exist in the system. By using variable speed drives on cooling water pumps, the excess discharge from the pumps can be reduced by shifting the operating point on the pump head-flow rate curve as required under high tide conditions.

5.1.2. Schemes for reducing water use in closed loop cooling systems

5.1.2.1. Variable speed drives on cooling pumps for part load or load following operation.

Variable speed drives can be used on pumps in various cooling systems with closed loop cooling tower circuits in order to reduce water consumption from evaporative loss and blow-down. During part load operations as well as shutdown operations where there is only decay heat load, the cooling water flow through cooling towers will be less and by reducing cooling water flow rates water loss can be reduced.
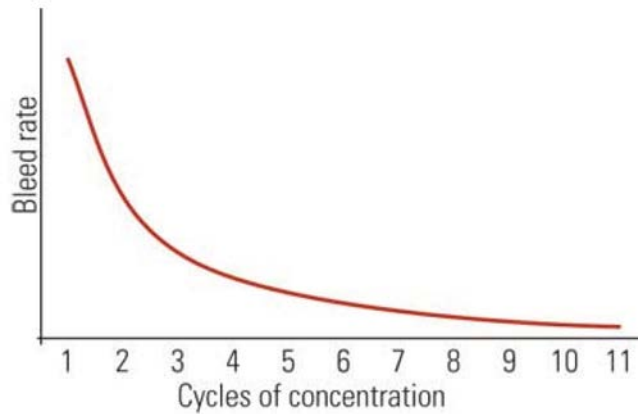
FIG. 57. Bleed rate vs. cycle of concentration.

5.1.2.2. *Variable speed drives on cooling tower fans for part load or load following operation*

The cooling effect depends on the difference of the wet bulb temperatures of the air going in and coming out of the tower. NPPs that have constant heating loads throughout the year may find that during the summer months, they need to operate the towers close to their design capacity. In the winter, due to lower wet bulb temperatures, towers may be operated at reduced water or air flow rates. In western Washington State in the USA, the average seasonal wet bulb range between summer and winter is 11°C, and in eastern Washington it is around 17°C. In a tropical country like India (northern part) the wet bulb temperature varies 15°C between summer and winter. A variable frequency drive to control the cooling tower fans is one way of conserving water and energy. Evaporation rates can be optimized for variable cooling loads or seasonal temperature swings if the operator can control the throughput of air. Another option is to have a modular system that allows for shutting down a tower module when not needed.

5.1.2.3. *Increasing cycles of concentration in cooling towers by adopting water treatment*

Maximizing the cooling tower cycle of concentration COC (see Sub-section 3.2.1.2) offers many benefits in that it reduces water consumption, minimizes waste generation, decreases chemical treatment requirements, and lowers overall operating costs. Potential cost savings vary from plant to plant, depending on the cost for raw water, waste disposal costs, chemical treatment dosages, and energy. The maximum COC that can be achieved will depend on make-up water quality, circuit maximum operating temperature, treatment methods and economics.

Major gains in water conservation can be achieved by increasing the COC from 2 to 3. However, as we approach higher cycles, the incremental gains decrease (Fig. 57). From a practical view, windage, leaks, and other uncontrolled losses limit COC to a maximum of about 10.

As an example, a cooling tower handling a 1000 MW(e) NPP condenser heat load operating at 3 cycles of concentration with a 11°C temperature drop across the tower has a make-up demand of 5400 m^3/h. Increasing the COC to 8 has the effect of decreasing the make-up demand to 4115 m^3/h. This reduces the make-up requirement by 23.8%. The wastewater produced by the cooling tower decreases from 1800 m^3/h at 3 cycles to 515 m^3/h at eight cycles, which is equivalent to a 71.4% decrease. If COC is further increased from 8 to 10, reduction in make-up water requirement is only 2.8%. Hence towers operating at six to eight cycles are acceptable for most applications. If make-up water quality is hard, even to increase COC to 8 from 2 to 3 needs various treatment methods. Achieving more than 10 cycles would be difficult while deriving a reasonable return on investment, unless zero discharge is the ultimate goal.

The cooling tower cycle of concentration (COC) can be maximized by water treatments shown in Fig. 58. Such treatments must be capable of lowering the mineral content (calcium, magnesium, alkalinity, phosphate, silica, etc.) and removing suspended material from the make-up and /or circulating water. Water treatment methods are chemical or non-chemical.
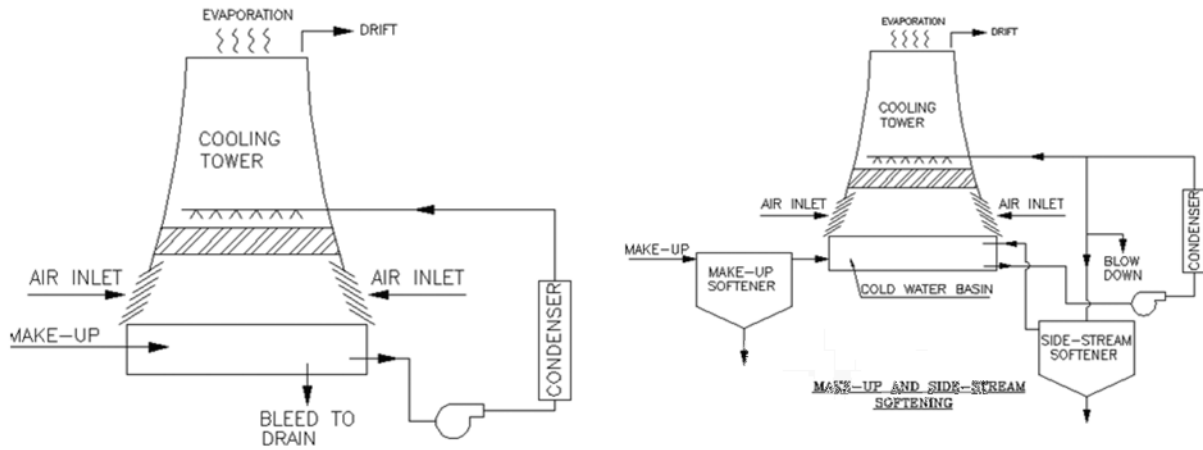
FIG. 58. Wet cooling tower water flow scheme.

TABLE 22. TREATMENT APPROACHES AND THE CONSTITUENTS THAT ARE INFLUENCED BY EACH TECHNOLOGY

Cooling tower chemical criteria	Pre-treatment		Side-stream treatment	
	pH adjustment	Lime or lime soda softening	Filtration	Warm lime or lime/soda softening
Ca		Pri		Pri
$Ca \times SO_4$		Pri via Ca		Pri via Ca
$Mg \times SiO_2$		Pri via Mg		Pri via Mg
M Alkalinity	Pri[1]	Sec[2]		Sec
SO_4		Pri via Ca		Pri via Ca
SiO_2		Pri (Partial)		Pri
PO_4		Sec		Sec
pH	Pri			
TSS		Sec	Pri	Sec

[1] Pri: primary means of reduction, intention of process.
[2] Sec: secondary means, incidental reduction in process.

Water treatment methods include make-up water pre-treatment and side-treatment (Table 22). Pre-treatment is applied to the water inlet from outside the plant, while side treatment methods are applied to a portion of the recirculating flow in the cooling systems. Each configuration includes several water treatment methods.

Pre-treatment of cooling tower make-up

The primary limiting factor for cycles of concentration is calcium hardness. As a general rule of thumb, the calcium hardness in the cooling tower should be maintained within the range of 350 to 400 ppm on a non-acid treatment programmeme. If the make-up water contains, say, 100 ppm calcium hardness, the cycles of concentration are restricted to 3.5 to 4.0. Reducing the calcium hardness to 50 ppm allows the tower to run at 7 to 8 cycles.

Hardness reduction or removal can be accomplished by lime softening, sodium ion exchange (water softener), or reverse osmosis. Low-hardness make-up is often available from recycled and reused plant wastewater such as

spent rinse water and steam condensate. Water of any desired hardness can be obtained by the controlled blending of softened water with untreated raw or recycled water.

Side stream treatment

Side stream treatment includes filtration, to control suspended matter in the cooling system, and softening, to control scaling compounds.

Side stream filtration is employed when suspended matter concentrations in the source water are high enough to exceed the limits set forth in Table 23 at planned cycles of concentration in the cooling system. Suspended matter is also known as total suspended solids, TSS. Recall, film fill cannot tolerate high suspended solids because of its potential to plug, especially in the presence of bacterial films. Side-stream filters are usually located on hot side of the cooling circuit to take advantage of the pressurized water coming from the main condenser (i.e. no pumping is required). A stream of water is drawn from the return line/CT basin and fed to the filters. Filtered water is returned to the cooling tower basin through nozzle jets that agitate the water at the basin floor, which places the debris in suspension to increase the chances of it being withdrawn by the filter suction piping. Many side-stream filters are sized on a rule-of-thumb basis; i.e. typically at one percent of circulating water flow. The filters can also be sized on a mass flow basis.

Side stream lime/soda softening: Source water with high levels of silica (or silica and magnesium) can severely limit cooling tower cycles of concentration (Table 23) for cooling tower water quality criteria. For example, if a make-up water source has a silica (SiO_2) concentration of 40 mg/L, the cooling tower would be limited to 3.8 cycles of concentration. Recall that 8 cycles of concentration is considered a reasonable value. At 3.8 cycles of concentration, 150 percent more blow-down will be generated than a tower operated at 8 cycles. Make-up softening will remove some SiO_2, however, the amount of removal is usually not significant. Silica removal depends on the amount of magnesium removed as $Mg(OH)_2$ and the temperature of the water. $Mg(OH)_2$ floc (agglomerated particles of precipitate) is highly charged and silica is attracted to and adsorbs onto its surface. Other variables like re-circulating sludge can be controlled to maintain high floc density (and therefore floc surface area) within the reactor clarifier to enhance silica removal. The advantage of side-stream softening is that the water is warm, usually 40.5–46 °C.

pH adjustment

Traditionally, cooling towers operating on high-hardness, high-alkalinity make-up water utilized pH adjustment with sulphuric acid to maximize cycles of concentration. One part of 66° Baume acid is required to neutralize one part of alkalinity. Sufficient acid is injected into the make-up to maintain the total alkalinity of the cooling water in the range of 50 to 100 ppm or at a level that will maintain the pH within the range of 6.8 to 7.5. The Langelier, Rysnar, or practical scaling index is used as an additional control measure to correlate the calcium hardness, total alkalinity, pH, total dissolved solids, and temperature to maintain water chemistry at the neutral point of the index (neither scaling nor corrosive).

The problem with using acid to increase cycles is one of control. Accidental overfeed conditions (low pH) make the cooling water very corrosive to system metals. And reducing the M alkalinity (i.e. M alkalinity= $HCO_3 + CO_3$ expressed as mg/L $CaCO_3$) removes the natural passivating effect that carbonate and bicarbonate alkalinity have on steel. Operating the cooling tower at pH levels above 8.5 creates an environment that passivates steel and minimizes corrosion of galvanized steel and copper.

Unlike scale deposition, which can be removed by chemical or mechanical cleaning, damage caused by acid corrosion cannot be reversed and is very expensive to repair. In addition, the handling, transporting, and feeding of concentrated sulfuric acid creates additional environmental, health, and safety issues.

Chemical scale inhibitors

Various chemical additives and formulations are marketed that enhance the solubility of calcium and magnesium salts while at the same time controlling corrosion to within acceptable rates. These chemicals are generally phosphonates (organically bound phosphate compounds), polymers (mono-, co-, and ter-), and organic

TABLE 23. BASIC WATER QUALITY PARAMETERS TO BE MAINTAINED IN COOLING TOWER LOOP

Parameters	Units	Basic parameters
Ca	mg/L_{CaCO_3}	$900_{(max)}$[5]
$Ca \times SO_4$	$(mg/L)^2$	500–20 000
Ca with PO_4 present	mg/L_{CaCO_3}	(Refer to Table 18)
$Mg \times SiO_2$	$mg/L_{CaCO_3} \times mg/L_{SiO_2}$	35 000[2]–75 000[3]
$HCO_3 + CO_3$	mg/L_{CaCO_3}	30–50[2] — 200–250[3]
SO_4	mg/L	Note[5]
SiO_2	mg/L	150
Fe (Total)	mg/L	<0.5
Mn	mg/L	<0.5
Cu	mg/L	<0.1
Al	mg/L	<1
S	mg/L	5
NH_3	mg/L	<2[8]
pH		6.8–7.2[2] — 7.8–8.4[3]
pH with SO_4 Present		7.0–7.5[4]
TDS	mg/L	70 000
TSS	mg/L	<100[6]–<300[7]
BOD	mg/L	<100[4]
COD	mg/L	<100[4]
Langelier scale index		<0
Rysnar scale index		>6

[1] Cooling tower circulating water concentrations. PO_4 refers to total phosphate concentration.
[2] Without scale inhibitor.
[3] Assumes scale inhibitor is present.
[4] Consult with specialty chemical provider before finalizing control parameters.
[5] Refer to the $CaSO_4$ limit.
[6] <100 mg/L TSS with film fill.
[7] <300 mg/L TSS with open fill.
[8] <2 mg/L NH_3 applies when copper bearing alloys are present in the cooling system. Not applicable to 70–30 or 90–10 copper nickel.

corrosion inhibitors. These products are used alone or in combination with supplemental acid feed to maximize tower cycles.

Proven effective in lab tests and in the field, cooling water additives are usually limited to keeping calcium and magnesium salts soluble up to a Langelier index value of about +2.5. Other chemical programmemes push through the calcium solubility limit by claiming to maintain clean heat transfer surfaces at even higher cycles, despite the precipitation of hardness salts, which are chemically conditioned into a fluid, non-adherent sludge that is removed by routine bleed. Notwithstanding the benefits of a sound chemical treatment programmeme, if the cooling tower cycles are limited to fewer than five, significant water savings can be realized by improving the quality of the tower make-up.

TABLE 24. MAXIMUM COOLING TOWER CALCIUM WITH PO$_4$ PRESENT

pH	PO$_4$ (mg/L)	Max Ca, mg/L CaCO$_3$ at cooling tower TDS, mg/L				
		500	2 500	5 000	10 000	20 000
7.00	5	110	160	200	250	285
7.25	5	70	100	130	165	190
7.50	5	40	65	85	105	125
7.00	10	70	100	125	160	180
7.25	10	45	65	80	105	120
7.50	10	25	40	50	65	80
7.00	15	55	75	95	120	140
7.25	15	35	50	60	80	90
7.50	15	20	30	40	50	60

[1]   Cooling tower circulating water concentrations. PO$_4$ refers to total phosphate concentration.
[2]   Assumes scale inhibitor is present.
[3]   Consult with specialty chemical provider before finalizing control parameters.

   Non chemical treatment methods can be carried by adapting latest technologies of microfiltration (MF), ultrafiltration (UF), nano-filtration (NF), reverse osmosis (RO) and electro dialysis.

   Microfiltration is used to remove suspended solids, colloidal particles, cysts and bacteria. Unlike tighter membranes such as RO and NF that alter the chemical composition of the feed water, microfiltration is a particle removal process, primarily used for clarification and disinfection and thus is an excellent pre-treatment for RO and NF membranes. Microfiltration (MF) has demonstrated the ability to significantly reduce membrane fouling and provide stable, predictable RO performance. A microfilter removes particles as the feed water flows through the microfilter membrane. Microfilters remove particles down to 0.1 micron in size 10 to100 times finer than media filters. Microfiltration is a purely physical process in which particles are captured on the surface on the membrane. Any particle larger than the pore size of the membrane cannot squeeze through. MF pre-treatment typically achieves a silt density index (SDI) less than 3 compare to SDI 5 achieved by conventional methods.

   Reverse osmosis (RO) membranes are well suited for removal of dissolved solids, but adversely affected by suspended solids. Membrane fouling from suspended solids, colloidal material, bacteria and scale are the major reasons for RO system failure. The implications of membrane fouling are a decrease in flux and salt rejection, an increase in feed pressure and energy consumption and often irreversible membrane damage. Appropriate pre-treatment is the key to long term stable performance of RO membranes. Polyamide membranes, although able to operate at lower pressures and produce higher quality product water were subject to rapid fouling and possible irreversible bio-fouling due to their incompatibility with oxidants. The adoption of MF as the pre-treatment for RO systems reduced this fouling potential, enabled the reliable use of polyamide composite membranes even on wastewater treatment and allowed for a 20% increase in flux, resulting in a significant reduction in capital and operating costs. Overall, the total chemical costs for both microfiltration and RO units are just over $0.03 (US) per 10 m^3 of reclaimed water produced.

5.1.2.4. Recycling of cooling towers blow-down water to use as make-up water

   Blow-down from natural draft cooling towers (NDCT) or induced draft cooling towers (IDCT) is generally discharged to the nearby water bodies. However this blow-down water can be recycled up to 85 to 90% by using multimedia filter or micro–filter (MF) and RO or high efficiency electro-dialysis (HEED) process. This process controls cooling water quality by continuously removing suspended solids and dissolved minerals from the system.

Electro-dialysis allows salt to be removed at specified levels and can adapt to changing mineral content of either feed water supply or desired product water to maintain the desired water quality limits in the cooling tower. If microfiltration (MF) and reverse osmosis (RO) based treatment is provided to blow-down, about 85% of blow-down water can be reused as make-up water to cooling towers. After MF plus RO treatment, the total dissolved solid (TDS) will be reduced to 25 ppm. This process will reduce the actual make up required.

Considering an example of a 1000 MW(e) unit, the NDCT flow is 180 000 m^3/h with heat load 2125 MW(th) (Efficiency = 32%) and the IDCT flow is 25 000 m^3/h with heat load 260 MW(th). Considering river water chemistry for a tropical country, the make-up water requirement and blow-down quantities are worked out with treatment and without treatment and these values are indicated in Table 25. From this table it can be seen that the total NDCT blow-down quantity can be recycled using MF and RO and fed to the IDCT make-up. When the IDCT is fed from recycled NDCT blow-down, the IDCT COC can be increased to 28. Hence, the net make up requirement of 455 m^3/h can be reduced by NDCT blow-down recycling.

5.1.2.5. Reducing the cooling tower drift losses

Cooling towers are frequently used in industrial cooling and are accompanied by water drift. Drift is the loss of water (sometimes with water treatment chemicals dissolved in it) from the cooling tower because of the velocity of the air. This water is in the form of droplets and these can be trapped economically by impingement separators. The basic purpose of a drift eliminator is to control the undesirable loss of water, to reduce the damage to mechanical components and to reduce the nuisance caused to equipment in the surroundings due to spray. A drift eliminator does not directly take part in cooling the water, but has an indirect effect due to its pressure drop component making the air flow through the fill uniform.

Drift eliminators are specially designed to capture liquid droplets trapped in the exhaust air and to prevent these droplets from escaping from the cooling tower. Since these drift eliminators are in continual use, they can wear out over time, especially if no proper preventive maintenance is applied.

TABLE 25. BLOW-DOWN QUANTITIES

	Description	Condenser cooling circuit NDCT	Equipment cooling and nuclear process cooling circuit IDCT	Reduction
1	Heat load	2125 MW	260 MW	
2	ΔT	11^0C	9^0C	
3	Total flow (m^3/h)	180000	25000	
4	Evaporation loss (m^3/h) (2.0% of recirculation flow)	3600	500	
5	Drift loss (m^3/h) 0.005%	9	1.25	Negligible
6	Blow-down (COC=3 without any treatment)	1800	250	Base
7	Make-up required with COC = 3	5400	750	Base
8	Net blow-down required with COC = 8 (Chemical/MF+RO treatment and part NDCT blow-down recycling)	515	70	71.2%
9	Make up with COC = 8	4115	570	23.8%
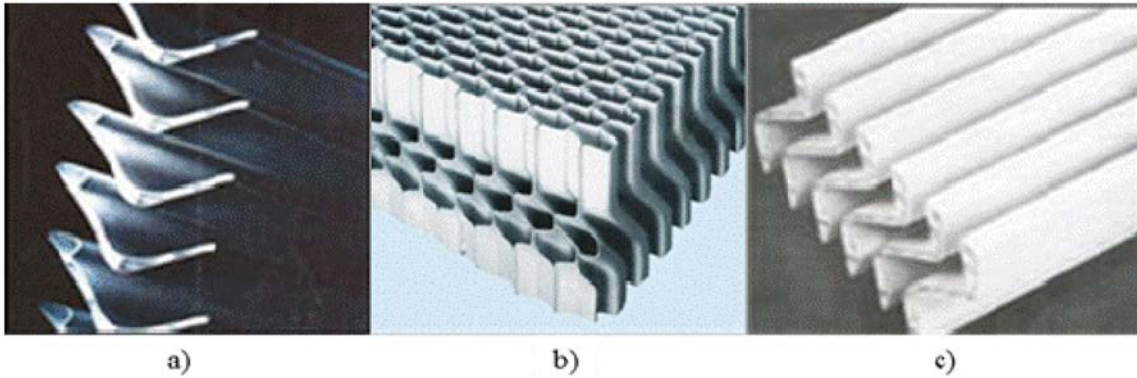
FIG. 59. (a) Munter/MM Aqua- Spectra. — Drift loss 0.003% for cross flow and counter flow cooling tower (b) Munter/MM Aqua D-15 Model — Drift loss of 0.001 % of total circulating watern(c) Munter/MM Aqua D-31 model -Drift loss 0.007% of total circulating water. Most suitable for cross flow CTs.

Drift loss without drift eliminator provision is in the order of 0.2% of the quantity of water circulated. Industry acceptable practice reduces water loss for large power plant towers equipped with drift eliminators to about 0.05% of the quantity of water circulated. However the efficient designs of drift eliminators currently available restrict drift loss rates to between 0.005 % and 0.001%. For a 1000 MW(e) power plant the loss of water due to drift can thus be reduced to less than one litre per second which should greatly minimize the drift problem.

By providing efficient drift eliminators the make-up requirement can be reduced and the plume effect on the environment can be reduced. For a typical 1000 MW(e) NPP with cooling tower base cooling they can save (0.2–0.001) = 0.199% of be circulating flow (180 000 m^3/h) through a condenser cooling tower (NDCT) and (25 000 m3/h) flow through an equipment cooling tower IDCT. The total saving is 408 m^3/h.

5.1.3. Reduction of heat rejected from power plant to decrease cooling requirements

An option to reduce water withdrawal or consumption in cooling systems is to reduce waste heat rejection. Heat rejection to the environment is reduced by increasing plant efficiency or by using excess heat for a thermal application. Several low temperature applications could use part of the waste heat from the nuclear power plant reducing the amount of heat rejected in the condenser. Possible low temperature heat applications (applications with temperature requirements up to 250ºC [42]) are:

— District heating;
— Heat for industrial applications;
— Thermal desalination;
— Aquaculture and Agriculture: Extensive pond aquaculture, animal shelters, algal ponds, intensive raceway aquaculture, undersoil heating, greenhouses.

As electricity is the main product of most nuclear power plants, expanded steam flowing to the condenser (especially in LWRs) is at a low temperature. Therefore, depending on the application, it could not be used on its own. High temperature steam from the power plant can be extracted only with reduction of electrical output.

According to the IAEA's PRIS database, 74 out of 433 reactor units worldwide are connected to non-electric applications (Fig. 60) and have delivered more than 720 TW·h heat energy to their linked non-electric application during 2008 [43]. However, this represents less than 1% of the waste heat available, emphasizing the unused potential for reduction of thermal loads released into the environment.

5.1.3.1. Waste heat recovery for district heating

Examples of waste heat being used for district heating or process heat can be found in nine Member States of the IAEA: Bulgaria, Switzerland, India, Czech Republic, Hungary, Romania, Russian Federation, Slovakia and
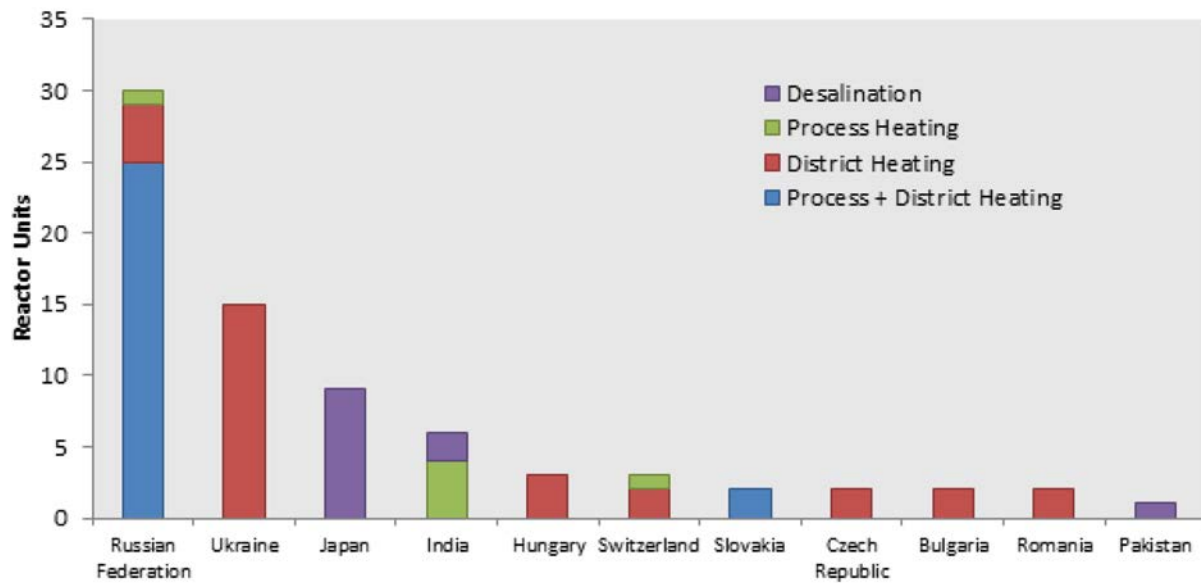
FIG. 60. Reactor units worldwide with non-electric applications and its application.
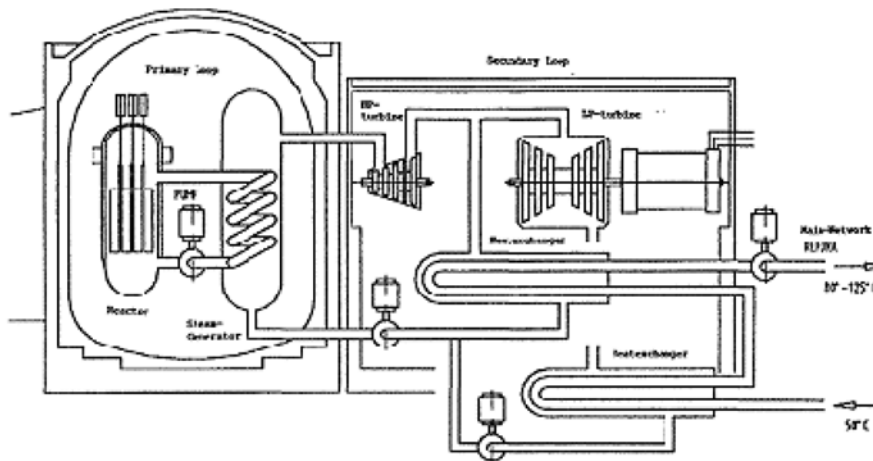
FIG. 61. Nuclear power plant with district heating at Beznau, Switzerland.

Ukraine [43]. Sweden also used 65 MW(th) for district heating from its 10 MW(e) research heavy water reactor in Ågesta 1964–1974 [44].

The Beznau nuclear power plant in Switzerland, with a total installed power of 750 MW(e), shows river water use of up to 40 m³/s for cooling when both units are in operation. The district heating network installed provided 142 GW·h in 2006/2007 [44] reducing cooling water needs in the condenser. The system described in Fig. 61 extracts steam at 128ºC between the high pressure and the low pressure turbine, while the preheating is done with steam extracted from the low pressure turbine with steam of 85ºC. The electricity penalty for the 80 MW(th) supplied to the district heating network is 10 MW(e) or 25 GW(e)h per year [42]. The water losses in the district heating system are usually 1–1.5 m³/d.

5.1.3.2. Waste heat recovery for industrial applications

An industrial complex adjacent to a nuclear power plant can be planned consisting of a heavy water plant, paper industry, desalination plant etc., in order to utilize waste heat from turbine. This waste heat is essentially free and available to stabilize heating and cooling costs as well as to provide readily available process water. Currently one such type of complex exists worldwide (Fig. 60).
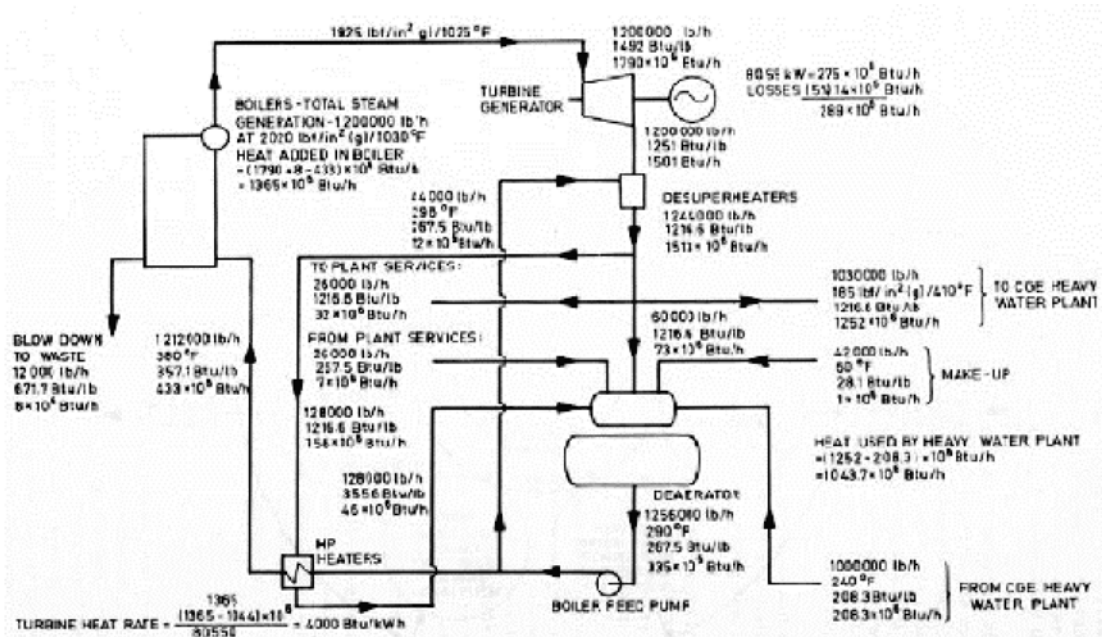
FIG. 62. Simplified heat balance diagram of unit No. 1 Point Tupper generating station.

Point Tupper industrial and power complex in Canada is an example of multi cogeneration plant. The complex (Fig. 62) is comprised of a power generating station, with 80 MW(e) capacity of which 26 MW are used by a heavy water plant, an oil refinery and a paper mill. Without a turbine condenser, of the 524 MW(th) supplied to the turbine, only 2.3 MW(th) are discharged into the environment as boiler blow-down [45]. The rest of the heat is used for the processes in the other plants in the complex. Of course, the problem here is the low electricity generation, but as an example it shows how heat rejection can be minimized.

5.1.3.3. Waste heat recovery for desalination

Low temperature evaporation (LTE) desalination technology utilizing low quality waste heat in the form of hot water (as low as 50°C) or low pressure steam (0.13 bar) has been developed to produce high purity water (conductivity <2 µS/cm) directly from sea water. LTE technology has found major applications in nuclear reactors to produce high quality desalted water for make-up water requirements. Continuous and successful operation of a 30 m³/d LTE desalination plant utilizing waste heat from the CIRUS nuclear research reactor in India has demonstrated the safety, reliability, availability and economics of nuclear desalination by LTE technology. Utilization of waste heat from the main heat transport (MHT) purification circuit of an advanced heavy water reactor (AHWR) to produce about 250 m³/d of high quality desalinated water is also proposed. Recently, a 50 m³/d two-effect low temperature desalination plant was commissioned with cooling tower where the specific energy and cooling water requirements are significantly reduced.

As an example, India is building a demonstration plant at Kalpakkam using a 6300 m³/day hybrid desalination system (MSFRO) connected to an existing PHWR. The RO plant, with a production capacity of 1800 m³/day, was set up in 2002 and has been operating since. The CIRUS research reactor, providing waste-heat to an LT-MED plant, has been operating since 2004. It is also planned to couple the forthcoming AHWR with a desalination plant. Indo-French collaboration on an integrated nuclear desalination system is progressing well.

5.1.3.4. Waste heat recovery for aquacultural uses

Oak Ridge National Laboratory Environmental Sciences Division, studies evaluated an aquaculture system using extensive culture techniques and natural ecosystem food supplies. Fin and shellfish that feed on the lower trophic levels of the food chain were utilized in the system. Addition of waste heat was used to provide regulated growth temperatures for phytoplankton and zooplankton cultures and for the fish systems. Planktonic growth is

further enhanced by the addition of nutrients available from a variety of waste streams. The planktonic biomass is used as the food source for fish culture and polyculture techniques are employed to utilize all feeding niches in the pond. The species selection concentrated on freshwater varieties because the majority of power plants, especially nuclear plants, are located inland.

Conceptually, the system functions in the following manner. A nutrient stream is heated using power plant waste-heat and flows into pond I with an appropriate amount of diluents. Algae begin the uptake of nutrients, in Pond I, and are grazed upon by zooplankton. The overflow from Pond I, loaded with algae and zooplankton, flows into Pond II where fish are grown. In Pond II fish consume algae, zooplankton, aquatic macrophytes (grown in the pond mud bottom) and benthic organisms. Water flows into Pond III loaded with fish waste products and algae are again used to remove the nutrients. In Pond IV clams are used as living bio filters, straining algae and bacteria out of the water. Crayfish are used in Pond IV to consume the clam wastes. Protein production is, therefore, concentrated in fish, clams, and crayfish. A final 'cleaning' pond containing aquatic vegetation may be necessary to produce a clean effluent.

5.1.3.5. *Waste heat recovery for heating and cooling greenhouses and animal shelters*

This involves the use of a conventional pad and fan system with finned-tube coils mounted downstream of the pads. The pads are typically filled with a fibrous material. Condenser cooling water drips vertically down along the fibers while air flows horizontally through the pad. The air is heated or cooled depending on the ratio of sensible to latent heat transfer. The cooled water is collected at the bottom of the pad and returned to the condenser. Warm water from the condenser can also be pumped through the finned-tube coils. The air coming from the pads is heated and dried by the addition of sensible heat from the fins. By varying the relative fractions of water pumped through the pads and coils and the airflow rate, the temperature and humidity of the air entering the greenhouse or animal shelter can be adjusted. This system can be used for summer cooling and winter heating. Heated or cooled air can be allowed to pass through the house and out the other end through exhaust fans. Under certain environmental conditions, such as cold weather, automatically controlled louvers would permit recirculation of the air through the attic (top part of house).

Oak Ridge National Laboratory studies carried out in the year 1978 indicate that for a 2.5 ha greenhouse located within 305 m of the nuclear power station, waste heat is the economic choice, when compared to fossil fuels at $1.66–$2.37/GJ, for greenhouse winter heating if the condenser cooling water outlet temperature is 27°C or above. If the condenser outlet temperature drops to 21°C, the economic feasibility of using waste heat depends upon climate and the cost of fossil fuels. For condenser outlet temperatures below 21°C the waste heat system is not economically feasible.

5.2. REDUCTION OF INDUSTRIAL AND POTABLE WATER USE AND CONSUMPTION

The industrial and potable water quantities used in nuclear power plants depend on several factors such as the number of closed loop heat sink circuits, the type of purification method adopted (i.e. resin basis or membrane base), the type of water used in the closed loop circuits (i.e. demineralized water, freshwater, heavy water), waste treatment methods being followed and the number of persons present in the plant. Common reduction strategies for industrial and potable water use/consumption provide tight closed loop circuits and avoid operational leaks, provide mechanical seal pumps or reduce gland leaks, provide a leakage collection system and recycle leakage water and system blow-downs. In nuclear power plants apart from potable freshwater there are two more types of industrial water to be handled: one is primary (contaminated water), the other is secondary (non-contaminated water). Strategies to be followed in optimizing water use and consumption differ depending on the type of water, as explained in following paragraphs.
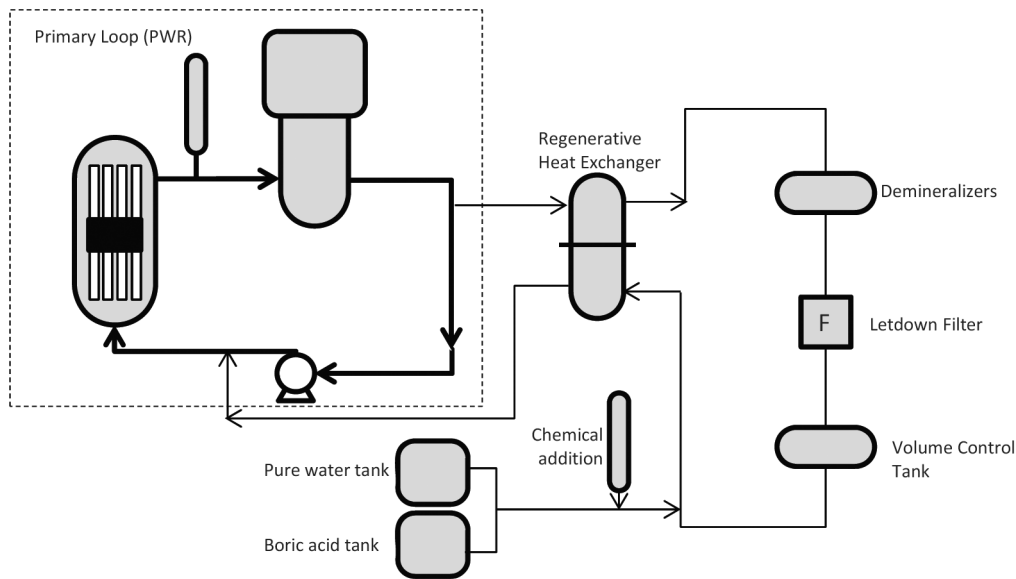
FIG. 63. PWR chemical volume control system.

5.2.1. Schemes for reducing primary water use and consumption in light water reactors

5.2.1.1. Recycling primary cycle letdown water

Potentially radioactive liquid wastes from the chemistry laboratory, containment sumps, floor drains, showers, and miscellaneous sources are collected in waste holdup tanks. Also liquid from the reactor coolant loop drains, accumulators, and excess letdown are collected and transferred to the boron recovery system (BRS) hold-up tank for recovery. Liquids flow to the wastewater hold-up tank by gravity, and then they are treated for reuse or discharge by the evaporator and demineralizer. Liquids should be cleaned up before being discharged to the environment. The activity level of the liquid waste is determined and recorded prior to discharge through a radiation monitor. Liquid requiring cleanup before being discharged to the environment is processed by the waste disposal de-mineralizers.

5.2.1.2. Recycling of chemical volume control system (CVCS) bleed flow

During plant operation most of all nuclear power plants have a continuous bleed flow rate. After being purified through the filter and demineralizer system the RCS bleed is returned to the reactor coolant system and there is no loss of reactor coolant. Feed and bleed functions of the CVCS (Fig. 63) are employed to maintain a programmed water level in the reactor coolant system pressurizer, thus maintaining the appropriate reactor coolant inventory during all phases of plant operation. This is achieved by means of a continuous process during which the feed rate is automatically controlled from the pressurizer water level.

5.2.1.3. Boron recycle system (BRS) condensate water reuse

The boron recycle system is designed to collect, through the letdown line in the chemical and volume control system, excess reactor coolant that results from plant operations during one core cycle. The boron recycle system (BRS) recycles reactor coolant effluent for reuse as boric acid and make-up water. The system decontaminates the effluent by means of demineralization and gas stripping, and uses evaporation to separate and recover boric acid and distilled water. The distilled water is sent to the reactor make up water storage tank.
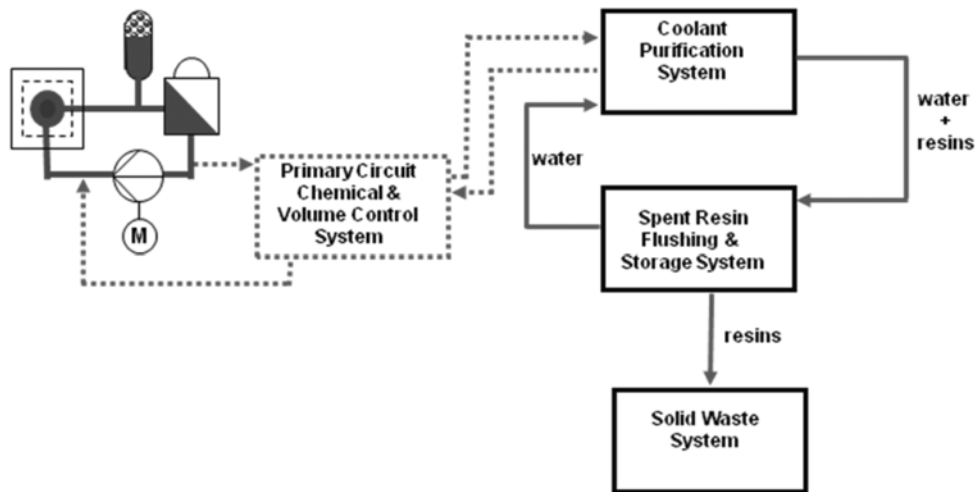
FIG. 64. Schematic diagram for recycling spent resin flushing water.

5.2.1.4. Recycling spent resin flushing water

In PWRs, the primary circuits (demineralized water base) are continuously purified by using filters and ion exchangers (Fig. 64). These ion exchangers (IX) need resins replacing after they get saturated. Demineralized water is used to flush out the resin from the ion exchange vessel and clean the vessel before recharging it with fresh resin. This water is recycled by straining the resin from water and disposing the resin as a solid waste.

5.2.2. Schemes for reducing primary water use and consumption in pressurized heavy water reactors

In PHWR plants, primary and moderator circuits utilize heavy water (D2O). Heavy water has very high production costs and it can also cause tritium activity to be spread in the area if there are leakages from circuits. Hence heavy water circuits are designed to provide leak tightness during operation by providing mechanical seal pumps, canned pumps and leakage collection systems for valve glands, double gasketed flange joints and sampling station cabinets.

5.2.2.1. Recycling of moderator circuit leakage

This circuit is provided with a D_2O leakage collection system to collect leakages from various flange joints, valve glands and sampling system cabinets. Any leakage is transferred to the D_2O addition and transfer system tank in order to transfer it back to the circuit through the purification system if the isotopic purity (IP) is the same as for the system inventory. If the IP of the leakage is less, then it is transferred to the downgraded D_2O storage tank. The deuteration and de-deuteration process in the resin of the IX vessel of the circuit's purification system also causes a loss of system inventory and generates downgraded D_2O. This downgraded D_2O is transferred to the downgraded D_2O storage tank. This inventory is sent to be upgraded through the plant evaporation and cleanup system. From the upgrading plant upgraded D_2O having an IP of 99.8% is sent back to the moderator purification circuit through the D_2O addition and transfer system. The upgrading plant reject water having an IP of 0.2% is sent to the waste management plant's liquid effluent segregation scheme area for disposal.

5.2.2.2. Recycling of PHT circuit drains and leakage

On similar lines of moderator circuit, PHT circuit drains and leakages are also recycled directly or after up gradation depending on purity of D_2O.
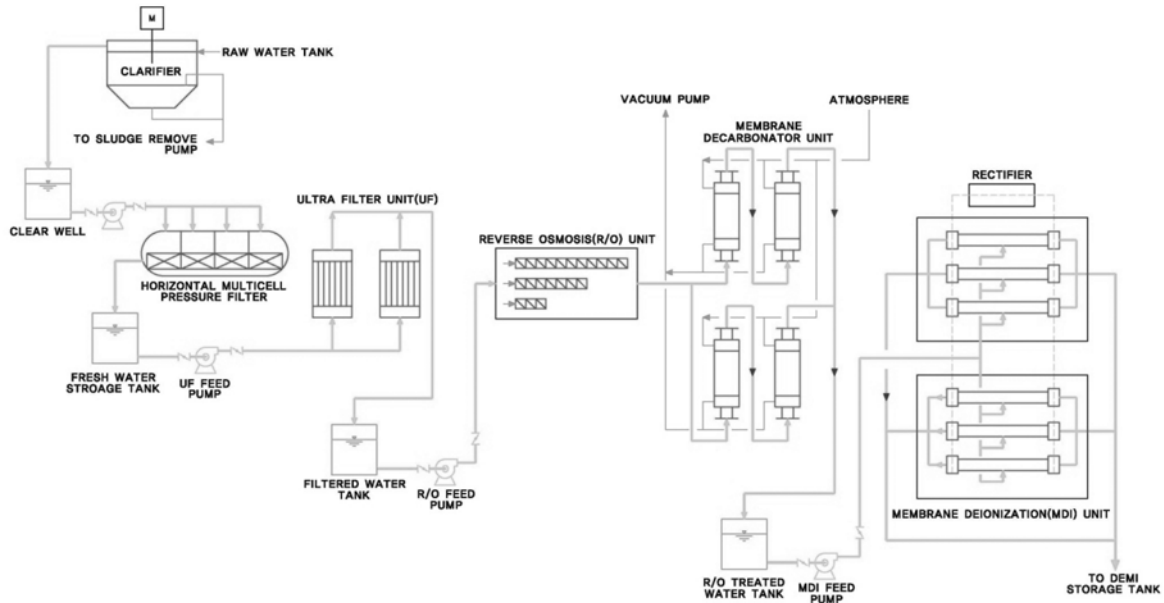
FIG. 65. Schematic diagram for the recycling of PHWR moderator circuit drainage and leakage using membranes.

5.2.2.3. Recycling of plants heavy water leaks and drains

To recover D_2O from plant system leaks without IP degradation, the various floor area drains in the reactor building and reactor auxiliary building are segregated and different leakage collection systems are provided. The fueling machine area has a high potential of PHT circuit inventory leakage. Hence at this area a separate leakage collection system is provided to collect D_2O leakages from the drains in this floor area in the PHT inventory recovery tank. The D_2O is transferred back to the PHT circuit storage tank through the purification circuit if its IP is not lower than circuit inventory. If, on the other hand, the IP is lower, the D_2O is sent to the downgraded D_2O storage tank for further processing and upgrading. Upgraded heavy water is sent back to the circuit through the D_2O addition and transfer system. All floor drains from the reactor building and floor drains from potentially active areas in the reactor auxiliary building containing D_2O equipment and active equipment like the spent fuel bay cooling system pumps and HX are collected in separate sumps and pumped after sampling either to the downgraded D_2O storage tank or to the waste management plant (WMP) liquid effluent segregation system (LESS) depending on the IP of the water. From the downgraded D_2O storage tank this inventory is sent for upgrading and then recycled into the circuit. The inventory of the WMP-LESS is disposed of after treatment. As the WMP LESS liquid discharge quantity is very small, having low IP and low tritium concentrations, it is discharged to the environment via air and water routes. For schematic flow diagram of the system see Fig. 66.

5.2.2.4. Recycling the system inventory drain during maintenance

In case of the PHWR, each heavy water circuit is provided with independent storage tanks and a drainage and transfer system due to considerations of activity and purity. These system lines are drained and the heavy water transferred to storage tanks for reuse after maintenance.

To conserve demineralized water either each circuit is provided with a storage tank equivalent to its inventory (Table 26) or there are common demineralized water storage tanks equivalent to the maximum capacity expected from any one circuit (for a PHWR the capacity of demineralized water storage tanks is 1200 m^3). During part/total maintenance of each demineralized water circuit, provision is made to transfer each circuit inventory into these tanks. After maintenance, this inventory is to be transferred back into system after adequate purification. A design provision is made to drain the circuit lines directly or to local sumps followed by pumping to these tanks.
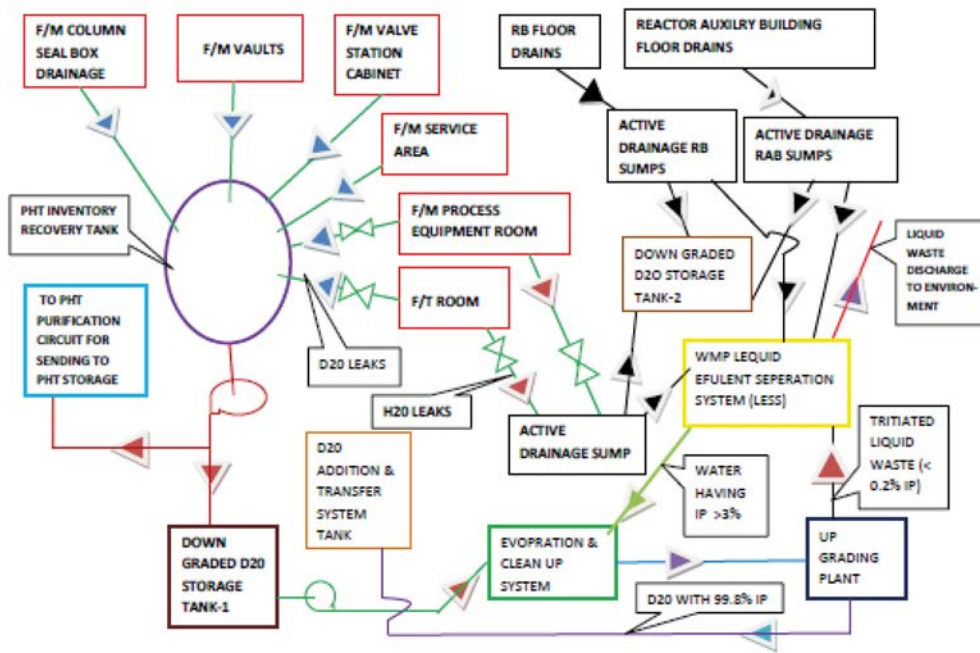
FIG. 66. Recycling of plant D_2O leakages and drains.

TABLE 26. TYPICAL NPP SYSTEM INVENTORIES

System	PHWR-700 MW(e)			LWR 1300 MW(e)		
	Type of water	Inland (m³)	Costal (m³)	Type of water	Inland (m³)	Costal (m³)
Condenser cooling water circuit (NDCT)	Fresh water	6500	Sea water	River water	6500	Sea water
Service water circuit (IDCT) + 7 days storage	Fresh water	18.600	Sea water	River water	18.600	Sea water
Fire water circuit — pipes	Fresh water	415	415	Demineralized	300	300
Fire water circuit — storage				Fresh water	1000	3000
Nuclear systems and component cooling circuit	Demineralized	1200	1200	Demineralized	500	500
TG component cooling circuit	Demineralized	400	400	Demineralized	450	450
Feed water circuit	Demineralized	600	600	Demineralized	1800	1800
Steam generator secondary side inventory				Demineralized	300	300
Reactor auxilary circuits	Demineralized	780	780	Demineralized	500	500
Spent fuel bay cooling circuit	Demineralized	5100	5100	Demineralized	1700	1700
Emergency core cooling circuit including sump inventory	Demineralized	1200	1200	Demineralized	1900	1900
Emergency feed water pools and circuit				Demineralized	1700	1700
Primary heat transport system	Heavy water	400	400	Demineralized	400	400
Moderator system	Heavy water	310	310	—	—	—
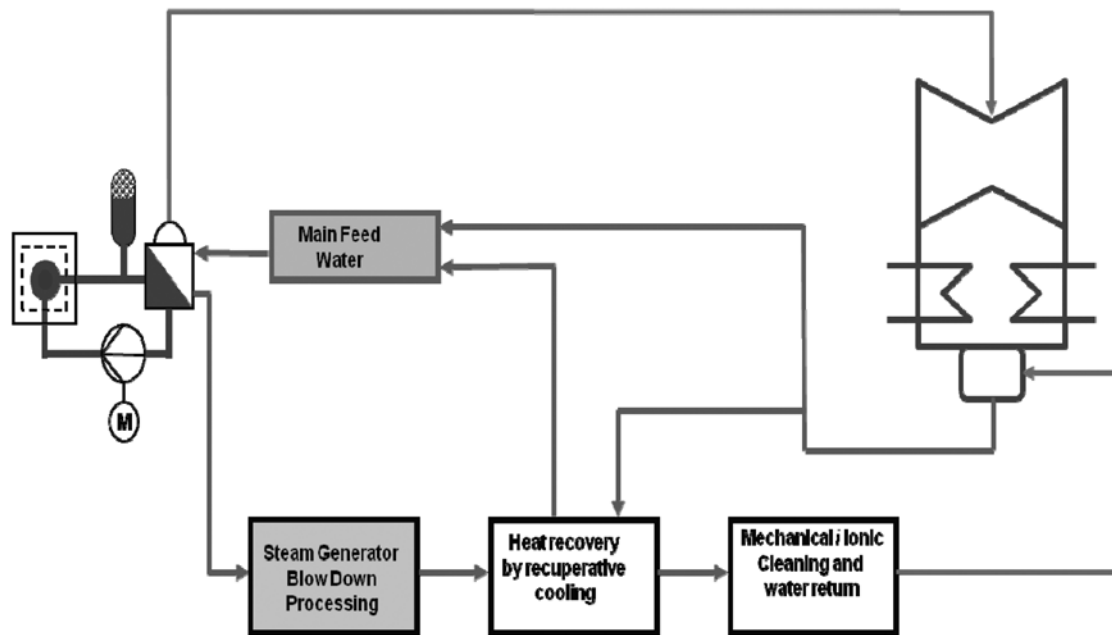
FIG. 67. Steam generator blow-down recycling circuit.

Presently fresh water is not considered as costly as demineralized water. Normally during maintenance the fresh water circuit inventory is drained and sent to inland water bodies or the sea through plant drains. To conserve water, whenever there is a requirement to drain the system at the next planned plant shutdown, then make-up to cooling tower circuits is stopped and the circuit allowed to operate until water in the cooling tower basin reaches the minimum level for submerging the pumps. The provision of a dry pond equivalent to the natural draft cooling tower (NDCT) basin capacity is created so that CCW system lines/tunnel inventory or the cooling tower basin inventory can be transferred one at a time during lines/tunnel maintenance or basin cleaning. This water is reused after passing through a treatment plant so that system water quality can be maintained.

5.2.3. Schemes for reducing secondary water use and consumption

5.2.3.1. Recycling of steam generator blow-down

The steam generator blow-down (Fig. 67) function is a necessity for the long term health of these very large components. The steam generator, in the course of generating steam for the turbine, will concentrate impurities. Because the impurities cause corrosion of the steam generator internals, they must be removed. Therefore, each steam generator should be operated with a continuous blow-down. In normal operation the blow-down flow rate is 10~30m^3/h per steam generator, but it depends on the policy for each plant. The typical blow-down rate is about 1% of the main feed water flow. The larger the blow-down flow rate, the greater the loss of thermal efficiency. In the event of a large ingress of impurities, such as a condenser leak or polisher contamination by chemicals, the blow-down flow rate should be increased (the expected peak is about 3%). Steam generator blow-down water is purified by a filter and demineralizer before recycling to a hot well. Since the blow-down recovery system is designed for 1% blow-down, whenever excess blow-down is carried out this is normally discharged to the plant drain. To reduce water consumption this excess blow-down can be recycled as cooling tower make-up, as has been employed at a number of locations. The primary concern when employing this technique is the interaction of polymers used as dispersants in boiler water and the polymers used as dispersants in cooling water systems.

5.2.3.2. Pump sealing water (main feed water pump and condensate pump)

Most pumps require sealing and cooling. In some plants the condensate water is supplied to the main feed water pump for sealing and recycled to the hot well. More than 30 m^3/h is needed for the main feed water pump
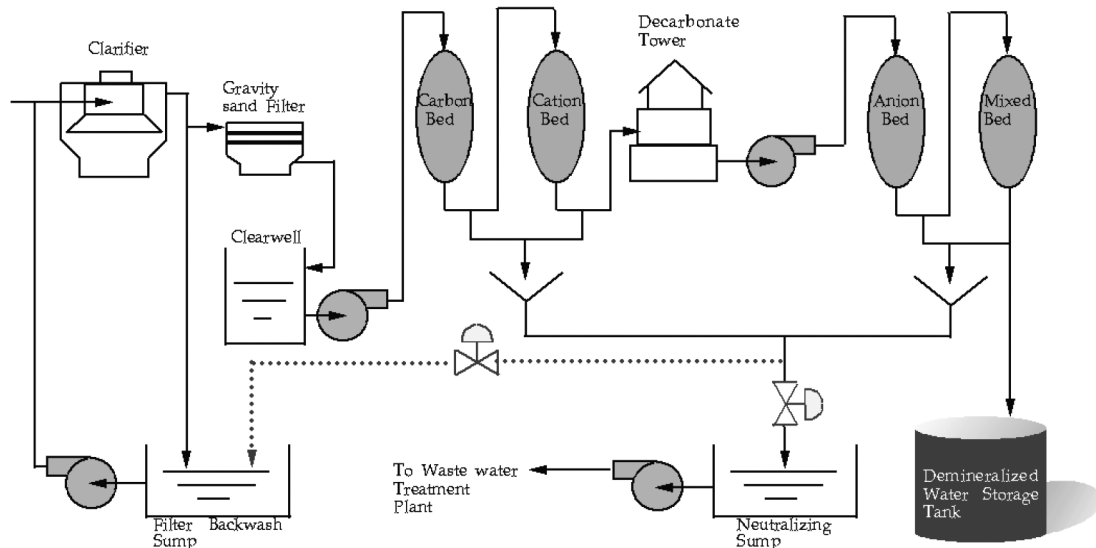
FIG. 68. Recovery of the WTP blow-down water.

sealing. In the case of condensate pump sealing water, this is discharged to the turbine sump because the quantity is so small compared to that of the main feed water pump. Currently mechanical seals are being adapted for pump gland sealing with a provision to cool mechanical seals by jacket cooling and oil cooling in order to reduce water consumption.

5.2.3.3. Recycling water treatment plant (WTP) and condensate polishing plant (CPP) blow-down and rinse water

In the case of a WTP using ion exchange resins (Fig. 68), the demineralizer needs to be blown down before servicing because the water in the bottom of the demineralized vessel is slightly high in conductivity. The blow-down water is either discharged to the wastewater treatment system or recycled to the recovery system. Even though the discharged water quantity in the recovery system is small it needs to be recycled. The blow-down of a demineralizer is recovered to the clarifier through the backwash sump.

In case of the CPP, after regeneration the stand-by vessel needs to be rinsed before operation to prevent contamination of the feed water from ionic species, especially the Na ion. Most plants discharge the rinsing water to the waste sump, but if there is a rinsing water storage tank, this water can be recycled. The quantity of water used for rinsing ion exchange resins depends on factors such as the plant chemistry criteria of the rinsing endpoint and regeneration state, etc.

5.2.3.4. Recycling of secondary system continuous sampling water

In PWR and PHWR plants, secondary systems sampling water is normally sent to plant drains after analysis, because there is always a possibility of contamination. The sampling water quantity is about 15–20 m^3/d. This quantity is one of the most important components of the recovery system. This sampling water can be recycled after treatment back into the hot well.

5.2.3.5. Recycling plant wastewater

Recycling plant wastewater is an important water conservation strategy. Steam generator blow-down water and pump sealing water is recovered. Contaminated water from sampling drains and regeneration water that is used for regenerating ion exchange resins for both the water treatment facility and the condensate polishing plant are drained to the wastewater treatment system. As Fig. 69 indicates, wastewater generated from the turbine building is collected separately, depending on its contamination level, and stored in the appropriate ponds.

Highly chemically contaminated wastewater that is usually generated from ion exchange resins of the water treatment plant and the condensate polishing plant is collected in chemical waste ponds, from which it is transferred
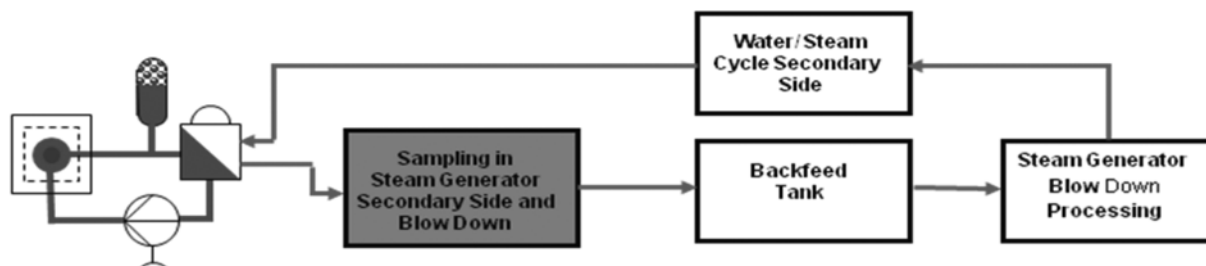
FIG. 69. Recycling of secondary system sampling water.

to the wastewater treatment system. Wastewater with less contamination is stored in the recycle pond and transferred to the water treatment system for reuse as a mixture of raw water.

5.2.3.6. Recycling non active plant wastewater

Apart from schemes indicated above for reducing secondary water (demineralized water) use/consumption, wastewater generated in the turbine building, leakage and drainage from potable water systems like condenser cooling water systems, domestic water system, chilled water systems and tertiary loop service water systems can be recycled. All non-active plant drainage is collected separately, stored in ponds and transferred to the water treatment system to mix with the fresh water supply.

5.2.3.7. Recycling of laundry water and reduction of water usage

Wastewater from laundry operations is high in oil, grease, biochemical oxygen demand (BOD), chemical oxygen demand (COD), total suspended solids (TSS), total dissolved solids (TDS) detergents and surfactants. These contaminants must be removed to achieve the highest percentage of recycling. Reducing TDS using desalting technologies is required to prevent long term greying of garments rendering them unusable. This threshold is believed by industry sources to be 2000 ppm.

Several different methods of pre-treatment are used on the washwater before it is discharged to the sanitary sewer. The complexity of pre-treatment varies from location to location depending on the size of the facility, the volume of water and chemicals consumed, the type and usage of products used by the customers being serviced, and the specifics of local, state, and federal requirements. Generally, most plants use shaker screens to remove lint, acid cracking to break the oil water emulsion and the addition of coagulants and flocculants to facilitate oil and soil removal. The oil/soil phase is normally separated by use of dissolved air flotation (DAF) and the resulting sludge is dewatered for off-site disposal. Another possibility to reduce the amount of fresh water use and liquid waste generation in the laundry is by using single use overalls or the use of various technologies as dry cleaning, ozone cleaning systems, ultrasonic cleaning.

5.3. REDUCTION OF WATER USE AND CONSUMPTION FOR WASTE DILUTION

5.3.1. Reduction of water use for waste dilution in light water reactors

All wastewater generated in the radiologically controlled area (RCA) is collected in the liquid waste storage system and treated in the liquid waste processing system before being recycled or discharged. During operation of an NPP, wastewater is produced by system drainage, leakage, flushing, cleaning and decontamination, etc. All radioactive wastewater generated in the RCA is processed in the liquid radioactive waste storage/processing system and finally discharged into the environment.

The liquid waste storage/processing system includes the following functions during operation:

— Wastewater collection: for optimum treatment the wastewater is collected according to chemical, physical and radiological characteristics in groups;

— Short term storage: the capacity of the tanks is designed to collect at least the volume generated during normal power operation per day;
— Liquid waste treatment: the treatment is based on evaporation, a universal method able to deal with all kinds of wastewater generated, which assures the best cleaning and decontamination effect to achieve a low discharge of activity and other nonradioactive matter into the environment;
— Liquid effluent release: the treated wastewater is sampled, analyzed and, provided all relevant environmental requirements are fulfilled, released;
— Control of liquid effluent discharge to the environment: during discharge of the treated radioactive wastewater the radioactivity is continuously monitored to avoid exceeding the limit established by the regulatory authority.

All water from the RCA which reaches the liquid radioactive waste storage/processing system has to be discharged after treatment. To reduce the amount and activity of wastewater discharged the first important countermeasure is a reduction in generation. This can be done if only water, which must inevitably be removed (e.g. wastewater from decontamination measures) is routed to the liquid radioactive waste storage/processing system. Leakages should be avoided and if they occur stopped immediately. Liquids from system or component drainage (e.g. during outage) should be transferred into systems or components of similar water quality with sufficient capacity and not to the liquid radioactive waste storage/processing system.

5.3.2. Reduction of water use for waste dilution in pressurized heavy water reactors

Tritium in radioactive liquid effluents is the prominent pollutant and is of major concern in the area of effluent management. There is no economically viable process available on an industrial scale for removal and retention of tritium from low level liquid streams. Presently, dilution and dispersal of low level tritiated liquid waste through the liquid route is practised.

The primary and moderator circuits in PHWR plants contain tritium activity due to the use of heavy water in the inventory of these circuits. Heavy water leakages are minimized to control activity release from the reactor building ventilation system and known sources are collected and recycled based on isotopic purity (IP). Where the water IP is greater than 0.3% it is sent to the upgrading plant. If the water IP is less than 0.3% it is sent to the centralized waste management plant for disposal. Upgrading plant reject water having an IP less than 0.2% is also sent to the waste management plant for disposal. Typical waste generation quantities and the respective tritium concentrations are indicated in the pie charts shown below.

The main plant waste streams containing tritium are the active non chemical waste (ANCW), tritiated waste (TTW) from the reactor building (RB) and the deuterium upgrading plant (UPG), neutralized active chemical waste (ACW) and potential active waste (PAW). Tritiated waste is generated mainly from reactor building drains (TTW-RB) and upgrading plant reject (TTW-UPG) even though combined quantity is 10% of the total waste. Yet, the tritium concentration is 99.48%. Potentially active waste generated from laundry and washing accounts to 48% of the quantity but tritium concentration works out to be 0.164% (Fig. 70).

The total liquid waste quantity of most of the older plants was discharged to external water bodies like sea, rivers, ponds and reservoirs utilizing once-through circuit condenser cooling water flows or cooling tower blow-downs without drawing extra fresh water for dilution. A typical 1000 MW(e) PHWR requires a dilution flow of about 80.000 m^3/day from the plant for mixing the active water and the further fresh water flow with external water bodies, which is equivalent to three times the effluent discharge from the plant. Since such water quantities are not available for new plants, a new methodology is used where highly tritiated water is discharged by evaporation through a stack. The evaporation of effluents having a relatively high level of activity ensures that the discharges to water are kept to a minimum. The air route mode of disposal offers a unique advantage of higher release limits per unit of dose allocation as compared to the liquid route. This mode of disposal suits inland sites where water is scarce and extensively used by the surrounding population.

As an example, tritium discharge system from a new 700 MW(e) PHWR plant in India is described. After filtration, the waste streams, having a relatively higher activity and lower volume of generation, will be diverted to a synthetic non regenerative ion exchange column to remove the dissolved beta-gamma activity and then stored in an evaporation feed tank. These waste streams (free of beta gamma activity) are vaporised either by a steam heated
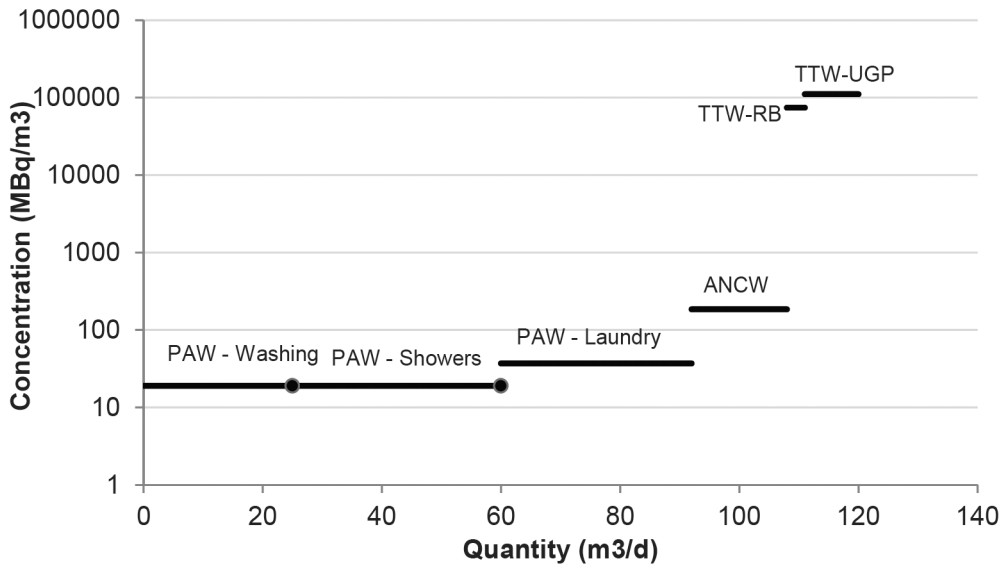
FIG. 70. Typical 1000 MW(e) PHWR active liquid waste generation (m³/day) and tritium concentration of each stream (MBq/d).

evaporator or by atomizing spray nozzles and the vapour is diluted with ventilation exhaust air, having a large flow rate of approximately 110 m³/sec, before discharging it through a stack.

Dilution of vapour with exhaust air is achieved through an evaporation chamber. Two evaporator feed pumps (one working and the other in standby) are provided to transfer the effluents either to an evaporator or to an evaporation chamber. This evaporation chamber is of stainless steel construction and is located at the main exhaust ducting (after HEPA filter housing and exhaust fan) leading to a 100 metre high stack. A sufficient number of atomizing spray nozzles with flow regulating valves and mist eliminators are provided in the chamber. Hydraulic atomising spray nozzles designed to deliver a very finely atomised hollow cone spray are employed to vaporize the liquid stream and also to inject the vaporized stream into exhaust air for dilution. These nozzles contain a precisely machined insert with tiny passages. Two banks of atomising spray nozzles are mounted in the vertical plane counter to the air flow to achieve better moisture loading in the air. A sufficient number of nozzles are provided in the chamber to obtain a controlled evaporation rate of 1 m³/h.

Facilities are provided with mist eliminators downstream of the spray nozzles, a glass viewing window for monitoring nozzle performance and a sloped bottom with a drain pit for collecting non-vaporized water particles from the chamber as well as from the mist eliminator. Any water collected from the drain pit of the evaporation chamber is discharged to the feed tank. As the ratio of dilution is very high (1:400.000), the increase in relative humidity (RH) will be insignificant. Due to the relative dryness of exhaust air, the vapour will be completely absorbed in air before release from the stack. Control logic is incorporated to stop the waste stream injection, when the RH of exhaust air reaches 85%, to avoid any possible condensation in the stack.

By releasing the 23% of highly concentrated TTW and ANCW waste by evaporation through a stack, the dilution flow requirement for the other 77% of potentially active waste with low activity has been reduced to 31 500 m³/d. To reduce fresh water withdrawal for dilution from external bodies further, it is planned to utilise cooling tower blow-down and plant drainage. A pond is created within the plant boundary for holding the water for some time and discharging it the environment over a period of 5 to 10 hours duration whenever active waste is discharged. This demand can be further reduced if water harvesting methods are implemented. The PHWR liquid waste management scheme being followed in one of the new plants is shown in Fig. 71.
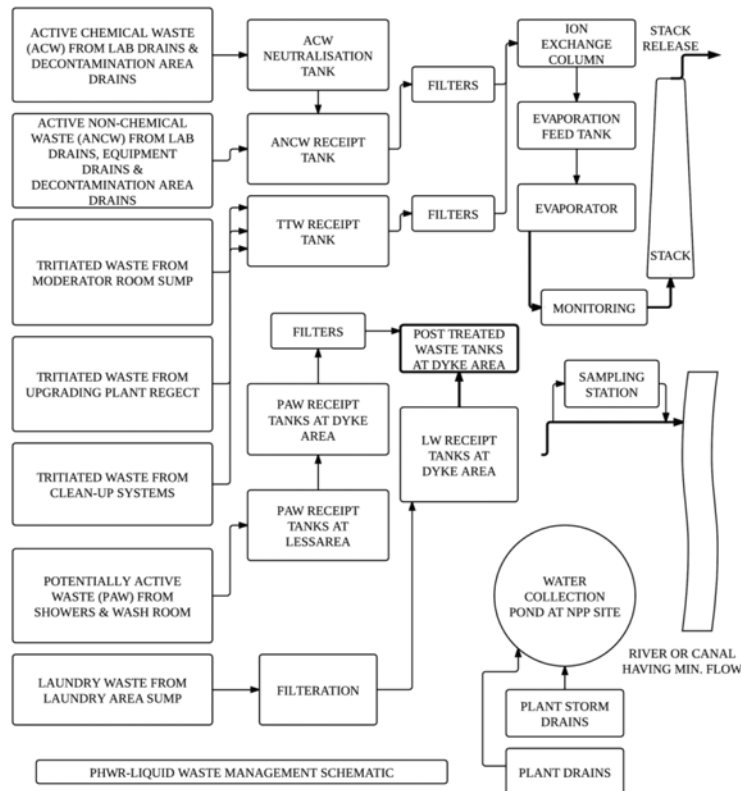
FIG. 71. PHWR liquid waste management scheme.

5.4. STRATEGIES FOR OPTIMIZING WATER USE AND CONSUMPTION IN MAJOR PHASES OF A NUCLEAR POWER PLANT

5.4.1. During design stage

— Compact layout: The plant shall have a compact layout to minimize pipe lengths in the various cooling circuits, so that the system inventory, leakage and other losses are at a minimum;

— Multi-unit sites: where services (such as demineralized water systems, domestic water systems, service water systems, chilled water systems, fire water systems) can be combined thus reducing water inventories and make-up requirements;

— Storage tanks for demineralized water based closed loop circuits and storage tanks/ponds for fresh water based closed loop circuits are to be provided. The capacity of these tanks/ponds is to be based on the largest volume of the circuit in each type of water so that the inventory of these systems can be drained during maintenance of any one of the circuits. After maintenance this stored water can be recycled after purification;

— A pond should be provided to collect plant drain water and cooling tower blow-down without discharging them directly to environment. This pond water can be recycled back into the main system after passing through the water treatment plant so that the system water quality can be maintained.

5.4.2. During commissioning

Closed loop circuits are cleaned with fresh water by adopting open loop flushing first and subsequently closed loop flushing. This water is normally drained and sent as a plant waste. As large quantities are involved, this water can be diverted to a pond provided within the site boundary. Subsequently this pond water can be recycled as make-up water to the cooling towers after treatment if necessary.

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5.4.3. During operation

Operators have to take proper precautions to ensure vent valves, drain valves and sampling valves are properly closed and leak tight, so that system inventory losses can be reduced.

Pump gland leaks are important; if glands are leaking heavily, the problem needs to be rectified.

During partial or total maintenance of any of the closed loop circuits, whether demineralized water, heavy water or freshwater, the circuit inventory has to be drained or transferred to storage tanks by either permanent or temporary connections. After maintenance, this inventory has to be transferred back to the system.

During maintenance of pumps in open recirculation loops (NDCT/IDCT) while at power, the sump inventory of each pump can be transferred to other sumps by reducing make up to the cooling towers. If cooling tower basins require cleaning as per the annual maintenance plan, prior to plant shut down, make-up to cooling towers is stopped until the system pumps operate at mimimum submergence condition. Then the basin inventory can transferred to storage ponds for refilling after maintenance. Similar action can be taken while draining circuit tunnels or piping for inspection and maintenance. The pond water can be reused after it is passed through a treatment plant so that the system water quality can be maintained.

In the case of a site with multiple units, if one of the unit's circuits is drained during maintenance, the inventory can be diverted as a make-up to other unit after adequate treatment/purification.

5.5. CONCLUSION

Use of variable speed drives on cooling pumps under various scenarios as discussed above can be an effective strategy for reducing water consumption in both once-through and closed loop circuits.

Improving the cooling tower cycle of concentration by pre-treatment of the tower make-up, pH adjustment, side stream treatment and chemical scale inhibitors and achieving an optimum COC based on technoeconomic considerations can prove to be another effective strategy for reducing water consumption. Micro filtration (MF) and reverse osmosis (RO) based treatment on cooling water blow-down can facilitate recycling of 85–90% of blow-down as make up water. Use of drift eliminators and recycling the system inventory drain during maintenance are potential strategies for water consumption reduction.

Utilization of waste heat and increasing the plant efficiency of future NPPs can reduce heat rejection. This in turn will reduce the water withdrawal or water consumption rate.

Recycling primary cycle contaminated water in LWR and heavy water drainage and leakage from moderator and PHT circuits of PHWR can lead to a substantial reduction in water consumption.

On the secondary side, recycling SG blow-down, water treatment plant and condensate polishing plant blow-down and the use of mechanical seals for pump gland sealing are effective ways to reduce water consumption. Recycling laundry water and the adoption of new technologies such as the use of supercritical CO_2, the Ozone cleaning system and ultrasonic cleaning can also lead to reduced water consumption.

In PHWRs, instead of dilution and dispersal of low level tritiated liquid waste through a liquid route, a new methodology of discharging highly tritiated waste (about 23% of waste discharged) by the evaporation method through a stack and the remaining 77% low activity waste through a liquid route can lead to a reduction of about 60% in liquid waste dilution water requirements.

In spite of adapting various methods to reduce water consumption in NPPs, the plant with the least water consumption will be the one with a once-through circuit even though there is an impact on thermal pollution in bodies of water, although in the case of seawater cooled plants this impact is less. There will not be any additional water withdrawal requirement for liquid waste dilution purposes.

The plant with the second lowest water consumption will be one with indirect dry cooling with water spray in the air inlet cooling tower circuit (Heller system) even though there is a reduction of plant efficiency. However water withdrawal for liquid waste dilution and also a large body of water such as a lake, pond or flowing canals/rivers is required.

There will not be any significant variation in industrial and potable water consumption based on the type of cooling circuit used but a 3%–5% higher consumption is expected in power plants in tropical countries due to higher water intake, regular showers and air washing plants in fresh air ventilation circuits.

6. FUTURE NPP DESIGNS FOR
IMPROVED WATER MANAGEMENT

As it is expected that water will become less and less available in the future and regulation will get more strict (if not prohibitive), the once-through or open-cycle system, today being the most efficient and economical cooling technology for an NPP, will probably be less common. The environmental concerns over the performance of this cooling system are rising, regardless of the water source, be it sea, lake or river. Furthermore, even with such a heat sink as an open sea, not every seashore can accommodate an NPP. Not only are there other site considerations, especially seism, but also in many instances the water is not deep enough for a large water intake and release.

The next best alternative is the recirculating system involving wet cooling towers, but this involves higher capital as well as higher operating and maintenance expenditure. Another drawback as compared to once-through cooling is the fact that, even if limited, it entails some water consumption since a fraction is evaporated inside the tower and not directly returned to the environment.

Since water is becoming more and more a scarce resource, other possibilities than oceans and rivers are being carefully analyzed. One possibility is the use of 'grey' or impaired waters and the pioneering Palo Verde NPP in the USA is the object of much attention nowadays. But the use of sewage effluent provokes a plethora of new issues with its impact on plant metallurgy, civil works, chemical treatments, corrosion control, solid waste management, etc. Meeting these challenges will be part of the development of future NPPs.

Another field that is opening is sea water desalination combining, in an industrial complex, a desalination plant and an NPP. New safety issues arise requiring in-depth analysis of the interaction between the two plants.

Beyond the availability of the resource other considerations can arise with recirculating systems and their wet cooling towers, notably the public acceptance of very large structures in the landscape with, additionally, the shadow of their plumes. Additionally, the hot and wet environment of the inner structures of the towers is favorable to the development of some germs that can subsequently spread with the plume. R&D programmes are being conducted to better assess the risks and to develop appropriate mitigation measures. Future NPPs will undoubtedly have to deal with this issue. Towards this direction the Idaho National Laboratory in the USA is recommending the initiation of a comprehensive R&D programme aimed at improving the environmental performance of cooling towers, targeted at reducing water consumption rates and at preparing for expanded use of towers in salt water environments. Focused effort is recommended also to be made in applications of hybrid dry cooling (e.g. plume abatement) and to operation of power plants under a range of climatic conditions [46].

With even more trade-off in terms of capital expenditure (CAPEX) and operation expenditure (OPEX), other cooling solutions will probably either spread more widely with new nuclear power plant constructions or even enter the world of existing plants.

Hybrid cooling towers are in the first category. They will probably meet an increasing success for they address aesthetic concerns with their lower profile. Additionally, with both wet and dry components being included in the system, they can be used separately or simultaneously for either water conservation or plume abatement purposes.

Dry cooling is in the second category, which so far has been applied only too conventional coal or gas fired plants. With the push to limit water requirements and the interest expressed in nuclear development by some countries with scarce water resources, the dry cooling solution will undoubtedly appear in the future in NPP designs.

This section discusses the foreseeable evolutions that will affect nuclear and conventional nuclear island designs. It then presents possible evolutions in terms of improving water management in nuclear power reactors. Opportunities regarding water cooled reactors are addressed first, through new concepts for systems and components designs, with a discussion on the research on new tertiary coolant as well as on new heat exchanger materials. The trends in their spent fuel management and the technologies to reduce their active liquid waste dilution requirements are also discussed. Finally, the next generation reactors (Generation IV) are considered: their high operating temperature will induce a better overall efficiency than that of the water cooled reactors, hence offering better avenues for dissipating heat at the condenser.
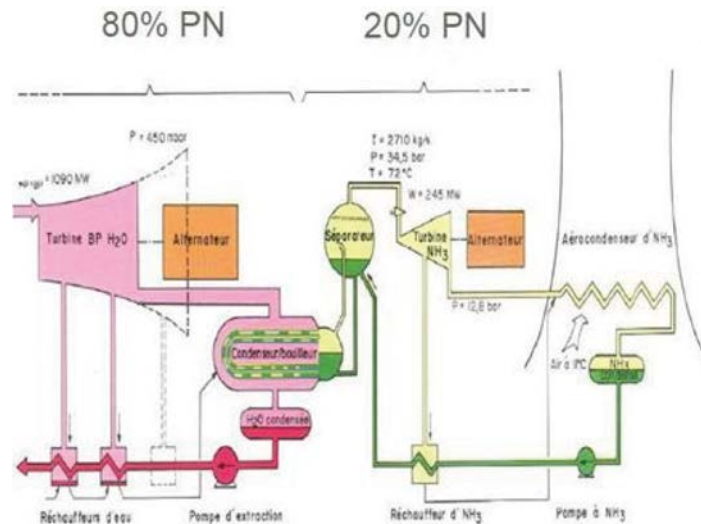
FIG. 72. CYBIAM cooling scheme.

6.1. NEW CONCEPTS OF WATER COOLED REACTOR SYSTEMS AND COMPONENTS TO IMPROVE WATER MANAGEMENT

6.1.1. Steam pressure increase

In the field of water cooled reactors following decades of developments, the improvement of overall plant efficiency remains limited mainly by the steam pressure that can be achieved at a reasonable cost but also due to manufacturing limits. Most steam generators operate at saturation conditions, which dictate the reactor operating temperature and pressure: the higher the pressure, the larger the forgings needed. Advanced steam generators recourse to an axial economizer, a built in plate and wrapper device, which directs 100% of the cold feed water to the cold leg of the tube bundle and which leads to a gain of a few bar on the operating pressure, hence to an increased plant efficiency. However, the manufacturing constraints remain in any case.

6.1.2. Research on tertiary coolants

An original approach was attempted by EdF during the 1980s with research on ways to reduce the turbine size. A pilot experiment, shown in Fig. 72, was built in Gennevilliers, France: a 22 MW(e) installation called CYBIAM (for BInary CYcle with AMmonia). The aim of the R&D was to reduce turbine size by generating steam with a denser vapor in the lowest pressure stages. The lowest pressure stages in the vapor cycle and steam condenser were replaced with an ammonia cycle (NH_3). It offered the advantages of increased power supply and dry cooling, and the technology appeared promising. But market conditions were not favorable, and the technology was never scaled up. The CYBIAM test loop has been dismantled but the experiments have been well documented, and, with today's greater interest in new cooling methods, the concept could be viable again, with a possible shift in interest and focus from the 'smaller turbine' feature to the 'dry cooling' feature.

6.1.3. Improvement in heat exchanger properties

No breakthrough is foreseeable with the materials used on a large scale in NPPs and so conventional materials will be around for years to come. Some advanced cooling solutions are being tested with high thermal conductivity graphite foams. These materials offer a thermal conductivity equivalent to that of aluminum alloys at 1/5th of their weight. Moreover, their porous structure increases drastically their surface area as compared to conventional heat exchangers. However, these materials have emerged only recently and are still in the infancy of their development. They seem confined for the time being to very small applications like cooling electronic components.

Some other applications are being explored like cooling brake and clutch parts in the automobile industry. They are also being tested in space where they should find dedicated applications because of their weight/efficiency ratio. Using them on very large industrial applications like the heat exchangers of a dry cooled NPP is a giant leap, though, and if it ever happens it will take many years of development, testing and qualification.

6.1.4. Heat recovery from the secondary cycle

As water is the perfect material to be used for energy conversion in large size power plants, the water inventory in the secondary cycle itself cannot be reduced significantly. Water consumption results mainly from leakages, blow-down, flushing and cleaning of the secondary cycle systems.

Two aspects may drive future development:

— The increasing cost of water makes it economically reasonable to reprocess wastewater;
— Environmental aspects will further decrease limits for the discharge of polluted water.

Recovering heat for other uses from the turbine and the condenser can reduce the cooling needs and subsequently the water needed in the condenser. However, the temperature of the turbine condenser is very close to that of the environment. Extracting heat from its water has only limited interest like warming up green houses for agricultural purposes, fish farms or perhaps crocodile farms for tourism and ultimately for the animals' skins.

On the other hand, heat can be extracted from the turbine itself as process steam. This can be used for industrial purposes or for heating buildings. The consumer is required to be near the NPP though. Probably a more promising trend will be the use of a large part of the energy to produce drinking water from sea water through a desalination plant. Usually steam is extracted from the low pressure turbine at a pressure of approximately 5 to 6 bar and process steam is then produced in a separate loop, to be used for desalination. This increases the overall plant efficiency, because this part of the steam will not transfer its latent heat of condensation to the cooling water (where it is lost to the environment). It is a well-known technology, though not so much used in the past because NPPs are located mostly on isolated sites, far away from other industries.

6.1.5. Reduction of blow-down losses

Secondary side blow-down can be reduced by using high corrosion resistant materials in the turbine condenser (to stop possible ionic pollution due to loose condenser tubes) and application of adequate water chemistry (reducing the production of corrosion products). Older plants often discharged the blow-down water completely. Current design is to clean the blow-down and charge it back to the secondary cycle. Thus the water consumption is reduced to that necessary for cleaning and backwashing resins used for blow-down cleaning. As the blow-down of heated water represents a loss of energy, it is beneficial also for plant efficiency to decrease the blow-down rate, which reduces water consumption.

The development of cooling system materials that are resistant to scaling, corrosion and fouling may make it possible to operate at higher concentrations of solids, significantly reducing blow-down losses. A study by EPRI and the California Energy Commission found that doubling cycles of concentration of a cooling tower from 4 to 8, which exceeds the usual allowable range, could reduce blow-down by about 380 liters per MW·h. Examples of plants running high cycles of concentration cooling towers with zero liquid discharge systems are available in the literature [47, 48].

The technologies for cleaning and reusing the effluents on secondary side are available; to implement them is only a decision of economics. Efforts to shorten the outage time for refueling, which also improve the overall plant performance, will be beneficial for decreasing drinking and potable water consumption as the duration of stay for the additional personal on site will be reduced.

6.1.6. SMR implications for cooling water

The SMR world seems to be moving fast towards industrial reality; SMRs can be more appealing to investors than large units because of their lower capital cost and shorter construction time. They cannot rely on the traditional

economy of scale. Instead, they offer economy of identical multiples, lower financing requirements, and faster response to market needs.

Regarding water consumption, precise figures are not available since these models are still under development. However, looking at target thermal power versus electrical output, their overall efficiencies cluster around the 30% mark, which is much lower than for advanced large units being built that target up to 37–38%. Hence the cooling water need per MW(e) produced will be at least 5% higher for SMRs than for large Gen III+ plants currently being built. Dry cooling of course remains an option to reduce water usage, bearing in mind that it can affect heavily their moderate efficiency. The precise impact depends on local conditions of wet and dry bulb temperatures. But usually dry cooling would be most sought after in hot and dry areas where water is scarce and it is unfortunately under such conditions that the penalty for dry cooling is the highest.

6.2. TRENDS IN SPENT FUEL MANAGEMENT

During the past 15–20 years the storage capacity of fuel pools was increased using high density spent fuel storage technology. To achieve maximum capacity, storage racks were replaced in many of the power reactors in operation and some of them went through various re-racking cycles.

Nevertheless, the amount of accumulated spent fuel to be stored is growing. For now, nuclear power plants have to keep their growing supplies of spent fuel on site in fuel pools that were never intended to double as long term storage bins. Besides the current storage of spent fuel in the fuel building pools in nuclear power plants there is a remarkable need in additional storage capacity for following reasons:

— Pools in the fuel building have a limited space, thus in the most plants its maximum capacity can only be achieved after re-racking and utilization of high density storage racks (HDSR).
— Increased burn up in fuel assemblies is an attractive economic aspect for two reasons. On the one hand the increase in burn up provides the predominating influence on the costs if disposal costs are quoted in €/kgU. On the other hand, in order to reduce fuel cycle costs, an important technical target is to minimize the amount of spent fuel discharged from the reactors.
— But the consequence of these developments in the fuel cycle strategy is an extended storage of the spent fuel before transportation, because decay heat and radiation levels increase with higher burn up.
— Transportation to reprocessing plants or final disposal facilities is often politically difficult or impossible due to non-availability of the respective facilities.

Therefore, out of pool storage facilities, so called independent spent fuel storage installations, (Section 2.3.2.1) have to be established, either at the site of power reactor or away from them, as has the been the case for a couple of years. These independent spent fuel storage installations use either wet or dry storage technology, the latter in form of metal casks and concrete silos or vaults.

One of the latest achievements in wet storage technology is used in a currently designed new spent fuel storage building at Goesgen nuclear power plant in Switzerland. The advanced design provides a passive cooling system which reliably removes the heat generated by the spent fuel by natural circulation through air cooled heat exchangers. The passive cooling is based on the principle of natural circulation (Fig. 73).

The fuel pool cooling system consists of four trains. Each train is equipped with plate heat exchanger(s) installed inside the fuel pool and water/air heat exchanger(s) installed in one of two cooling towers. No active components such as pumps are needed in this system. Natural circulation transfers the heat from the pool to the cooling towers.

Natural air circulation ensures reliable heat transfer from the water/air heat exchanger to the ambient air. In order to provide comfortable conditions for the operators at the operating floor in the case of high ambient temperatures during summer at the same time as maximum heat load in the pool, electrical fans can be used to limit the pool water temperature to the desired level. During normal operation power supply is required only for the fans of the cooling towers. In the case of abnormal operating condition the electrical fans are not needed. The system is designed for absolute passive operation, no emergency power supply and safety-related I&C are necessary.

Due to the passive nature of the operating system, the number of active components, such as pumps, which require maintenance, is substantially reduced. This progressive design not only makes extensive use of
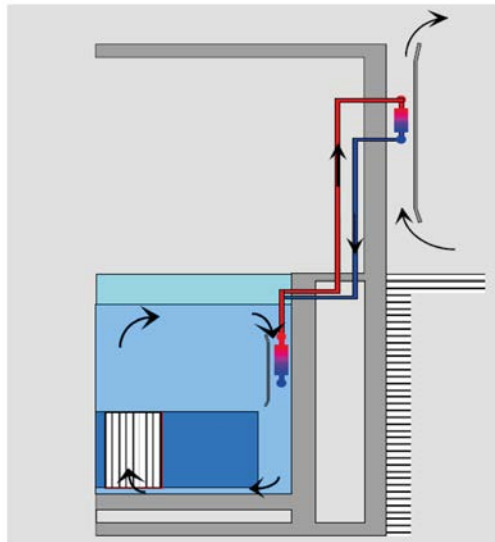
FIG. 73. Passive spent fuel pool cooling system (principle).
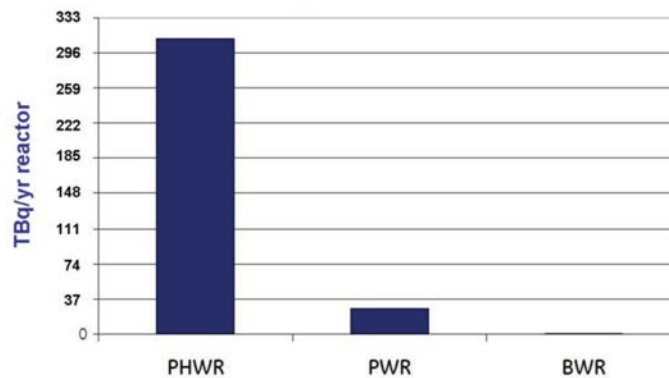
FIG. 74. Annual liquid tritium releases by type of reactor.

well-balanced safety technology with largely passive safety features but also results in low operating costs and reduces the use of water for cooling purposes. The water consumption is limited to make-up for the pools due to evaporation on the surface and cleaning processes.

6.3. NEW TECHNOLOGIES FOR REDUCING ACTIVE LIQUID WASTE DILUTION REQUIREMENTS

Water reactors produce tritium in their coolant, moderator and control rods following activation of deuterium, lithium and boron. In heavy water reactors, neutron absorption by the deuterium of the heavy water produces large quantities of tritium (Fig. 74).

Unfortunately, tritium isotope separation technologies available for small capacity need further development for commercial application at NPPs. Hydrogen isotope separation technologies include processes that separate deuterated water (HDO and D_2O) from H_2O and/or tritiated water (HTO) from HDO and D_2O. None of these processes are used on a large commercial scale for separating very low concentrations of tritium from light water or heavy water. Processes listed below would require some work before they can be adapted for tritiated waste treatment or for the reduction of tritium concentrations in primary circuit water (light water or heavy water) and the heavy water moderator in PHWRs, so that the water dilution requirement can be reduced and this waste converted to solid waste for easy disposal.

6.3.1. Water distillation

Isotope separation by water distillation is based on the small differences in vapour pressure between water species containing different hydrogen isotopes. Water distillation for separation of HDO and D_2O from H_2O is a safe and well-established process that has been used on an industrial scale at commercial heavy water nuclear reactors for many years in the USA, Canada, and Europe. However water distillation has not generally not been used to remove traces of HTO from large volumes of wastewater. GE-Hitachi nuclear energy has recently implemented water distillation for tritium removal from a relatively small waste stream at a radiochemical processing facility in the United Kingdom (UK). GE has also proposed water distillation for the treatment of wastewater at commercial nuclear power plants. A key feature of the GE process is the use of vapour recompression to reduce energy consumption and cooling water demand.

Water distillation separation is based on the relative volatility of HTO and H_2O. At 60°C, the H_2O vapour pressure is about 1.056 times that of HTO. Thus the equilibrium liquid mole fraction of HTO is 1.056 higher than the gas phase mole fraction [49]. To reduce overall energy consumption and cooling water requirements, mechanical vapour recompression (MVR) is utilized to heat the re-boiler. The overhead vapour stream is compressed and it condenses in the re-boiler. The condensing energy of the overhead steam is used for boiling the bottoms product in the re-boiler. By this method, approximately 90% of the energy used for standard distillation is conserved [50].

The cost of this method will be approximately $71 per cubic meter. This is a high energy consuming method.

6.3.2. Combined electrolysis catalytic exchange

Combined electrolysis catalytic exchange (CECE) is one of several processes based on the use of the hydrogen/water exchange equilibrium reaction (Eq. 1) that favours formation of liquid HTO when liquid H_2O is contacted with tritiated hydrogen (HT) gas.

$$HT(g) + H_2O(l) \leftrightarrow HTO(l) + H_2(g) \tag{1}$$

The CECE process has a high isotopic separation factor at near ambient temperature and pressure operating conditions. A catalyst is required for the reaction to proceed at an appreciable rate, and the development of improved hydrophobic catalysts in recent years has been key to the commercial success of the process.

The CECE process requires electrolysis of all feed water plus some deionized water used for stripping (approximately 1.4 times the feed flow is electrolyzed).

$$2H_2O(l) \rightarrow 2H_2(g) + O_2(g) \; E_0 = 1.229 \tag{2}$$

$$2HTO(l) \rightarrow 2H_2(g) + O_2(g) \; E_0 > 1.229 \tag{3}$$

The electrolysis separates tritiated water into elemental hydrogen (H_2), tritiated hydrogen (HT), and oxygen (O_2) gases. H_2O is more easily electrolyzed than HTO, so that H_2O is depleted from the liquid causing the HTO concentration in the electrolyzer liquid to increase. The CECE process is energy intensive because of the requirement to electrolyze 1.4 times the feed water.

A variation on the CECE process uses a palladium membrane reactor to separate elemental hydrogen from water to provide the required elemental hydrogen feed to the catalytic exchange unit. This has the advantage of eliminating the electrolysis cells and their associated power consumption. However, it has the disadvantage that a reducing agent (e.g. carbon monoxide) be must be added to drive the chemical reactions that split hydrogen from water.

The process consists of counter current gas/liquid exchange columns packed with catalyst beds, an electrolysis cell, and a hydrogen/oxygen re-combiner (omitted if hydrogen co-production is desired). A platinum based hydrophobic solid catalyst is used. Tritiated water is added mid-column. As the water flows down the column, the tritiated hydrogen is transferred from the rising gas stream to the descending liquid stream according to Equation 1.

The rising hydrogen gas stream is partially depleted in tritium in the bottom half of the upper section of the column. In the top half of the upper section, clean water further reduces the tritium content of the rising hydrogen, resulting in a hydrogen stream exiting the top that is nearly exhausted of tritium.

The combined water stream (feed plus added clean water) exits the bottom of the column to an electrolysis cell where it is electrolyzed to oxygen, hydrogen, and tritiated hydrogen gases by Equations 2 and 3. The enriched tritium stream can be taken from the bottom of the column as tritiated water or tritiated hydrogen gas depending on the desired form of the product.

However, a recent cost estimate by AECL prepared for the SRS provides a rough idea of costs that may be expected. The estimate indicated a treatment cost of ~$0.32 per litre for treating 1.3 L/s of water with a tritium concentration of 7.4MBq/L based on 1999 costs and an electric power cost of $0.02 per kW·h. With escalation for today's capital, operating and power costs this estimate would approach $0.5 per litre. The energy cost for CECE tritium separation is approximately four times the cost for conventional water distillation using mechanical vapour recompression [49].

6.3.3.   Bithermal hydrogen-water process

The bithermal hydrogen-water process is based on the same hydrogen/water exchange reaction as the CECE process, and may be able to use similar catalysts. However it does not require electrolysis of the feed water, but instead relies on a recycled stream of hydrogen coupled with dual temperature separation columns.

This process consists of cold-stripping and cold-enriching columns and hot-enriching and hot-stripping columns stacked in a vertical orientation with hydrogen gas flowing upward counter-current to the aqueous streams. Tritiated water to be treated is introduced between the cold-stripping and cold-enriching columns. Three conditions are important to maximizing separation factors: (1) use of an active hydrophobic catalyst, (2) temperature control to enhance the stripping and enriching conditions, and (3) high pressure. Hydrophobic catalysts are used, similar to the CECE process. However, some catalysts developed for CECE are not suitable because their upper temperature limit is about 100°C, which is lower than the optimum temperature for the bithermal process

In the upper 'cold stripper' section, non-tritiated water is used to absorb tritium from the circulating hydrogen. The resulting hydrogen gas, essentially free of tritium is re-circulated to the hot-stripping column to remove tritium from the wastewater to be discharged. The tritium-rich product stream is withdrawn from between the cold and hot enrichment columns. The columns are operated at near 49 atmospheres pressure to achieve maximum separation factors. The hot enrichment and stripping column sections are operated at about 170°C, and the cold-stripping and cold-enrichment column sections are operated at about 50°C.

Total treatment costs (capital, utilities, labour, etc.) for this process are expected to be similar to the costs for the CECE process with the lowest cost option depending on capacity, operating duration, power cost, and other site specific factors.

6.3.4.   Palladium membrane reactor

The palladium membrane reactor (PMR) has been developed for the separation of hydrogen gas from other molecules (i.e. oxygen, carbon monoxide, and carbon dioxide). It is not a direct method for producing hydrogen isotopes, but the PMR generates a crude product for further purification by hydrogen isotope separation processes (e.g. H_2/H_2O catalytic exchange, cryogenic distillation, gas diffusion, thermal diffusion, or gas adsorption).

PMR directly combines two techniques which have been long utilized for hydrogen processing:

— The water gas shift reaction: A platinum or nickel catalyst is typically used to increase the rate of the water gas shift reaction at practical operating temperatures.

$$CO + H_{2O}\ H2 = CO_2 \tag{4}$$

— Palladium/silver membrane separator: Palladium silver membranes selectively allow diffusion of hydrogen isotopes with essentially zero diffusion of the other gaseous species (CO, H_2O, and CO_2). These membranes have long been used for the production of ultra-pure hydrogen.

A gaseous mixture containing carbon monoxide (CO) and water vapor is fed to the palladium metal reactor. The feed mixture can be produced by boiling the feed water and blending it with CO, or by reacting the feed water at high temperature with a reducing agent such as coke, charcoal, or hydrocarbons.

The PMR contains a bed of catalyst (typically nickel or platinum) where hydrogen is split from the water and CO_2 is produced. Hydrogen is removed by diffusion through palladium tubes located inside the catalyst bed. Removal of hydrogen allows the shift reaction to proceed further to the right increasing conversion of water to hydrogen. The high purity hydrogen stream is transferred to a second process for separation of tritium from the other hydrogen isotopes.

To provide a high extent of conversion of water to hydrogen, a substantial pressure differential is required between the catalytic reaction side of the palladium silver membrane and the high purity hydrogen permeate side of the membrane. For tritium separation, a vacuum on the permeate side has typically been used to provide the pressure differential. Multi-stage vacuum units may be considered to reduce energy consumption by removing most of the hydrogen at moderate vacuum followed by succeeding steps with higher permeate vacuum.

The PMR is expected to provide some incremental cost savings for selected tritium separation processes depending on site specific factors. The isotope separation processes that would be supported by the palladium membrane reactor have not been used at near the scale required for NPP tritiated waste treatment.

These processes are considered to be excessively costly and needs further development. This process also requires handling of large volumes of toxic and/or potentially explosive gas mixtures (CO and H_2) resulting in additional safety hazards [50].

6.3.5. Tritium adsorption bed separation

The tritium concentration in water effluents can be reduced to acceptable discharge levels by processing the water through an adsorption bed. Under the direction of MSI at Clemson University, extensive pilot-plant testing with fixed-bed ion-exchange media has been conducted with both simulated and process feeds. Demonstration testing was conducted in the laboratory with actual reactor cooling water in the year 2000.

Tritiated water at low concentrations in light water is preferentially loaded on a proprietary adsorption bed as hydrated water, allowing the tritium-depleted stream to pass through the bed. Cation sites attached to the bed medium are employed to preferentially hydrate the tritiated water. This loading process is conducted at about 30°C. The tritiated water feed stream is introduced at the bottom of a column. The water flows up through the bed where it is removed from the top of the column as a depleted tritiated water stream. The bed medium material is introduced at the top of the same column and flows downwards to form a counter-current flow through the column. Tritiated water adsorption on the bed was found to be directly proportional to feed concentration and bed volume. Depleted tritiated water streams with a tritium concentration below the MCL (maximum concentration level) are possible by using the appropriate bed length and residence time to accomplish the necessary exchange. The appropriate bed length and residence time to obtain target tritium concentrations will be determined from demonstration tests.

As the medium moves down through the column and becomes loaded, it is removed from the bottom of the column to a tritium-removal and media-regeneration system. Free water is drained from this removed medium and recycled back to the column's tritiated water feed tank. More than one medium-receiving tank will be used to provide the capability of continuous processing through the column. The removed medium is then heated to a moderate temperature of about 105°C to remove the remainder of the interstitial water and the lightly held hydration water. These waters are returned to the column's feed tank for reprocessing and constitute approximately 50% of the feed-flow stream. The medium-bed material is then heated to about 145°C and the more strongly bonded hydrated water (including the bulk of the tritiated water) is swept off the medium as water vapour with a heated nitrogen gas flow and is passed through a condenser. The condensate from the condenser, containing the bulk of the tritiated water, is collected as liquid in a receiving tank. The volume of condensed water amounts to 0.25-0.5% of the original volume of feed and contains about 99% of the tritiated water. The gas from the condenser is recycled to a heater for reuse. The regenerated adsorber material is then recycled to the top of the column for reuse.

This smaller volume of tritiated water is then pumped to the bottom of another column. This column is smaller, has a moving bed similar to the first column, and receives the medium at the top of the column. The tritium is loaded on the bed medium, and the tritium-depleted stream is removed from the top of the column and recycled

back to the feed tank of the first column. This recycled stream constitutes only a small fraction of the volume of the feed stream to the first column.

The medium is removed from the bottom of the second column media-recovery system, where it is drained and the tritium is removed the same as for the first column media-recovery system. The drained water is pumped back to the second column feed tank. The tritiated water in the gas stream is loaded on a molecular sieve and then grouted for disposal. The gas from the molecular-sieve bed is recycled and reheated for reuse. The dehydrated medium is recycled to its respective column for reuse to load additional tritiated water with no detrimental effects [51].

Typical adsorption materials included custom-loaded commercial exchange resins such as sulfonated polystyrene/divinylbenzene. The commercially available adsorber material is pre-treated by loading selective sites removing exchangeable hydrogen, and thorough drying. The resin was first loaded with aluminium sulfate to form an Al^{+3} site bonded to at least one sulfonated group on the medium. Aluminium in this form has a high number of waters of hydration and has a greater affinity for tritiated water over light water. Adsorption was typically run at $30^{o}C$, pressures varied with adsorption material, ranging around 2 bar absolute. The feed solution was de-ionized in a mixed bed system to remove all potential interfering ions. The bed medium can be occluded with colloids and adsorbs certain organic compounds if they are present in the feed stream. The adsorption material was added dry from the top and the feed was pumped vertically upwards through the column(s). Water outlet samples were collected in vials for subsequent scintillation counting in a Packard Instrument Model 2300.

6.3.6.   Water distillation column packed with silica-gel beds

Water distillation has been considered a useful measure to enrich or deplete tritium in water continuously, because a counter-current flow between vapour and liquid water is established easily by means of simple apparatus. The equilibrium isotope separation factor, α^{evp}_{H-T}, defined as a relative volatility between H_2O and HTO is not so large that a very long distillation tower is necessary to decrease the activity of tritium in distilled water lower than a level demanded by law.

In order to improve the separation performance, various kinds of packing were previously investigated experimentally such as Dixon ring, porcelain packing and others. These packing materials improved the value of HETP (height equivalent to a theoretical plate) to a certain degree. The HETP value calculated lately was estimated to be around 10 cm. In addition, the HETP values depended on vapour rate in the column. Therefore careful operation to maintain stable separation was necessary to achieve high enrichment performance.

On the other hand, it is known that some adsorbents used as an air dehumidifier have a slightly higher affinity for HTO and T_2O than for H_2O. If the packing material is made of silica gel or other kinds of adsorbent that have a larger isotope separation factor than unity, tritium separation may be enhanced by its adsorption and isotopic exchange action. The equilibrium separation factor of adsorption, α^{ads}_{H-T}, is defined as the ratio of the T/H ratio in adsorbate to that in vapour phase. The value of $\alpha_{H-T} - 1$ of the silica-gel column was about four times larger than that of a column without any packing and about two times larger than that of Dixon-ring packing. The total separation factor of the silica-gel column in the case of the high vapour rate became independent of it. The high separation performance indicated that the height of distillation column becomes very short by using the silica-gel adsorbent packing.

6.4. NEXT GENERATION REACTORS (GENERATION IV)

The next generation of reactors is being developed according to the framework by the GIF (Generation IV international forum) that was chartered in 2001. The following goals have been set:

— **Sustainability**: Generation IV nuclear energy systems will provide sustainable energy generation that meets clean air objectives and promotes long term availability of systems and effective fuel utilization for worldwide energy production. They will minimize and manage their nuclear waste and notably reduce the long term stewardship burden in the future, thereby improving protection for the public health and the environment;

— **Economics**: Generation IV nuclear energy systems will have a clear life-cycle cost advantage over other energy sources. They will have a level of financial risk comparable to other energy projects;
— **Safety and reliability**: Generation IV nuclear energy systems operations will excel in safety and reliability. They will have a very low likelihood and degree of reactor core damage. They will eliminate the need for offsite emergency response;
— **Proliferation resistance and physical protection**: Generation IV nuclear energy systems will increase the assurance that they are a very unattractive and the least desirable route for diversion or theft of weapons-usable materials, and provide increased physical protection against acts of terrorism.

The reactors currently being studied include the SFR (sodium fast reactor), the VHTR (very high temperature reactor), the GFR (gas cooled fast reactor), the SCWR (super critical water reactor), the LFR (lead cooled fast reactor) and the MSR (molten salt reactor). This next generation of reactors will all have in common much higher working temperatures than those of water and gas cooled reactors as we know them today. This will have a favorable incidence on the thermodynamic cycle efficiency, therefore reducing the needs for cooling water per MW·h produced.

For the high temperature reactors using a water-and-steam thermodynamic cycle, the best efficiency expected will be around 44%. With a combined cycle installation, 48% efficiency can be reached. These figures are to be compared to the 36–37% mark reached today by the most advanced water-cooled NPP. These advanced reactors that use less water per MW·h produced are based on technologies that can be mastered on a relatively short term.

The advanced sodium fast reactor is another promising 'short term' technology that reduces the water used per MW·h produced. With steam conditions a little below 500°C, the efficiency will be around 42%. By implementing some reheating that would give steam conditions a little above 500°C, the efficiency could reach 43%. Moreover, when the reactor is shutdown, the residual heat will be removed by a sodium-air heat exchanger, therefore reducing water use also in that mode (sodium melts at about the same temperature as water starts to boil; water cooling would necessitate steam generators).

Still other advanced reactor models will rely on a helium Brayton direct-cycle targeting an efficiency of 48%. In such a model, the heat rejection to the environment is done passively at about 110°C. This temperature, being much higher than that of the surrounding air in the environment, makes possible the implementation of dry cooling solutions with only a small impact on efficiency. Such reactors by nature drastically reduce water needs. The technology, though, still needs some development and its implementation is more remote. This is the case of the AHTR (advanced high temperature reactor) being developed by Oak Ridge National Laboratory, the University of California at Berkeley and Sandia National Laboratories. The AHTR combines high thermal efficiency and the use of a Brayton power cycle to dramatically reduce the cost and energy penalty of dry cooling systems. It will be significantly more efficient because of its higher temperature multi-reheat power cycle. For peak coolant temperatures of 705, 800 and 1000°C, the respective targeted plant efficiencies are 48%, 51.5% and 56.6% (Fig. 75).

Since the heat for such a reactor can be rejected over a temperature range rather at a single temperature, the appropriate design of counter-current dry-cooling tower heat exchangers maximizes the temperature drop across the heat exchangers, which reduces their size. With dry cooling, Brayton cycles have major advantages over Rankine (steam) cycles that deliver rejected heat at a constant temperature. The Rankine (steam) cycle characteristic is consistent with evaporative cooling, in which water is vaporized at nearly constant temperature. In contrast, a Brayton cycle delivers rejected heat over a temperature range that matches dry-cooling.

6.5. CONCLUSION

Water cooled reactors are constrained mainly by manufacturing limits since the main avenue to limit significantly their water usage is to improve their overall efficiency, which in turn can mainly improve by increasing significantly their steam pressure. This reasoning leads indeed to one of the Generation IV reactors being investigated: the super-critical water reactor targeting an overall efficiency of 45%. Since it requires operation at 25 MPa and 620°C, it still needs a lot of R&D on materials, not to mention some specific aspects of neutronics.

Another potential for a better use of the rejected heat of water cooled reactors is through a combination with a desalination plant. Some pilot installations already exist and the experience gained should help to spread the
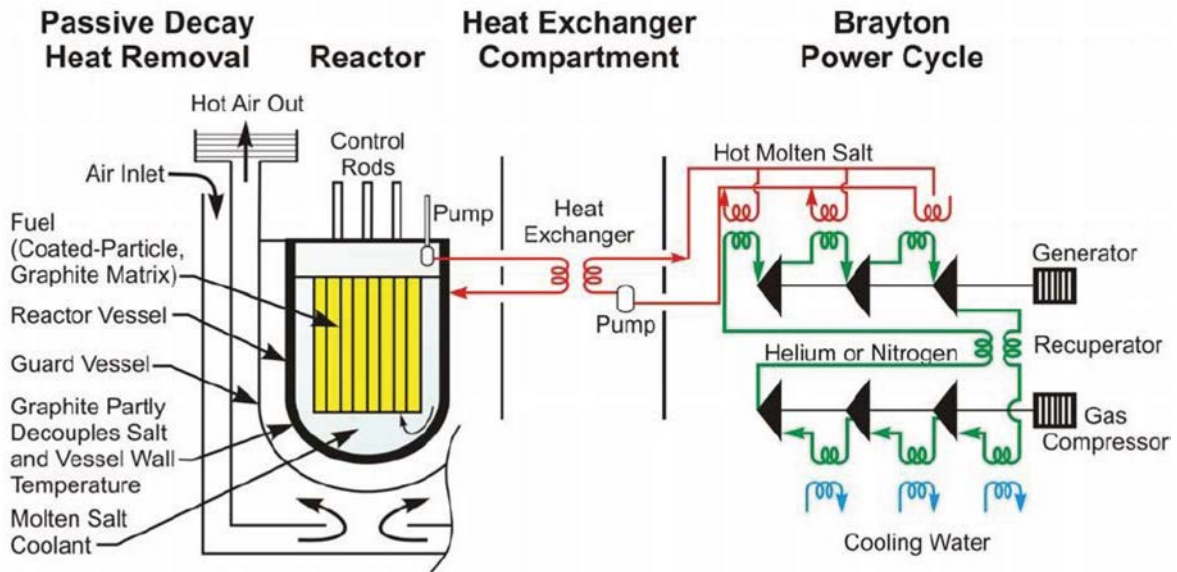
FIG. 75. Schematic of the AHTR for electricity production.

technology. Advanced tertiary coolants are still in the domain of R&D and interest in them could go through a revival especially because of their potential towards cooling by air.

If SMRs were to succeed in market penetration, most of them would not excel in their water usage; their overall target efficiencies cluster around 30% only. In terms of water usage, the Generation IV reactors will be much better positioned because they all target high operating temperatures, hence high efficiency. Also very important, their high operating temperatures make it possible to cool them by air without a heavy penalty on efficiency.

When water remains the cooling fluid for the secondary side, large quantities are involved and the trend is to design the installations such that processing and recycling of the water can be optimized. Once new technologies for tritium separation become available on industrial scale, the recycling of wastewater could be optimized and dilution flow requirements could be kept to a minimum.

7. CONCLUSION

Looking to the future, there are several reasons for focusing now on expanding nuclear power's contribution to desalination. Apart from the expanding demand for freshwater and the increasing concern about GHG emissions and pollution from fossil fuels, there is a renewed and growing emphasis on small and medium sized nuclear reactors. This is particularly important for desalination because the countries most in need of new sources of freshwater often have limited industrial infrastructures and relatively weaker electricity grids. Yet, a nuclear power plant requires the availability of sustainable source of water during construction, operation, and commissioning.

Nuclear power plants use large amounts of water — 20–83% more than coal-fired plants. Water consumption for nuclear reactors is typically 13–24 billion liters per year, or 35–65 million liters per day. Conversely, the water consumption of renewable energy sources and energy efficiency/conservation measures is negligible or zero. Water outflows from nuclear plants expel relatively warm water which can have adverse local impacts in bays and gulfs, as can contain heavy metals and salt pollutants. The warming effect is a problematic issue if exacerbated by heat waves. For example, a number of European reactors had to be taken offline during a heat wave in 2006, and others had to operate at reduced power.

There are a number of solutions to be considered to lower the use and consumption of water in nuclear power plants. One is to use dry cooling and dry scrubbing technologies. Another is to find innovative ways to recycle

water within the power plant itself. A third is to find and use alternative sources of water, including wastewater supplies from municipalities, agricultural runoff, brackish groundwater, or seawater. In addition, other alternatives are:

Alternative cooling (air cooling, hybrid cooling and closed loop water cooling): For instance, EPRI launched a collaborative project in order to evaluate the water use implications of various (current and new) cooling technologies;

Alternative water sources (desalination and water reclamation). For instance, researchers at Carnegie Mellon University and the University of Pittsburgh in the USA are conducting a project for the US Department of Energy on the use of secondary treated municipal wastewater as make-up water for cooling at thermoelectric power plants.

Any sensible improvement in the overall thermal efficiency of the nuclear power plant will result in a considerable reduction of water used and consumed by the plant. For this reason, future high temperature reactors like the supercritical water reactor may offer important alternative for countries having less water resources. Moreover, focus on strategies aiming at reducing water use should be pursued. Areas to be examined are:

— Decrease resin regeneration water;
— Development operation process to improve CPP capacity;
— Recover on-line sampling water, etc;
— Improving the wastewater treatment facility;
— Inspecting components and systems, replacing and maintaining aging equipment;
— Reuse of industrial wastewater;
— Replacing or maintaining aging equipment;
— Application of water saving devices;
— Development of alternative water resources using desalination;
— A continuous exchange of information and international cooperation on water resources.

Water withdrawal is dominated mainly by the turbine condenser cooling and is therefore independent from the type of reactor. High efficiency factors can notably reduce the cooling water demand. Water withdrawal is at a maximum with open loop cooling, where the cooling water flow represents often more than 95% of the total water usage. The use of cooling towers in closed loop cooling reduces the water withdrawal to evaporation and blow-down losses, but increases investment costs.

Industrial and potable water is used for plant service and operation. The amount of water used is less than 1% of the water withdrawal for cooling purposes in open loop. Compared to the evaporation losses if wet cooling towers are used, the water consumption of industrial and potable water is about 5%. Considering the life time of NPPs (30–60 years) the water consumption during erection, commissioning and decommissioning is negligible. But the water needs at these phases exceeds the industrial and potable water needs during normal operation.

Concerns over environmental impacts along with population growth in more arid regions of the globe are driving the need for more water efficient cooling technologies. Until the last quarter of the twentieth century the traditional power plant cooling technology was generally once-through cooling. It resulted in higher operating efficiencies and lower construction and operating costs than alternative methods. As the availability of cooling water has declined, the trend has been to shift to dry cooling towers either through regulatory restrictions or physical limitations.

The processes of desalination, wastewater reclamation and wastewater treatment can be considered as new sources of freshwater. In cases where desalination is a major source of water for a nuclear power plant, it is very important at the earliest stage of the construction of the nuclear power plant to foresee the mutual benefits of coupling a desalination plant to the nuclear power plant. In addition, a decision should be made to improve the efficient treatment and use of water. This could involve using less water via new conservation measures, reusing water for multiple purposes prior to disposal, or implementing innovative ways to reclaim usable water from non-traditional sources. New technology for producing demineralized water using membranes needs no regeneration water and can improve the efficient use of water through water reuse and water use reduction. There are numerous processes that can be used to clean up wastewaters depending on the type and extent of contamination. Most wastewater is treated in industrial-scale wastewater treatment plants (WWTPs) which may include physical, chemical and biological treatment processes.

The main avenue to limit significantly water usage in water cooled reactors is to improve their overall efficiency. This reasoning leads indeed to one of the Generation IV reactors being investigated: the super-critical water reactor targeting an overall efficiency of 45%. Another potential for a better use of the heat rejected by water cooled reactors is through a combination with a desalination plant. Advanced tertiary coolants are still in the domain of R&D and interest in them could go through a revival especially because of their potential towards cooling by air.

If SMRs succeed in market penetration, most of them will not excel in water usage; their overall target efficiencies cluster around only 30%. The general consensus is that one large nuclear power plant will consume and use less water than modular SMR units having a total capacity equivalent to that of the large unit. Therefore, any early decision on the introduction of SMRs has to consider water management very carefully along with the other relative merits of a large nuclear power plant and several modular units.

Appendix

CURRENT PRACTICES ON WATER USE/CONSUMPTION AND MANAGEMENT IN NPPs

A.1. TURKEY POINT NUCLEAR POWER PLANT

Florida Power & Light's (FPL) Turkey Point power plant, situated on the shores of Biscayne Bay and Card Sound, ~25 miles south of Miami, is the site for five existing electric generation units. FPL owns and operates all five electric generating units. Units 1, 2, and 5 are fossil-fired and Units 3 and 4 are nuclear reactors. The facility generates 2196 MW.

Units 1, 2, 3 and 4 went online in 1967, 1968, 1972 and 1973, respectively. Unit 5 went online in 2007.

Turkey Point was built on mangrove-covered tidal flats adjacent to Biscayne Bay. These mangrove wetlands extend inland approximately three to four miles. Most undeveloped portions of the site remain under one to three inches of water, even at low tide. The terrain is flat and rises gradually inland to –10 feet above mean sea level to a relic reef ridge, eight to 10 miles west of the site in Homestead.

Cooling canal system: Prior to construction and operation of the cooling canal system in the early 1970s, cooling water was drawn from Biscayne Bay at an intake point just north of Turkey Point and was discharged back into the bay via a series of short canals just south of Turkey Point. The heated discharge resulted in fish kills, reduced benthic seagrass communities, and loss of coral colonies within 350–550 meters of the discharge. Because of the biological damage caused by the thermal pollution from the discharge, a federal judge issued an order on September 10, 1971, prohibiting FPL from discharging heated water into Biscayne Bay, Card Sound or any other navigable water. Exceptions were provided to allow discharges to prevent excessive concentration of salt in the cooling canal system, or during national, regional or reactor emergency or when health, safety or welfare of public
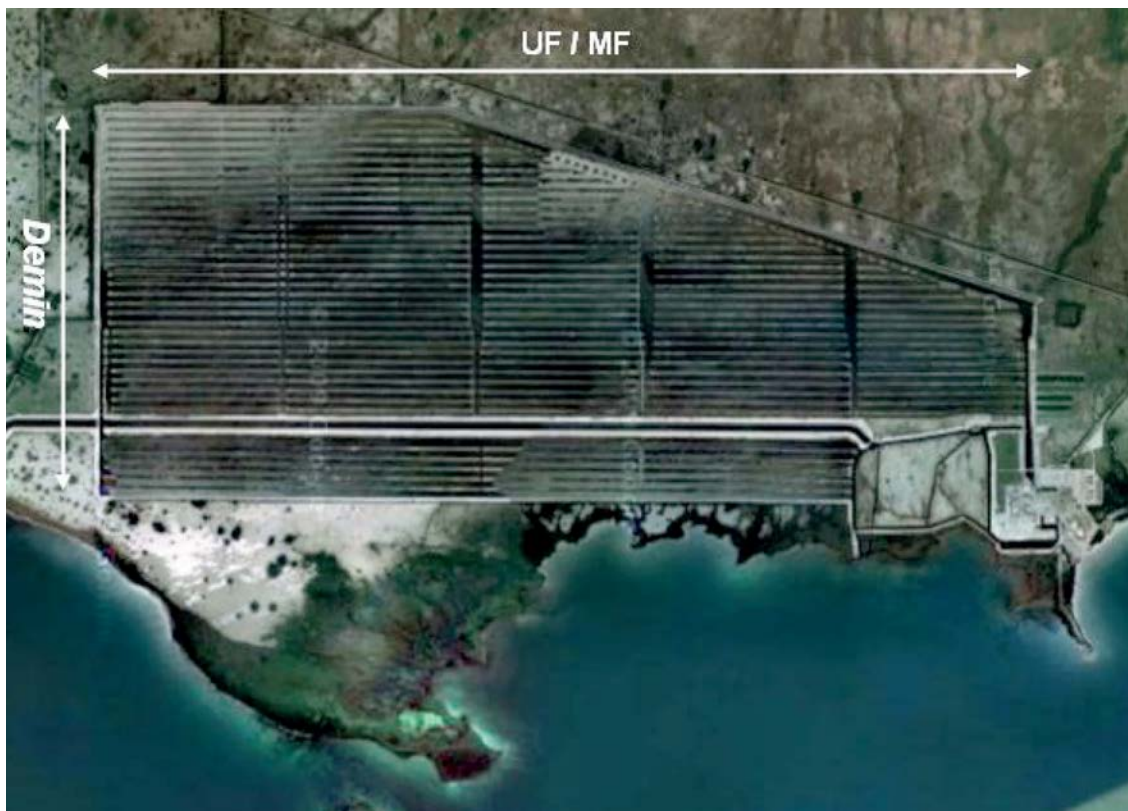

FIG. 76. Cooling water canals in Turkey Point power plant.

might be endangered by inability of FPL to supply electricity from other sources available to it. The order contained strict conditions on the location, timing, temperature, flow rate, and salinity of any such discharges.

As a result of the Judge's Order, a network of self-contained, closed-loop cooling water canals were constructed at the Turkey Point facility to handle all the process wastewater and cooling water needs of the plant. The canal system consists of 32 key-cut, shallow cooling canals, each –5.2 miles long, through which cooling water from the facility flows before being recycled back in the intake system. The residence time of the water is about 40 hours. The canal system provides about 9.7 square miles of water surface area for heat exchange with the atmosphere.

No water is withdrawn by FPL from surface water or groundwater for use as make-up water for the cooling canal system and no surface water flows into the canals. Evaporative losses from the cooling canal system are replenished by rainfall, plant storm water runoff, and treated process wastewater, which ultimately comes from the municipal supply. There may also be an exchange of water between the cooling canal system and the groundwater beneath the canal. The cooling canals supply cooling water for all five units.

Maintenance of the cooling canal system includes mechanical removal of submerged, rooted marine plants on about a 3-year cycle and removal of terrestrial woody vegetation from the canal berms on a 10-year cycle.

A.2. PALO VERDE NUCLEAR POWER PLANT

Depending on the design of the cooling system as well as the water management scheme, water consumption can be significantly reduced, with environmental as well as operational benefits. This is clearly seen in the comparative example of the Diablo Canyon and Palo Verde NPPs. Sited on the ocean coast, Diablo Canyon does not compete with other fresh water users, since it desalinates seawater to meet its freshwater needs; the cooling water is strictly seawater. As Palo Verde is situated in the desert, it uses reclaimed water from the Phoenix area municipal sewage treatment facilities, as well as closed loop cooling, avoiding large withdrawal rates of the magnitude used at Diablo Canyon.

The United States Argonne National Laboratory (ANL) authored a study in 2007 reviewing the use of reclaimed water [52]. Quoting from the introduction:

"Freshwater demands are steadily increasing throughout the world. As its population increases, more water is needed for domestic use (drinking, cooking, cleaning, etc.) and to supply power and food. In arid parts of the country, existing freshwater supplies are not able to meet the increasing demands for water. New water users are often forced to look to alternative sources of water to meet their needs. Over the past few years, utilities in many locations, including parts of the country not traditionally water-poor (e.g. Georgia, Maryland, Massachusetts, New York, and North Carolina) have needed to reevaluate the availability of water to meet their cooling needs. This trend will only become more extreme with time. Other trends are likely to increase pressure on freshwater supplies, too. For example, as populations increase, they will require more food. This in turn will likely increase demands for water by the agricultural sector. Another example is the recent increased interest in producing bio-fuels. Additional water will be required to grow more crops to serve as the raw materials for bio-fuels and to process the raw materials into bio-fuels. This report provides information about an opportunity to reuse an abundant water source — treated municipal wastewater, also known as "reclaimed water" — for cooling and process water in electric generating facilities. The report was funded by the U.S. Department of Energy's (DOE's) National Energy Technology Laboratory (NETL) innovations for existing plants research program. This program initiated an energy-water research effort in 2003 that includes the availability and use of "non-traditional sources" of water for use at power plants. This report represents a unique reference for information on the use of reclaimed water for power plant cooling. In particular, the database of reclaimed water user facilities described in Chapter 2 is the first comprehensive national effort to identify and catalog those plants that are using reclaimed water for cooling".

In its study ANL reports that as of the date of the report about 195 million US gallons per day (MGD) or 739 million liters per day, of reclaimed water is used for power plant/process cooling. The largest user (at 55 MGD or 208 000 cubic meters per day) is the Palo Verde nuclear power station in Arizona (USA). Palo Verde obtains all its cooling and plant water from the Phoenix 91st wastewater treatment facility through a 60 km combined gravity
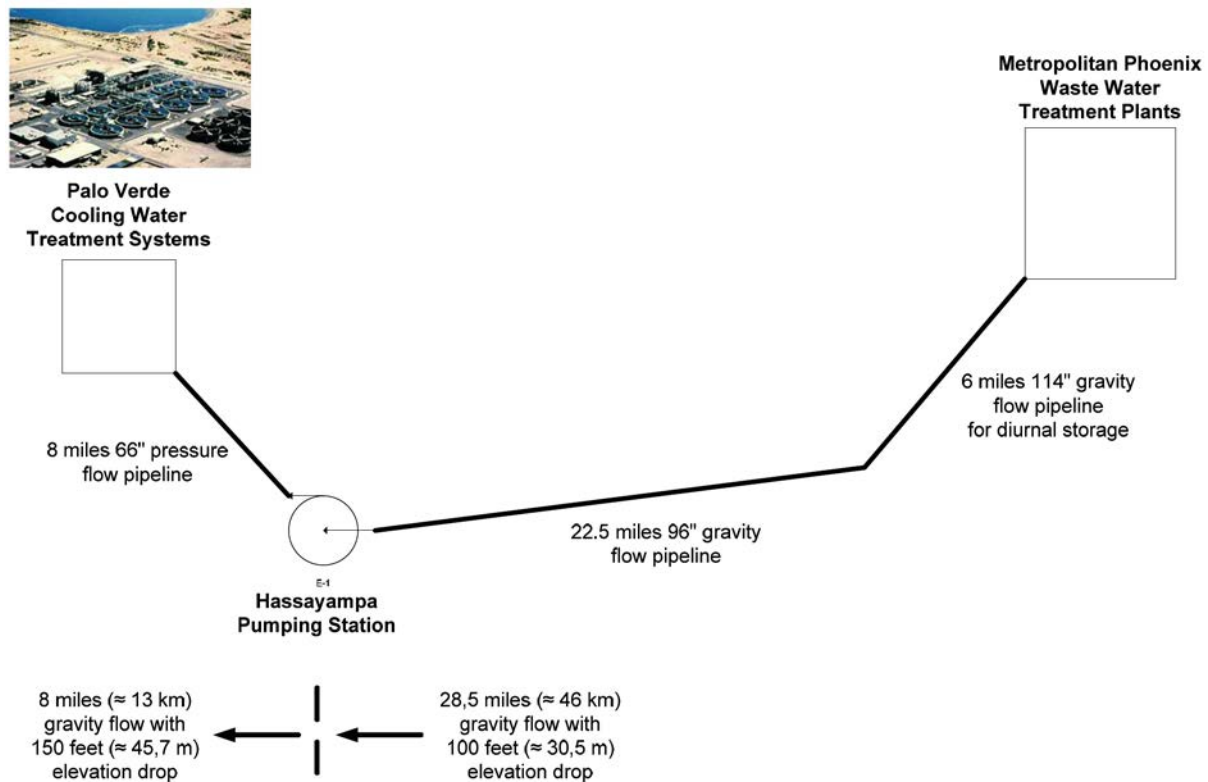
FIG. 77. Palo Verde NPP conveyance system.

flow and pumped piping system. Reverse osmosis is used to obtain potable water. Mixed bed demineralizers are used to process water for station process needs. Cooling tower blow-down is pumped to settling/evaporation ponds; solids are buried on site. Palo Verde operates as a zero discharge facility. Figure 77 shows Palo Verde NPP conveyance system.

This water is cleaned mechanically and chemically for use as cooling water. The cooling water treatment reduces the solids and salts in the water so that it is possible to reach 15 to 25 cycles of concentration (COC). The removed chemical solids (average of 100 tonnes/day) are be used for on-site landfill.

ANL concludes:

"Reclaimed water represents a valuable water resource with many potential applications. As the power industry sites new plants or expands capacity at existing sites, it must identify sufficient supplies of water to cool the steam. Reclaimed water can help meet that need. About 50 power plants are currently using reclaimed water for cooling. Several of these are also using reclaimed water for air pollution control equipment such as scrubbers. As more plants add scrubbers, the need for additional water will rise, too."

Reclaimed water will most likely not be a viable option for reducing water consumption in developing countries. Obtaining a significant source of reclaimed water requires a well-established municipal sewage treatment infrastructure; experience in the USA shows that this has lower priority than development of industry and modern living facilities.

A.3. DIABLO CANYON NUCLEAR POWER PLANT

Table 27 presents all the discharge components from Diablo Canyon NPP [53]. We can estimate the required intake from these average quantities of water. It should be noted that DCPP has a reverse osmosis plant incorporated into the facility. The desalinated water is used as make-up water for the primary and secondary loop, and possibly for sanitation.

TABLE 27. DISCHARGE COMPONENTS OF DIABLO CANYON NPP

Discharge No.	Discharge description	Volume (m^3/d) average flows
001 Pacific ocean (Diablo cove)	Once-through cooling	9 614 945
001B	Auxiliary salt water cooling	131 732
001D	Liquid radioactive waste treatment system (Batch 3-12 times/week)	30
001E	Service cooling water	46 939
001F	Turbine building sump (Intermittent)	189
001G	Make-up water system effluent (Brine)	365
001H	Condensate demineralizer regenerant (Intermittent)	126
001I	Seawater evaporator blow-down (Non-operational)	0
001J	Condensate pumps discharge header overboard (Intermittent)	7
001K	Condensate dump tank (Batch)	545
001L	Steam generator blow-down	556
001M	Wastewater holding and treatment system (Intermittent)	473
001N	Sanitary wastewater treatment system (Intermittent)	46
001P	Seawater reverse osmosis system blow-down	3168
001Q	Intake structure building sumps (Intermittent)	273
002 Pacific Ocean	Screen wash pumps overboard (Intermittent)	666
003 Pacific Ocean	Intake screen wash (Intermittent)	12 076
004 Pacific Ocean (Intake Cove)	Reverse osmosis system discharge	1783
005 Pacific Ocean (Intake Cove)	Biolab seawater supply pump valve drain (Batch)	8
006 Pacific Ocean (Intake Cove)	Seawater reverse osmosis system blow-down drain (Batch)	15
007 Pacific Ocean	Screenwash overspray	6
008 Pacific Ocean	Screen wash overspray	6
009 Pacific Ocean	Biolab/Reverse osmosis supply lines drain	63
010 Pacific Ocean	Circulating water pumps backflow (Intermittent)	11 356
011 Pacific Ocean	Screen wash collection sump overflow (Intermittent)	27 331
	Total discharge volume (average, rounded figure, m^3/d)	9 855 000

Although it uses the once-through cooling system, it can give a good general overview on what the water is used for, the quantities and the regularity of use in a typical NPP.

A.4. WATER USE DURING DECOMMISSIONING BASED ON US PRACTICES

Cessation of plant operations will result in a significant decrease in water consumption because reactor cooling is no longer required. Although water will still be required for spent fuel cooling, this demand will decrease as the fuel ages. Dewatering systems may remain active during decommissioning of a nuclear facility to control the water pathway for the release of radioactive material. Decommissioning activities that may influence water use include fuel removal, staffing changes, large component removal, decontamination and dismantlement (using high pressure water sprays), structure dismantlement, and entombment.

Impacts to water resources of decommissioning activities would be considered detectable if such activities result in a significant change in water supply reliability. The reliability of water supplies is impacted by a variety of factors, such as natural climatic variability and the reliability of the regional and local water supply infrastructures. For example, an additional incremental drawdown attributable to a groundwater well at a decommissioning site may be measurable at an offsite well. However, this does not necessarily constitute a detectable change in the reliability of the water supply. It would be detectable if the offsite well is unable to withdraw its permitted volumes as a result of this increased drawdown. The impacts of decommissioning activities are considered destabilizing if they result in a permanent and/or significant loss of water supply reliability. For instance, heavy pumping of an aquifer that results in subsidence may cause a permanent loss of aquifer capacity. Another example of a destabilizing impact is a change in site drainage or stream-channel changes that would result in a detectable and significant change in the probability of flooding.

In general, the impact of nuclear reactor facilities on water resources dramatically decreases after plants cease operation. The flow through the condenser of an operating plant can range from 3 to 78 m^3/s (49 000 to 1 200 000 gpm) (NRC 1996), depending upon the size of plant. This operational demand for cooling and make-up water is largely eliminated after the facility permanently ceases operation. As the plant staff decreases, the demand for potable water also generally decreases. However, in a few cases staffing levels have temporarily increased above levels that were common for routine operations. For these short periods of time, commonly during the early stages of decontamination and dismantlement activities, there may be a slight increase in demand for potable water.

Most of the impacts to water resources likely to occur during decommissioning of a nuclear facility are also typical of the impacts that would occur during decommissioning or construction of any large industrial facility. For example, providing water for dust abatement is a concern for any large construction project, as is potable water usage. However, the quantities of water required are trivial compared to the quantity used during operations. There are some activities affecting water resources when decommissioning nuclear facilities that are different from other industrial non-nuclear activities. The demand for water for spent fuel maintenance (approximately 200 to 2000 L (50 to 500 gal.) of water per day, depending on the size and location of the pool) and wet decontamination methods (such as a full flush of the primary system or hydrolysing embedded piping in place), although not large, are unique to nuclear facilities. One facility reported using approximately 9500 to 11 000 L (2500 to 3000 gal.) of water per day for spent fuel pool spray-cooling during the summer months. Additionally, water in some of the systems or piping may continue to be used during decontamination and dismantlement to provide shielding from radiation for workers who are dismantling structures, systems, and components (SSCs) in the vicinity. For example, 912 000 L (240 000 gal.) of water was used at one site to fill the reactor cavity in preparation for the segmentation of the reactor vessel.

Common engineering practices, such as water reuse, are used to limit water use impacts at most construction or industrial sites. However, use of some of these practices may be limited by radiological exposure considerations at decommissioning sites.

A.4.1. Water quality

There are quality standards for drinking water, protection of aquatic and terrestrial habitats, and release of potential pollutants to surface and groundwater environs. Nuclear reactor facilities are usually located above aquifers or adjacent to important sources of water. Intended and accidental releases of potential pollutants may impact the quality of these waters. This section considers water quality impacts of non-radioactive material for both surface water and groundwater during the decommissioning process.

A.4.2. Regulations

Intentional releases of non-radioactive discharges to surface waters are regulated through the national pollutant discharge elimination system (NPDES; Section 402 of the Federal Water Pollution Control Act, commonly referred to as the Clean Water Act [CWA] [33 USC 1251 to 1387]) to protect water quality. Congress has delegated the responsibility for NPDES implementation to the US Environmental Protection Agency (EPA). When the EPA determines that state programmes are equivalent to the federal NPDES programme, the NPDES permitting process is delegated to the state. Generally, discharge limits specified by the NPDES permit are revisited every 5 years. Ongoing monitoring programmes may be required as part of an NPDES permit.

A.4.3. Potential impacts of decommissioning activities on water quality

Major activities during decommissioning that may affect water include fuel removal, stabilization, decontamination and dismantlement, and structure dismantlement. Separate assessments of potential impacts were performed for surface water and groundwater. Surface waters are most likely to be impacted either by storm water runoff or by releases of substances during decommissioning activities.

Because water quality and water supply are interdependent, changes in water quality must be considered simultaneously with changes in water supply. For example, reduced groundwater pumping may result in a rise in the water table, providing a new pathway for contaminants currently in the subsurface. Changes in the landscape (terrain and vegetation) during decommissioning can alter the hydrologic pattern of recharge and surface-water runoff. The convergence of surface water over unvegetated soils may result in accelerated erosion and the delivery of sediment to important downstream habitats.

Impacts to water quality of decommissioning activities would be considered detectable if such activities result in a significant change in water-supply reliability. For example, storm water erosion at a facility undergoing decommissioning may result in a measurable increase in suspended sediment in an adjacent stream or disposal of concrete onsite could alter local water chemistry of the groundwater. However, this does not constitute a detectable change in the reliability of the water supply unless the incremental change in sediment concentration precludes permitted or environmental uses. The impacts of decommissioning activities would be considered to be destabilizing on water quality if they result in a permanent or significant loss of water-supply reliability. For instance, significant increases in erosion might result in a permanent loss of benthic habitat for certain fish species.Stormwater runoff and erosion control are issues faced at many industrial sites, and it is expected that after application of common best management practices, any changes in surface-water quality will be non-detectable and non-destabilizing.

All commercial nuclear power facilities have permits that regulate intentional releases of hazardous materials. Historically, unintentional releases of hazardous substances have been an infrequent occurrence at decommissioning facilities. Because the focus of decommissioning is the ultimate cleanup of the facility, considerable attention is placed on minimizing spills. Except for a few substances such as hydrocarbons (diesel fuel), such hazardous spills are localized, quickly detected, and relatively easy to remediate. Some of the groundwater parameters measured in the license termination plan (LTP) might also be indicators of a heretofore undetected non-radiological subsurface plume. If such indications were observed, further characterization and corrective actions would be dictated by the relevant regulations discussed in Appendix L of Ref. [20] and permits, if appropriate.

Certain decommissioning activities or options may result in changes in local water chemistry.

For example, if licensees dismantle structures by demolition and disposal of the concrete rubble on the site, then there is a potential that the hydration of concrete could cause an increase in alkalinity of groundwater. The pH of interstitial (pore) water very close to the concrete rubble would remain above 10.5 for several hundred thousand years (Krupa and Serne 1988). However, as the leachate migrates away from the demolition debris, it is reasonable to expect the leachate pH to be rapidly reduced (within meters) to natural conditions due to the large buffering capacity of soils. While the leachate's pH may not be a water-quality concern, such leachate may affect the transport properties of radioactive and non-radioactive chemicals (notably metals) in the subsurface although this transport would not be detectable offsite. Surface spreading of the demolition debris over large areas may provide adequate opportunity for soils to buffer the pH to background. Because the non-radiological impacts would be non-detectable, they are considered to be generic for all sites. However, concentrated disposal of demolition debris,

either within or outside of existing below-grade structures, would require below-grade compliance with RCRA guidelines. The radiological aspects of onsite disposal of slightly contaminated material would require a site-specific analysis and would be addressed at the time the LTP is submitted.

Current or anticipated decommissioning activities at the FBR or HTGR have not and are not expected to result in water-quality impacts that are different from those found at other nuclear reactor facilities.

A.5. VALUES REGARDING COOLING WATER SYSTEMS OF SOME EXEMPLARY PLANTS

TABLE 28. TYPICAL PARAMETERS FOR DIFFERENT TYPES OF REACTORS

Nuclear power plant	Primary coolant inlet and outlet temperature (°C)	Secondary steam parameters	
		Pressure (MPa)	Temperature (°C)
PHWR	250–295	5.6	271
PWR	280–320	6.5	280
BWR	278– 288	5.5	270
LMFBR	390–540	16.3	510
HTGR	390–540	17.3	541

TABLE 29. TYPICAL POWER PLANT WITH OPEN CYCLE COOLING SYSTEM (PWR)

	Unit 1	Unit 2
Plant rated thermal power, MW(th)	3304	3468
Net electrical output, MW(e)	1121	1085
Gross electrical output, MW(e)	1155	1117
Total water withdraw from lake michigan[1], GPM	$1\ 645\ 000 = 104 m^3/s$ (dT = 10 °C)	
Main condenser flow[1], GPM	$1\ 500\ 000 = 95 m^3/s$ (dT = 11 °C)	
Main condenser heat load[1], watts	4370	
Essential service water[1] (ESW)	$20\ 000 = 1.26 m^3/s$	
Non-essential service water[1] (NESW)	$11\ 000 = 0.7 m^3/s$	

[1]   Units 1 and 2 Combined.

TABLE 30. TYPICAL POWER PLANT WITH CLOSED CYCLE COOLING SYSTEM AND NATURAL DRAFT COOLING TOWER (PWR)

Item	Unit 1	Unit 2
Plant rated thermal power, MW(th)	3600.6	3600.6
Net electrical output, MW(e)	1210	1210
Gross electrical output, MW(e)	1242	1242
Maximum water withdraw[1], GPM	48 025 = 3 m³/s	—
Water consumed[1] (loss to evaporation and drift)	27 37 9 = 1.73m³/s	—
Water returned to source[1]	20 646 = 1.3m3/s	—
Main condenser flow, GPM	722 000 = 45.6m3/s (dT = 12.6 °C)	703 000 = 44.4m3/s (dT = 12.8 °C)
Main condenser heat load, MW	2338	2370

[1]   Units 1 and 2 combined.

TABLE 31. TYPICAL POWER PLANT WITH CLOSED CYCLE COOLING SYSTEM AND MECHANICAL DRAFT COOLING TOWERS (BWR)

	Unit 1	Unit 2
Plant rated thermal power, MW(th)	2886	—
Net electrical output, MW(e)	936	—
Gross electrical output, MW(e)	Not available	
Total water withdraw , GPM	32 000 = 2.0m3/s	
Main condenser flow[1], GPM	508 470 = 32.1 m3/s (dT = 15.7 °C)	
Main condenser heat load, MW	2111	

TABLE 32. TYPICAL POWER PLANT WITH CLOSED CYCLE COOLING SYSTEM AND COOLING POND (PWR)

	Unit 1	Unit 2
Plant rated thermal power, MW(th)	3600.6	3600.6
Net electrical output, MW(e)	1210	1210
Gross electrical output, MW(e)	1242	1242
Average withdrawal at 100% load, GPM	53 770 = 3.4 m³/s	
Water consumed (loss to evaporation and seepage)	28 770 = 1.8 m³/s	
Water returned to source	25 000 = 1.6m3/s	
Main condenser flow1, GPM	722 000 = 45.6 m³/s (dT = 12.3 °C)	703 000 = 44.4 m³/s (dT = 12.8 °C)
Main condenser heat load, MW	2338	2370

[1]   Both units combined.

TABLE 33. ESSENTIAL SERVICE WATER SYSTEM (ESW) FLOW REQUIREMENTS PER TRAIN (GPM)

Service[1]	Normal operation	LOCA injection	LOCA recirculation	Cool down
CCW HX	8700	50002	50002	9100
CTS HX	—	—	24003	—
EDG CLRS	—	540	540	—
AFW SYS[4]	—	450	450	—
AFP enclosure CLRS[5]	102	102	102	102
Control room air conditioners (CRAC)[6]	80	80	80	80
Totals	8882	6172	8572	9282

[1] The flows shown reflect the use of one ESW train in service corresponding to one CCW safeguard's train. The second ESW train may be placed in service provided the necessary equipment is operable or the second CCW safeguard train is operating. Single train operation results in minimum safeguard's requirements and a minimum cool-down rate.

[2] This flow path is aligned manually and required only as a backup to the normal condensate supply to the auxiliary feed water system. The required flow is reduced to 250 GPM corresponding to heat sink requirement following depletion of CST inventory.

[3] Auxiliary feed water pump enclosure coolers will be provided with a continuous supply of ESW in all modes of operation. Flow is nominal based on cooler rated heat capacity. Different flows are allowable based on engineering analysis, provided required heat removal is achieved.

[4] CRAC flow is nominal based on chiller rated heat capacity. Different flows are allowable based on engineering analysis, provided required heat removal is achieved.

TABLE 34. RESIDUAL HEAT REMOVAL SYSTEM DESIGN PARAMETERS OPENED CYCLE COOLING SYSTEM

Item	Value	Value
Component cooling water supply temperature design, °F	95	(35.0°C)
Reactor coolant temperature at startup of decay heat removal °F	350	(176.7°C)
Time to cool reactor coolant system from 350°F to 140°F, hrs (design basis)	20	
Refueling water storage temperature (minimum), °F	70	(21.1°C)
Decay heat generation at 20 hours after shutdown, BTU/hr	77×10^6	(22.6 MW(th))
Components		
Residual heat exchangers		
Number	2 (per unit)	
Design heat transfer, BTU/hr	41.1×10^6	(12.0 MW(th))
	Shell	*Tube*
Design pressure, psig	150	600
Design temperature, °F	200 (93.3°C)	400 (204.4°C)
Design flow rate, lb/hr	2.475×10^6 (1130 m³/h)	1.48×10^6 (680 m³/h)
Design outlet temperature, °F	111.6 (44.2°C)	112.3 (44.6°C)
Design inlet temperature, °F	95 (35.0°C)	140 (60.0°C)
Fluid	Component cooling water[2]	Reactor coolant (borated demineralized water)

[1] Licensed life is 60 years in accordance with UFSAR.

[2] The plant has been evaluated for a CCW HX outlet temperature range of 60°F (15.6°C) to 105°F (40.6°C). It is acceptable for the CCW temperature to rise to 120°F during cool-down and post-LOCA conditions.

TABLE 35. ESSENTIAL SERVICE WATER SYSTEM (ESW) FLOW REQUIREMENTS PER TRAIN (GPM/M^3/HR) OPEN CYCLE

Service[1]	Normal operation	Loca injection	Loca recirculation	Cooldown
CCW HX	8700/1975	5000[2]/1135	5000[2]/1135	9100/2065
CTS HX	—	—	2400[3]/545	—
EDG CLRS	—	540/ 23	540/123	—
AFW SYS[4]	—	450/102	450/102	—
AFP enclosure CLRS[5]	102/23	102/23	102/23	102/23
Control room air conditioners (CRAC)[6]	80/18	80/18	80/18	80/18
Totals	8882/2015	6172/1400	8572/1945	9282/2105

[1] The flows shown reflect the use of one ESW train in service corresponding to one CCW safeguard's train. The second ESW train may be placed in service provided the necessary equipment is operable or the second CCW safeguard train is operating. Single train operation results in minimum safeguard's requirements and a minimum cool-down rate.

[2] This flow path is aligned manually and required only as a backup to the normal condensate supply to the auxiliary feed water system. The required flow is reduced to 250 gpm (57 m3/h) corresponding to heat sink requirement following depletion of CST inventory.

[3] Auxiliary feed water pump enclosure coolers will be provided with a continuous supply of ESW in all modes of operation. Flow is nominal based on cooler rated heat capacity. Different flows are allowable based on engineering analysis, provided required heat removal is achieved.

[4] CRAC flow is nominal based on chiller rated heat capacity. Different flows are allowable based on engineering analysis, provided required heat removal is achieved.

TABLE 36. SPENT FUEL POOL COOLING SYSTEM COMPONENT DESIGN DATA OPENED CYCLE COOLING SYSTEM

System cooling capacity, BTU/h	29.8×10^6 (8.73 MW(th))	
Spent fuel pool heat exchanger		
Number	2 (Shared)	
Design heat transfer, Btu/h	14.9×10^6 (4.37 MW(th))	
	Shell	*Tube*
Design pressure, psig	150	150
Design temperature, °F	200 [93.3ºC]	200 [93.3ºC]
Design flow rate, lb/h	1.49×10^6 (680 m^3/h)	1.14×10^6 (520 m^3/h)
Design inlet temperature, °F	95 (35.0ºC)	120 (48.9ºC)
Design outlet temperature, °F	105 (40.6ºC)	106.9 (41.6ºC)
Fluid	Component cooling[1]	Spent fuel pool (borated ??????????)

[1] The plant has been evaluated for a CCW HX outlet temperature range of 60°F to 105°F. It is acceptable for the CCW temperature to rise to 120ºF during cool-down and post-LOCA conditions.

TABLE 37. NON ESSENTIAL SERVICE WATER SYSTEM (NESW) FLOW REQUIREMENTS OPENED CYCLE COOLING SYSTEM

Service	Quantity			Flow (gpm)					Remarks
	Installed	Min. required	Normal required	Min. design	Normal design	Max. expected	Station black-out	Cont. or inter. serv.	
Unit No.1 Main oil coolers	2	1	1	1000	1000	1258	—	C	
Unit No.2 Main oil coolers	4	2	2	1056	1056	1056	—	C	
Unit No.1 FPT oil coolers	4	2	2	270	270	270	—	C	
Unit No.2 FPT oil coolers	4	2	2	354	354	354	—	C	
Unit No. 1 Main turbine and feed Pump EHC control fluid coolers	1	1	1	60	60	60	—	C	
Unit No.2 Main turbine and feed pump EHC control fluid coolers	1	1	1	60	60	60	—	C	
Unit No.2 Generator seal oil coolers	2	2	2	160	160	160	—	C	Based on 95ºF ooling water
Containment ventilation: Unit No.1 upper units	4	3	3	240	240	320	320	C	
Unit No.1 Lower units	4	3	4	1320	1760	1760	1760	C	
Unit No.2 Upper units	4	3	3	240	240	320	320	C	
Unit No.2 Lower units	4	3	4	1320	1760	1760	1760	C	
Unit No.1 Instr. room vent.	2	1	1	50	50	50	50	C	
Unit No.2 Instr. room vent.	2	1	1	50	50	50	50	C	
Technical support center A/C units	4[2]	3	3	77	77	77	—	C	Shared system
Glycol refrigeration condensers	10	6	7	360	420	600	—	C	Shared system
Ice storage condensing units	3	0	3	0	12	12	—	I	Shared system and used during ice loading only
Fluidizer air pre-cooler	1	0	1	0	11	11	—	I	
Fluidizer air chiller condensing unit	1	0	1	0	15	15	—	I	
Unit No.1 RCP motor air coolers	8[3]	8[3]	8[3]	440	440	440	—	C	
Unit No.2 RCP motor air coolers	8[3]	8[3]	8[3]	440	440	440	—	C	
Plant air compressors[4]	2	1	1	80	80	160	160	C	Shared system
Control air compressors[5]	2	0	0	0	0	10	10	I	Shared system

TABLE 37. NON ESSENTIAL SERVICE WATER SYSTEM (NESW) FLOW REQUIREMENTS OPENED
CYCLE COOLING SYSTEM (cont.)

Service	Quantity			Flow (gpm)					Remarks
	Installed	Min. required	Normal required	Min. design	Normal design	Max. expected	Station black-out	Cont. or inter. serv.	
Degassifier vacuum pump 1st stage	1	1	1	25	25	25	—	C	Shared system
Degassifier vacuum pumps 2nd stage	2	1	1	50	50	50	—	C	Shared system
Demineralizer make-up system	1	0	1	0	600	800	—	I	Shared system
Unit No.2 RCP motor 22 and 23 fire sprinklers	2	0	0	200	200	200	—	I	
Heating boiler blow-down flash tank	1	0	0	110	110	110	—	I	Shared system
Unit No.1 Steam generator blow-down flash tanks	2	1	1	385	385	385	—	I	
Unit No.2 Steam generator Blow-down flash tanks	2	1	1	385	385	385	—	I	
Unit No.1 Steam generator Bbow-down heat exchanger	1	1	1	160	160	160	—	I	
Unit No.2 Steam generator blow-down heat exchanger	1	1	1	160	160	160	—	I	
Unit No.1 Auxiliary feed pumps	3	3	3	6	6	6	—	I	
Unit No.2 Auxiliary feed pumps	3	3	3	6	6	6	—	I	
Miscellaneous sealing and cooling water aystem (MSCW)	—	—	—	—	—	300	—	C	
Totals				9064	10 642	11 830			

[1] Water requirements based on 76°F maximum lake temperature except as noted. The system has been evaluated for operation with an NESW cooling water temperature of 87.4°F for Unit 1 and 88.9°F for Unit 2. Containment ventilation may require supplemental cooling at elevated temperatures.

[2] Does not include the 5th air-cooled unit.

[3] There are two motor air coolers per RCP. Cooler flow is nominal based on rated heat removal capacity. Different flows are allowable based on engineering analysis, provided required heat removal is achieved.

[4] It includes compressor oil cooler, after cooler and 1st and 2nd stage intercoolers.

[5] It includes compressor jacket cooler and after cooler.

GLOSSARY

Blow-down. Discharge of water from the cooling system and its replacement by fresh make-up water taken from a river, lake, or well.

Closed cycle cooling system. In a recirculating or closed-cycle system, cooling water is pumped from the condenser to a wet cooling tower, where the heat of the water transfers to the ambient air largely through evaporation. The resulting lower temperature cooling water is then returned back to the condenser. Minerals and sediment building up in the water that remains from the evaporative process for recirculation could potentially clog the cooling system. The 'blow-down' process controls these concentrations by discharging a portion of the recirculating water in the cooling tower to a water source and replenishing it with fresh "make-up" water. The amount of water that evaporates in the tower is also replenished. As an alternative to a wet cooling tower, recirculating cooling systems may use cooling ponds for the same purpose of heat transfer through natural evaporation [6, 55] (Also called: Recycled cooling, recirculated cooling, closed loop cooling). In wet closed-loop cooling systems, the total volume of water withdrawal can be reduced by nearly 95 percent compared to the water required for once-through cooling. The conventional type of wet cooling system uses towers that are designed to remove heat by pumping hot water to the top of the tower and then allowing it to fall down while contacting the air which comes in from the bottom and/or sides of the tower. As the air passes through the water, it exchanges some of the heat and evaporates some of the water. In cooling towers, as much as 50 percent or more of the water is evaporated. The cooled water is collected at the bottom of the tower and is then pumped back to the condenser for reuse. Cooling towers have been increasingly used because they require much less water and land than once-through cooling systems.

Cycle of concentration. Describes the proportion by which evaporation increases constituent concentrations (assuming the typical evaporation rate of 480 gal/MWh). For example, at two cycles of concentration, evaporation doubles constituent concentrations, relative to intake water.

Desalination. The removal of salt or other chemicals from something, such as seawater or soil. Desalinization can be achieved by means of evaporation, freezing, reverse osmosis, ion exchange, and electro-dialysis.

Decommissioning options. These options, first identified in the 1988 generic environmental impact statement (GEIS) using the acronyms DECON, SAFSTOR, and ENTOMB, are defined as follows:

Decon. The equipment, structures, and portions of the facility and site that contain radioactive contaminants are promptly removed or decontaminated to a level that permits termination of the license shortly after cessation of operations.

Entomb. Radioactive SSCs are encased in a structurally long-lived substance, such as concrete. The entombed structure is appropriately maintained, and continued surveillance is carried out until the radioactivity decays to a level that permits termination of the license:

— **Entomb 1** assumes significant decontamination and dismantlement and removal of all contamination and activation involving long-lived radioactive isotopes prior to entombment.
— **Entomb 2** assumes significantly less decontamination and dismantlement, significantly more engineered barriers, and the retention onsite of long-lived radioactive isotopes.

The choice of decommissioning option is left entirely to the licensee, provided that it can be performed according to the NRC's regulations.

Open cycle cooling system. Water is withdrawn from a water source for cooling. The water is heated and discharged back to the source. The discharged water can lead to enhanced evaporate loss to the atmosphere (water is consumed, ~1%) [54]. Water is only cycled once. (Also called: Open-loop Cooling, Once-through cooling).

Safstor. The facility is placed in a safe, stable condition and maintained in that state (safe storage) until it is subsequently decontaminated and dismantled to levels that permit license termination. The determination of SAFSTOR includes those activities necessary for the final decontamination and dismantlement of the facility. During SAFSTOR, a facility is left intact, but the fuel has been removed from the reactor vessel, and radioactive liquids have been drained from systems and components and then processed. Radioactive decay occurs during the SAFSTOR period, thus reducing the quantity of contaminated and radioactive material that must be disposed of during decontamination and dismantlement. The definition of SAFSTOR also includes the decontamination and dismantlement of the facility at the end of the storage period.

Water consumption. Water consumption occurs when water either ceases to exist as a liquid, through evaporation, or when water is degraded through contamination so that it is not fit to be returned directly to its original source [6].

Water usage. Water use consists of two processes that can occur separately or in sequence: water consumption and water withdrawal [6].

Water withdrawal. Water withdrawal occurs when water is removed from a source. This water may be consumed or returned to its source [6].

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ABBREVIATIONS

ACW	active chemical waste
AHWR	advanced heavy water reactor
ANCW	active non chemical waste
BOD	biochemical oxygen demand
BRS	boron recycle system
BWR	boiling water reactor
CCW	component cooling water
COC	cycles of concentration
COD	chemical oxygen demand
CPP	condensate polishing plant
CT	cooling tower
CVCS	chemical volume control system
CW	circulating water
DAF	dissolved air floatation
DBT	dry bulb temperature
DC	direct contact
DEC	direct evaporative cooling
DM	demineralised water
DT	temperature difference
EPR	European pressurized water reactor
ESBWR	economic simplified boiling water reactor
FBR	fast breeder reactor
HEED	high efficiency electro-dialysis
HEPA	high efficiency particulate air
H-Q curve	head vs. flow curve
HTGR	high temperature gas cooled reactor
HW	heavy water
HX	heat exchanger
IDCT	induced draft cooling tower
IP	isotopic purity
ISFSI	independent spent fuel storage installation
ITD	initial temperature difference
LESS	liquid effluent segregation system
LMFBR	liquid metal cooled fast breeder reactor
LOCA	loss of coolant accident
LTE	low temperature evaporation
LWR	light water reactor
MCU	modular cooling unit
MED	multi effect distillation
MF	micro filtration
MGD	million gallons (US) per day
MHT	main heat transport
MSF	multi stage flash
NDCT	natural draft cooling tower
NF	nano- filtration
NPP	nuclear power plant
PAW	potentially active waste
PHT	primary heat transport system
PHWR	pressurized heavy water reactor
PMR	palladium membrane reactor

PWR	pressurized water reactor
RAB	reactor auxiliary building
RB	reactor building
RCA	radiologically controlled area
RCS	reactor coolant system
RH	relative humidity
RHR	residual heat removal
RO	reverse osmosis
SDI	silt density index
SG	steam generator
TDS	total dissolved solids
TSS	total suspended solids
TTW	tritiated waste
UF	ultra filtration
UHS	ultimate heat sink
WMP	waste management lant
WTP	water treatment plant

CONVERSION FACTORS

Acre	0.4047 hectare
British Thermal Unit	1.055 kJ
Gallon (US)	3.79 litre
Inch	25.4 mm
lb	0.454 kg
psi	0.06897 bar
ºF	$ºC \times 1.8 + 32$

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Structure of the IAEA Nuclear Energy Series

Nuclear Energy Basic Principles
NE-BP

Nuclear General Objectives — NG-O

1. Management Systems
   NG-G-1.#
   NG-T-1.#
2. Human Resources
   NG-G-2.#
   NG-T-2.#
3. Nuclear Infrastructure and Planning
   NG-G-3.#
   NG-T-3.#
4. Economics
   NG-G-4.#
   NG-T-4.#
5. Energy System Analysis
   NG-G-5.#
   NG-T-5.#
6. Knowledge Management
   NG-G-6.#
   NG-T-6.#

Nuclear Power Objectives — NP-O

1. Technology Development
   NP-G-1.#
   NP-T-1.#
2. Design and Construction of Nuclear Power Plants
   NP-G-2.#
   NP-T-2.#
3. Operation of Nuclear Power Plants
   NP-G-3.#
   NP-T-3.#
4. Non-Electrical Applications
   NP-G-4.#
   NP-T-4.#
5. Research Reactors
   NP-G-5.#
   NP-T-5.#

Nuclear Fuel Cycle Objectives — NF-O

1. Resources
   NF-G-1.#
   NF-T-1.#
2. Fuel Engineering and Performance
   NF-G-2.#
   NF-T-2.#
3. Spent Fuel Management and Reprocessing
   NF-G-3.#
   NF-T-3.#
4. Fuel Cycles
   NF-G-4.#
   NF-T-4.#
5. Research Reactors — Nuclear Fuel Cycle
   NF-G-5.#
   NF-T-5.#

Radioactive Waste Management and Decommissioning Objectives — NW-O

1. Radioactive Waste Management
   NW-G-1.#
   NW-T-1.#
2. Decommissioning of Nuclear Facilities
   NW-G-2.#
   NW-T-2.#
3. Site Remediation
   NW-G-3.#
   NW-T-3.#

Key
BP: Basic Principles
O: Objectives
G: Guides
T: Technical Reports
Nos. 1-6: Topic designations
#: Guide or Report number (1, 2, 3, 4, etc.)

Examples
NG-G-3.1: Nuclear General (**NG**), **Guide**, Nuclear Infrastructure and Planning (topic **3**), **#1**
NP-T-5.4: Nuclear Power (**NP**), Report (**T**), Research Reactors (topic **5**), **#4**
NF-T-3.6: Nuclear Fuel (**NF**), Report (**T**), Spent Fuel Management and Reprocessing, **#6**
NW-G-1.1: Radioactive Waste Management and Decommissioning (**NW**), Guide, Radioactive Waste (topic **1**), **#1**

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