Safe and Economic Water Saving Cooling for Nuclear Units

(dry and dry/wet HELLER System derivatives)

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GEA Heat Exchangers BU ACC/HELLER

GEA EGI Contracting / Engineering Co. Ltd.

ABSTRACT

Reviewing the impact of cooling systems on NPP safety proves how the configurations of dry HELLER System with surface condenser and its dry/wet derivatives ensure the same or even improved level of isolation as provided by wet cooling systems.

The characteristics of an innovative dry/wet cooling system (separate circuit dry/wet HELLER System) and its impact on the NPP output & water need are investigated – highlighting its utmost flexibility both, in the design phase and during operation. The selected ratio of the heat rejection can easily be adapted to the electricity need and the targeted water conservation or by economic terms to the make-up water cost and the surplus electricity price. These valuable features position this water saving cooling system as one of the preferable choices for cooling nuclear units.

Importance of optimization plus comparative economics of all-dry and dry/wet cooling systems are shown through results of case studies made for different climates.

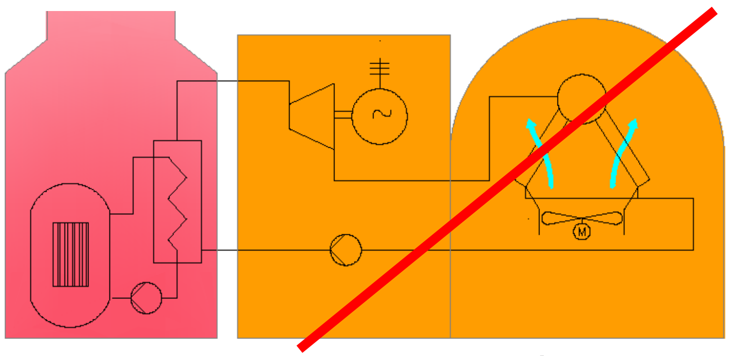
Contents

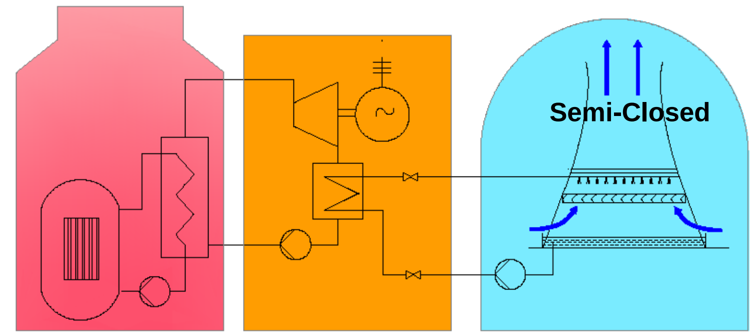
1. Impact of Cooling Systems' Configuration on NPP Safety

❖ ***Cooling system compliance with safety criteria***

Wet cooling system BASIS	Direct ACC	HELLER System with DC condenser	HELLER System with surface condenser & its dry/wet derivatives
1. Extent of area occupied by steam cycle & condensate			
BASIS - Limited to the turbine hall (ended at surface condenser)	Extended outside from the turbine hall to approx. an area of 3 football courts	Extended outside from the turbine hall to approx. an area of 3 football courts	Limited to the turbine hall (ended at surface condenser)
2. Time to spread potential steam / condensate contamination outside the turbine hall			
BASIS No chance for transmitting contamination	Immediate (within several seconds) Practically no time for countering action	Gradual: starts in minutes, ends within ½ hr Opportunity for countering / isolating action	No chance for transmitting contamination
3. Level of steam cycle isolation from environment			
BASIS Isolated by surface condenser	Same as with wet cooling isolated by closed cooling circuit	Same as with wet cooling isolated by closed cooling circuit	Surplus closed circuit adds extra isolation & safety - compared to wet cooling

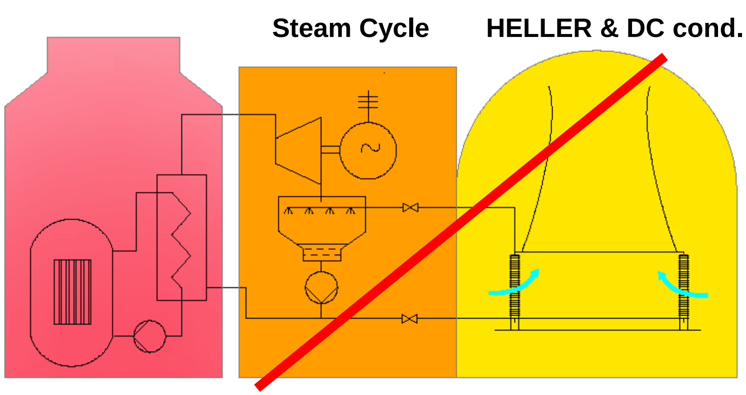
Dry HELLER System with surface condenser & its dry-wet derivatives have adequate configurations to be applied for NPP, since they can maintain the same or even an improved safety level as wet cooling can, by implementing a further closed circuit between the primary nuclear circuit and the environment.

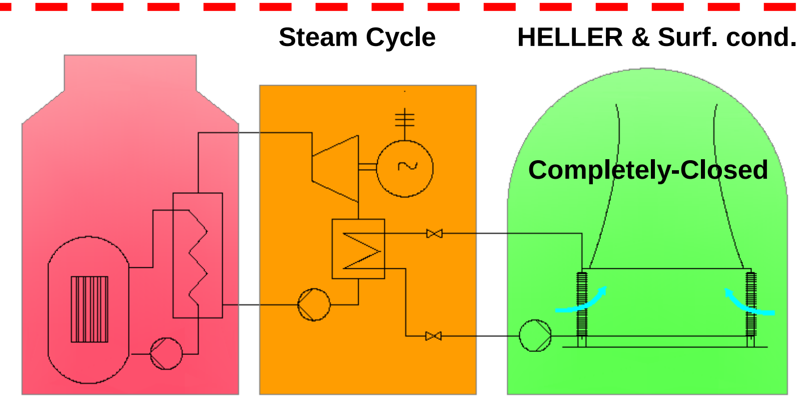




Primary circuit **Secondary circuit**

Primary circuit **Secondary circuit** **Tertiary circuit**





2. Why to Use Water Conserving Cooling for NPPs?

- ✓ The use of a high capacity LWR (PWR or BWR) based NPP results in extreme large heat dissipation, even 1.5-1.8 times that of similar output fossil fueled plants. Data herein offers information about the cooling water use of a PWR based 1200 MW_e output NPP in case of different cooling options:

Data for a 1200 MW_e Nuclear Unit	Once-through cooling (OTC)	Wet Cooling	Dry/Wet	Dry sprayed	All-dry
Water withdrawal (in million m^3/year)	1360	25	2-7	0.2-0.8	practically nil
Water consumption (in million m^3/year)	approx. 13	25	2-7	0.2-0.8	practically nil

- ✓ The mainstream NPP cooling systems (OTC or wet cooling) require a large natural body of water – restricting sites to coastal area or to the bank of a large river.

- ✓ OTC – due to the vast quantity of water withdrawal – harms and kills aquatic life and through the discharged warmed-up cooling water damages the ecosystem of natural waters;

- ✓ Wet cooling – besides its high water consumption (equates to the domestic water demand of nearly half a million people) – loads the environment through blow-down discharge and visual vapor plume emitted from the tower together with carryover droplets having salt & other contaminants.

- ***When not use water conservation?***

If ocean, sea or a large river is in the vicinity of a NPP site and if

- no restricting regulations on water use and effluent discharging
- raw water and discharged water have low costs or free of charge
- no limiting changes can be expected on regulations
- in case of river no high risk of repeated drought periods

- ***Why and when use water conservation?***

In short, just the opposite of the previous criteria, in more detail:

- no or only minimal environmental impact is tolerable at the area
- medium or high raw water cost and effluent fee, which reflects also the social and environmental costs of them
- reducing dependence on cooling water availability extends the opportunity to use nuclear power near any inland load center – thus reducing electricity transmission costs
- besides meeting or even improving safety by cooling system configuration, other aspects which may further increase nuclear plant safety:
    - operationally impassive to draught periods, abrupt water price increases, restrictive changes in regulations
    - inland site location excludes the threat of Fukusima-like disaster
- all the above may support public and political acceptance of nuclear power

3. What Kind of Water Consering Cooling to Be Used

3.1 Water conserving cooling systems for NPPs:

All-dry HELLER System and some b*asic dry/wet derivatives*

❖ **Dry cooling HELLER System**

Clean CW is circulated through the air coolers and returned back to the surface condenser.

✓ Practically zero water consumption (& also zero noise if with natural draft)

✓ Minimal maintenance, high availability if with natural draft

✓ Relatively high capital cost

✓ Reduced hot summer capability

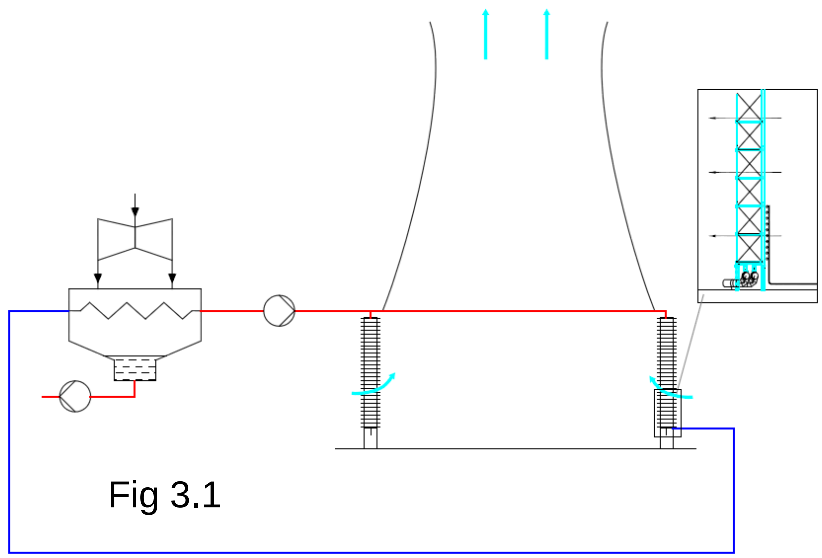


Fig 3.1

❖ **Dry cooling HELLER System with supplemental spraying**

It is essentially an indirect dry HELLER System with surface condenser operating throughout most of the year in all-dry mode. The bottom sections of the vertically arranged air coolers are equipped with sprayers. Spraying is activated only in the hottest summer hours (approx. 100-800 hours/year).

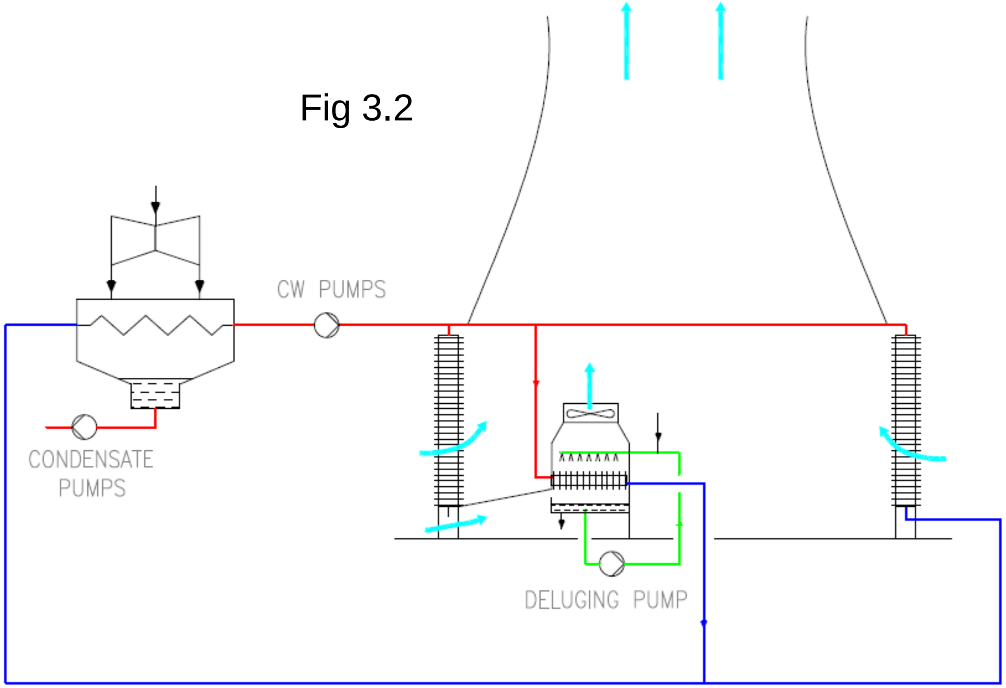
✓ Similar features like those of all-dry HELLER System - however: on cost of a small quantity of quality water use, improved hot summer capability can be achieved

❖ Dry HELLER System with delugable peak coolers

In addition to a dry HELLER System (either with mechanical or natural draft) delugable dry/wet peak coolers are added, which can be connected to the main dry cooling circuit in parallel or in series. If the main cooling system is of natural draft peak coolers can also be located within the natural draft tower. The peak cooler cells are operated throughout most part of the year in dry operation mode. However, in warm weather, when it coincides with electricity peak demand, their air cooler surface is deluged forming a relatively thin water film on the fins. Significantly higher water volume is used than what is evaporated and the rest (followed by blow-down and addition of make-up water) is recirculated to the nozzles which create the water films on the air cooler fins.

- ✓ Improved warm weather capability
- ✓ Deluged operation can be longer (abt. 1000-1500 hr/year) than that of supplemental spraying
- ✓ Not as high quality of water is required than for supplemental spraying, though higher quality than for wet cooling.

Fig 3.2



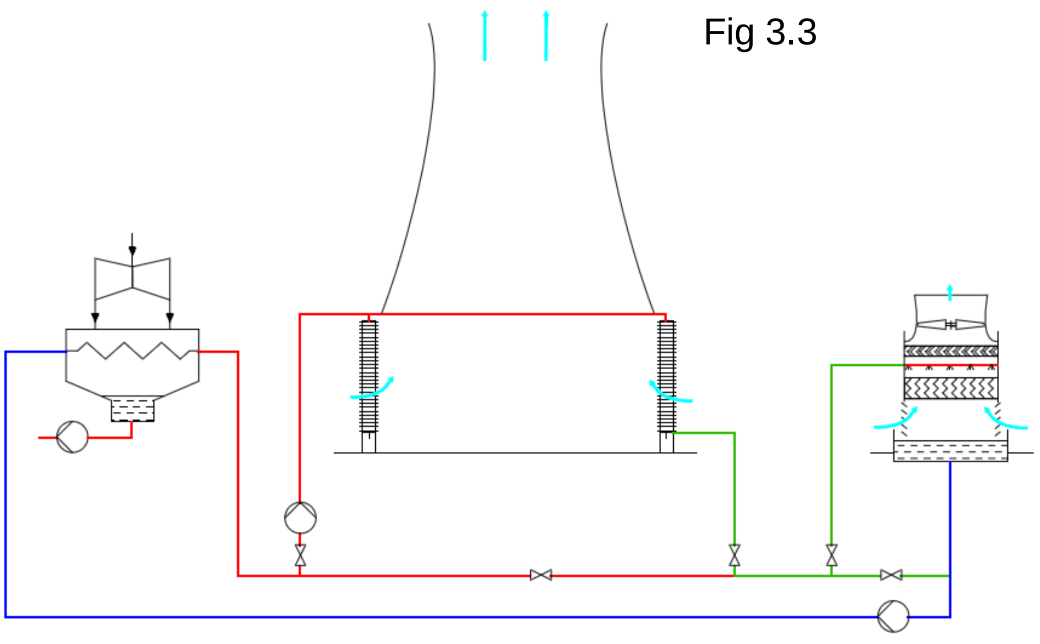
❖ Single circuit serial dry/wet cooling system

CW is circulated in a single circuit, comprising serially connected dry air coolers and wet fills.

Dry and wet sections can be bypassed and operated separately.

- ✓ If the wet part is designed with the same capacity as that of an all-wet system in the warmest period on cost of high water consumption same output can be achieved, though the annual water saving will be at medium level.
- ✓ Since in air cooler tubes the same water is circulated as in the wet cooling part air cooler tubes shall be made of stainless steel requiring high capital cost.
- ✓ High maintenance costs related to depositions within air cooler tubes – which may require limited operation period resulting in limited water conserving capability.
- ✓ Its seemingly high operational flexibility may negatively be influenced by need to reduce extent of depositions.

Fig 3.3



❖ HELLER-based separate circuit dry/wet cooling system

An all-dry HELLER System (natural or mechanical draft) is integrated with a wet cooling system, however maintaining separate circuits for both. Integration of the dry and wet circuits can be made via water-to-water heat exchangers (connected in series or in parallel with the air coolers) (Fig. 3.4). Another method for integration is through the surface condenser – in which there is a separate segment assigned for the dry circuit and another separate one for the wet circuit (Fig 3.5). The two kinds of integration can also be combined with each other (Fig 3.6).

The separate dry and wet circuits may have different draft options: natural/natural; natural/mechanical; mechanical/natural; mechanical/mechanical. If the dry part is with natural draft and the wet portion is less extensive, then wet cells can also be located within the dry tower.

Fig 3.4

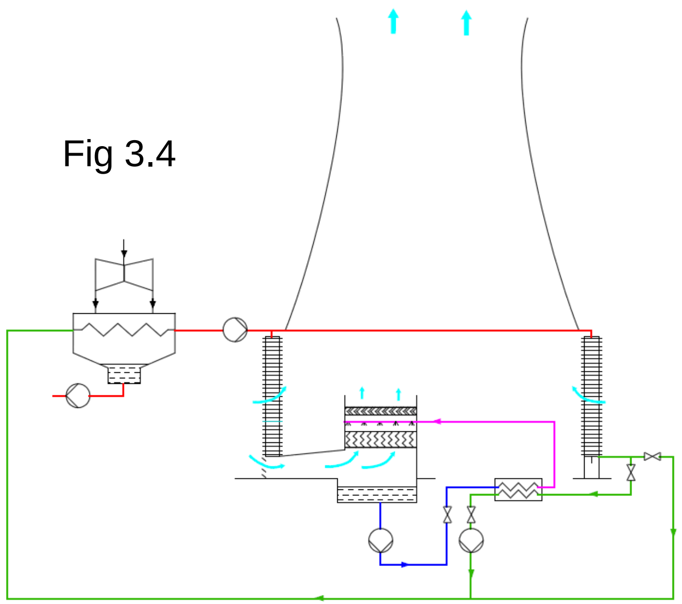
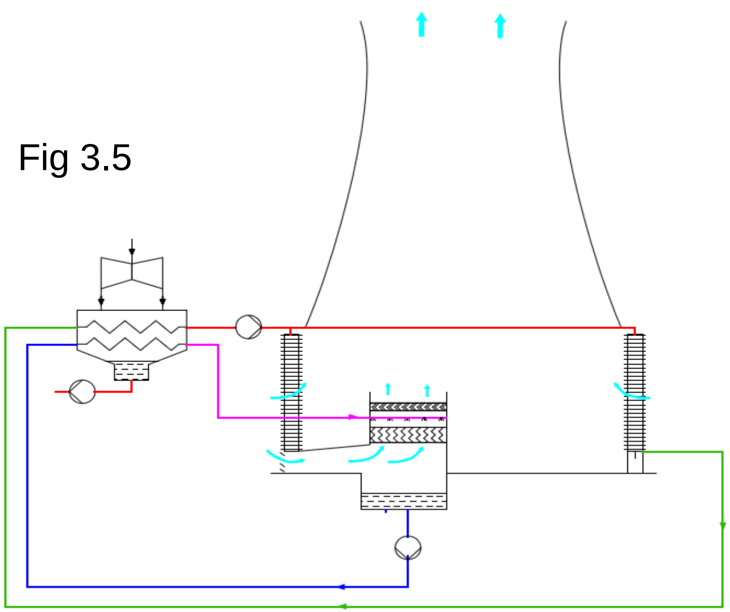


Fig 3.5



- ✓ **The separate circuit system variants** can favorably be used if high level of water conservation is targeted in parallel with significantly higher hot summer output compared to all-dry cooling and with annual power generation close to that of the all-wet cooling system.
- ✓ Its auxiliary power consumption is measurably lower than that of a single circuit serial dry/wet system.
- ✓ Due to the separate circuits for the dry and wet cooling its maintenance cost is significantly less than those of single circuit serial systems.
- ✓ It offers high design and operational flexibility, especially if the integration of the separate circuits are made via both, the divisible surface condenser and through water-to-water heat exchangers.

3.2 Characteristics of a separate circuit dry/wet HELLER derivative cooling system

- The annual water consumption of this cooling system (Fig 3.6) is 30% that of an all-wet system (though in the period above 77°F it is approx. 70%). The annual net electricity generation of a NPP unit equipped with this dry/wet cooling system is practically the same as that of a wet cooled unit; in the assumed peak period (DBT ≥ 77°F) the electricity production is lower only by 0.25% compared to the wet cooled unit; even the net power output at the highest ambient temperature (100°F) lower only by 0.7% (see Figs 3.7-3.10).

✓Integration between the dry and the wet circuits is via condenser and water-to-water HEX. A part of wet cooling cells are located inside the tower, whereas major part of it outside

✓The surface condenser can operate seasonally as an all-dry condenser „in the colder period", when at higher temperature hours the water enhancement is made through water-to-water HEX and for a short period also by supplemental spraying.

✓ In the warmer period of the year the condenser is divided half and half for serving the dry and wet circuits. Additionally, at the hottest temperature hours also some parts of the water-to-water HEX participates in the capability enhancement.

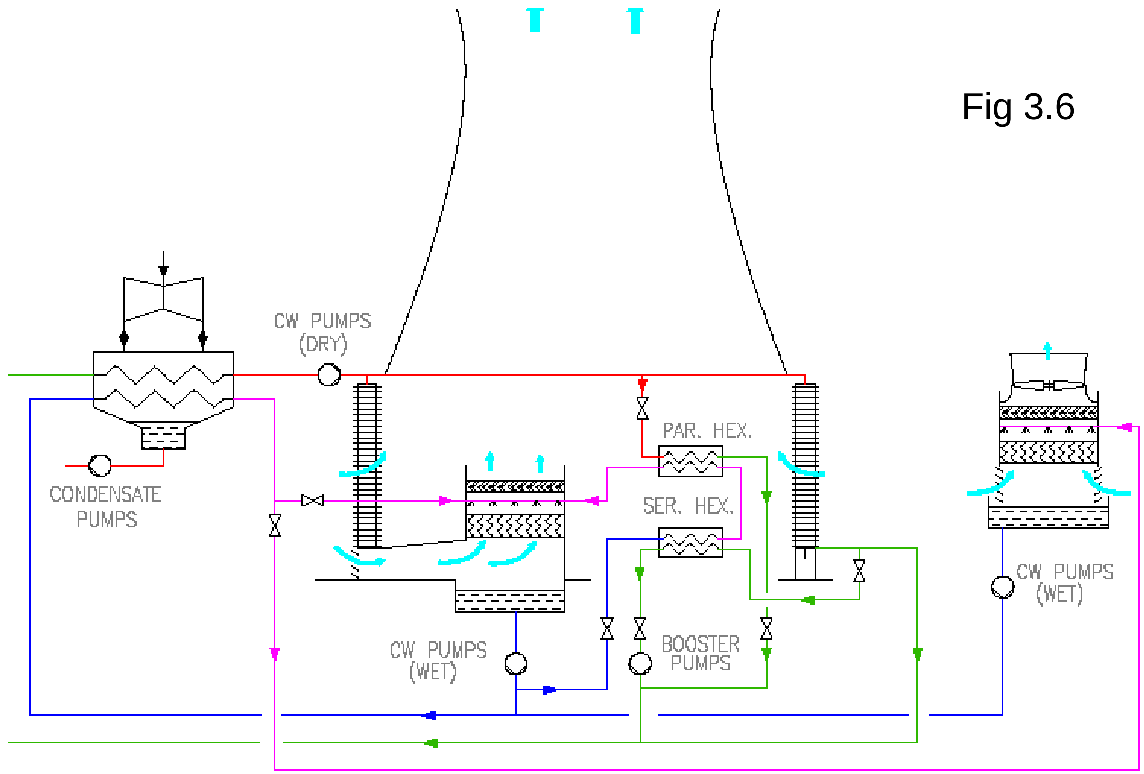


Fig 3.6

Fig 3.7

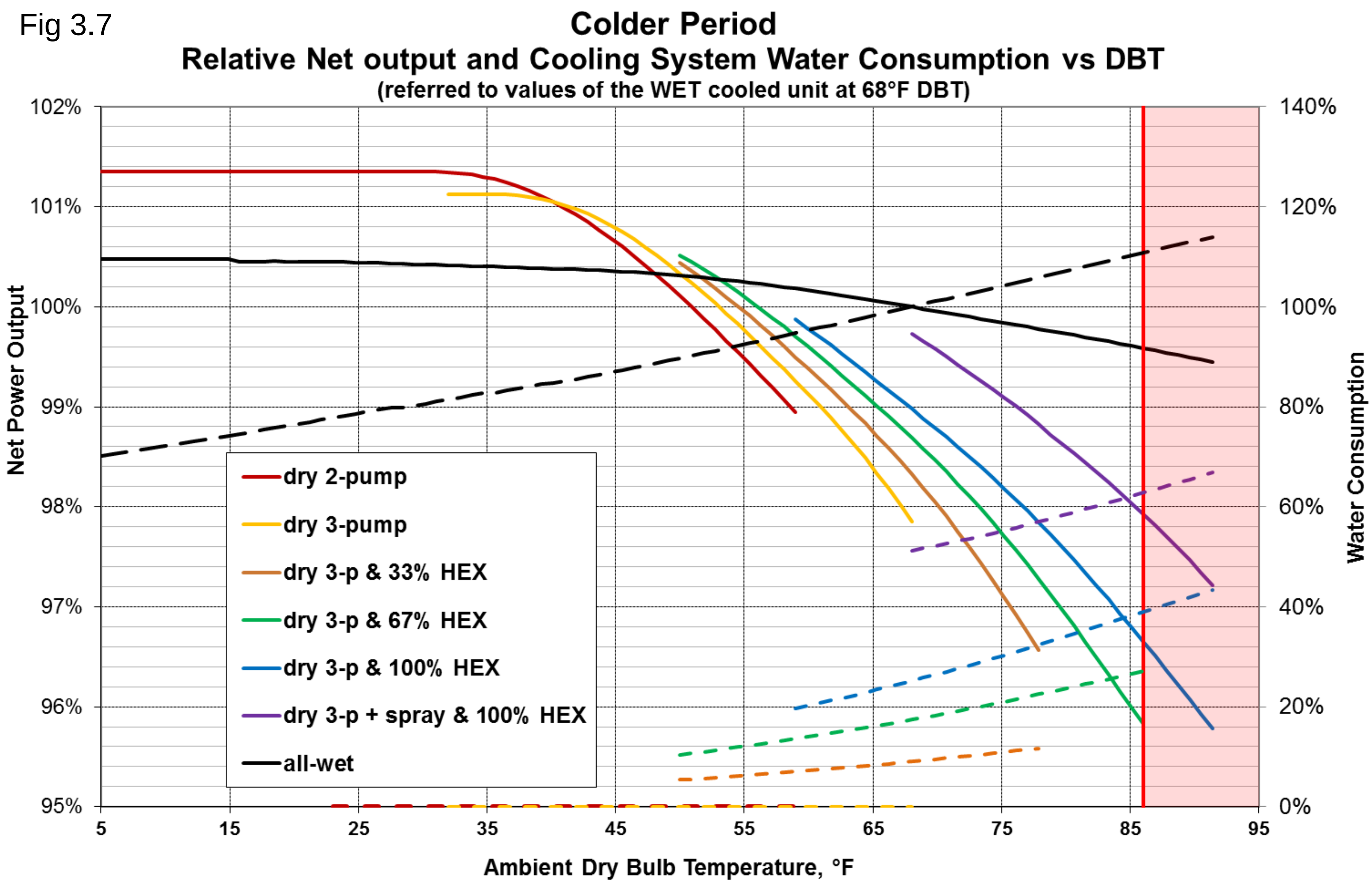
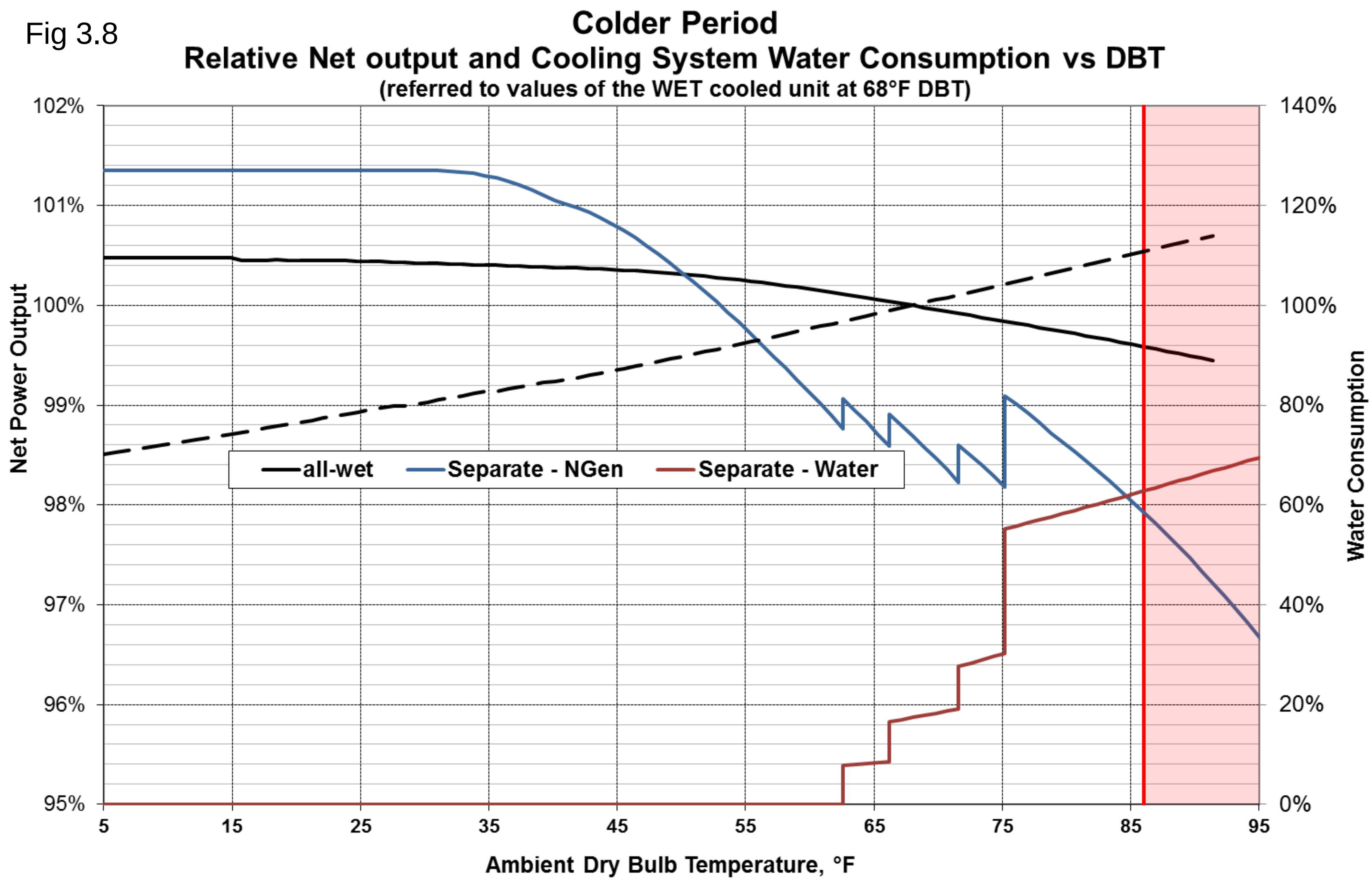

Colder Period
Relative Net output and Cooling System Water Consumption vs DBT
(referred to values of the WET cooled unit at 68°F DBT)
Net Power Output
102%
101%
100%
99%
98%
97%
96%
95%
Water Consumption
140%
120%
100%
80%
60%
40%
20%
0%
5
15
25
35
45
55
65
75
85
95
Ambient Dry Bulb Temperature, °F
dry 2-pump
dry 3-pump
dry 3-p & 33% HEX
dry 3-p & 67% HEX
dry 3-p & 100% HEX
dry 3-p + spray & 100% HEX
all-wet

Fig 3.8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Relative Net output and Cooling System Water Consumption vs DBT
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Net Power Output
102%
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96%
95%
Water Consumption
140%
120%
100%
80%
60%
40%
20%
0%
all-wet
Separate - NGen
Separate - Water
5
15
25
35
45
55
65
75
85
95
Ambient Dry Bulb Temperature, °F

Fig 3.9

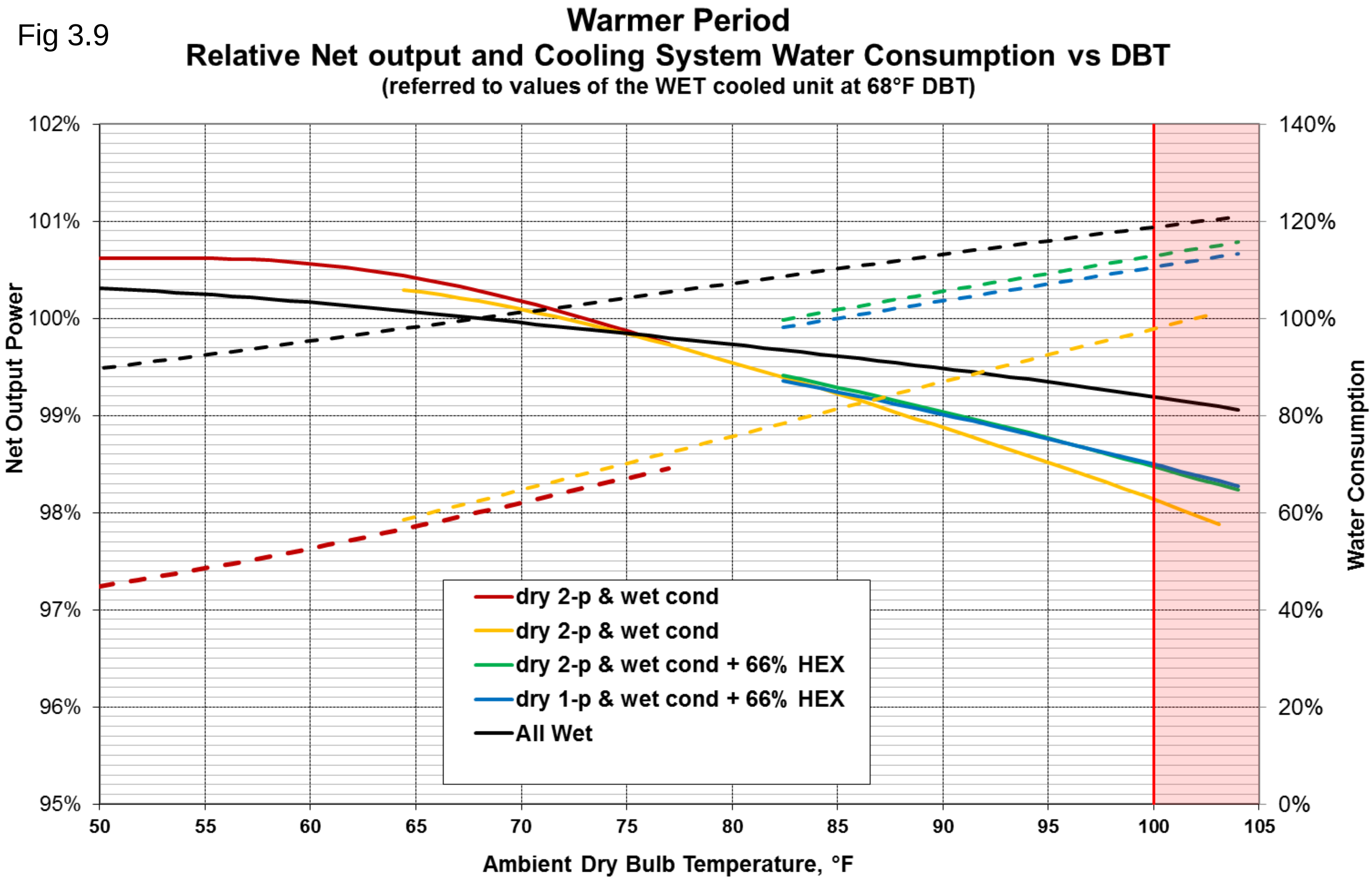
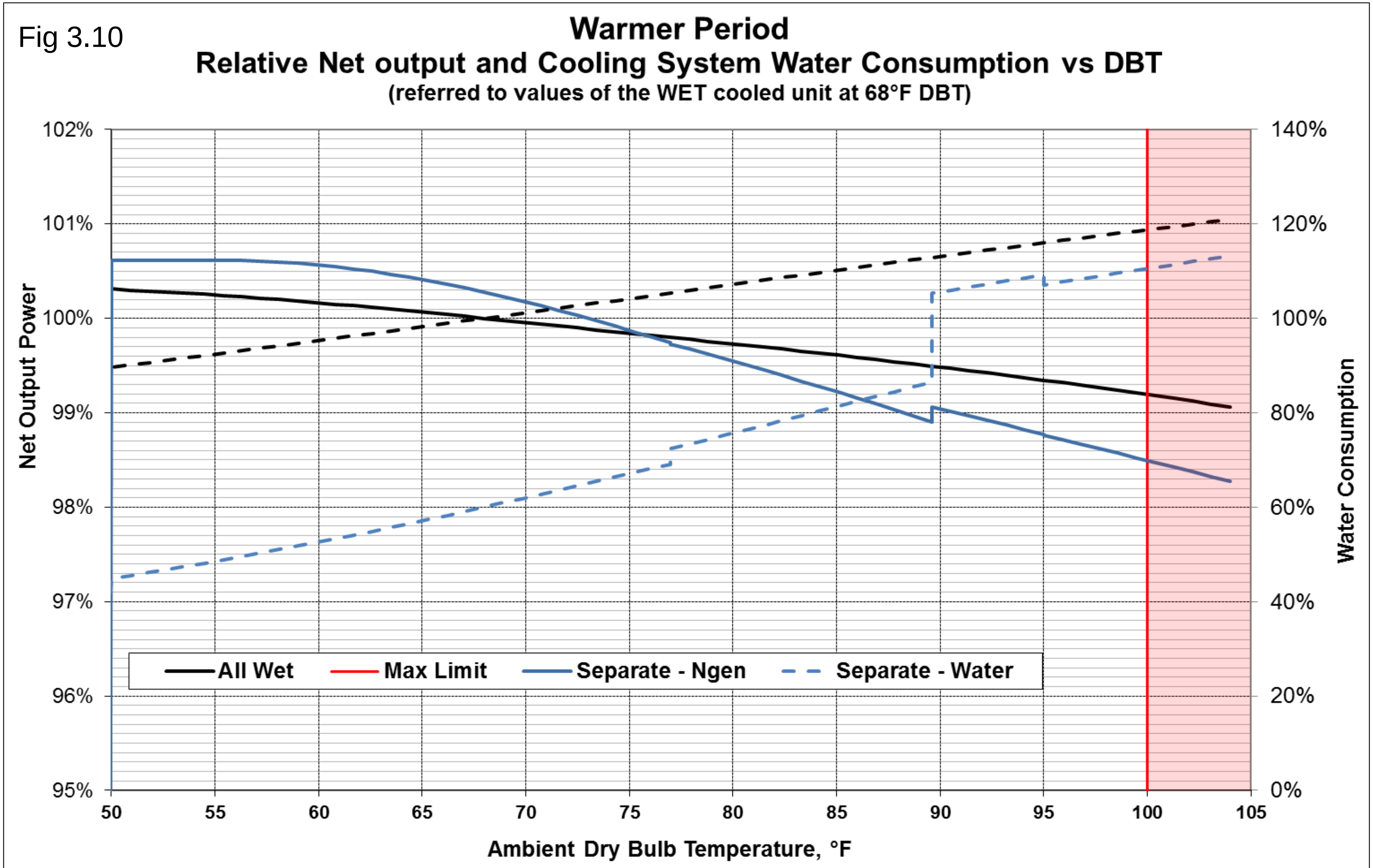

Warmer Period
Relative Net output and Cooling System Water Consumption vs DBT
(referred to values of the WET cooled unit at 68°F DBT)
Net Output Power
102%
101%
100%
99%
98%
97%
96%
95%
Water Consumption
140%
120%
100%
80%
60%
40%
20%
0%
50
55
60
65
70
75
80
85
90
95
100
105
Ambient Dry Bulb Temperature, °F
dry 2-p & wet cond
dry 2-p & wet cond
dry 2-p & wet cond + 66% HEX
dry 1-p & wet cond + 66% HEX
All Wet

Fig 3.10


Warmer Period
Relative Net output and Cooling System Water Consumption vs DBT
(referred to values of the WET cooled unit at 68°F DBT)
Net Output Power
102%
101%
100%
99%
98%
97%
96%
95%
Water Consumption
140%
120%
100%
80%
60%
40%
20%
0%
50
55
60
65
70
75
80
85
90
95
100
105
Ambient Dry Bulb Temperature, °F
All Wet
Max Limit
Separate - Ngen
Separate - Water

4. How to Apply Water Conserving Cooling for NPPs?

❖ higher dependence of water conserving cooling systems capability on ambient temperature

❖ high value of heat rejection due to large power unit capacity & further increase due to saturated steam cycle

result in

Increased sensitivity to backpressure variation

thus

At nuclear power plants there is a special importance on executing:

- **adequate matching of the cooling system and the LP turbines**
- **an intense cold-end optimization**
- **comprehensive economic analysis**

- **Case Study 1: selecting non-(or minimal) water consuming cooling system for a 1200 MW_e class NPP** (planned for a moderate continental climate)

The original concept (i.e. BASE variant) considered a rather small exhaust area LP turbine (high end-loading, short LSB) with a small capacity cooling system (small tower = large tower ITD and small surface condenser area). The technical and economic impacts of other variants were investigated aiming at selecting near optimum solutions.

✓ **Variant A:** increased capacity cooling systems (larger tower and condenser surface area) applied for the same LP turbine and steam cycle: see curve A in Fig 4.1. **Matching the original LP turbine with a near optimum cooling system the relative PV gain may reach 60% - expressed in percent of the BASE variant cooling system capital cost.**

✓ **Variant B:** increased capacity cooling systems (tower & condenser) are paired with a larger exhaust area LP turbine (lower end-loading, longer LSB): see curve B in Fig. 4.1. **When selecting a larger exhaust annulus area LP turbine and applying an adequately high capacity cooling system, the relative PV gain may be nearly 120%.**

In Fig 4.1 the relative present values (PV) are plotted against the varying relative cooling plant capacities, where:

- ***relative present value gain*** *is the PV growth (over that of the BASE variant) divided by the capital cost of the BASE variant cooling system*

- ***the cooling plant capacity factors (CPC)*** *are the ratio of the cooling systems heat dissipation and the overall ITD, determined at the same design DBT*

- ***the relative cooling plant capacity*** *is the actual CPC factor referred to the CPC of the BASE variant.*

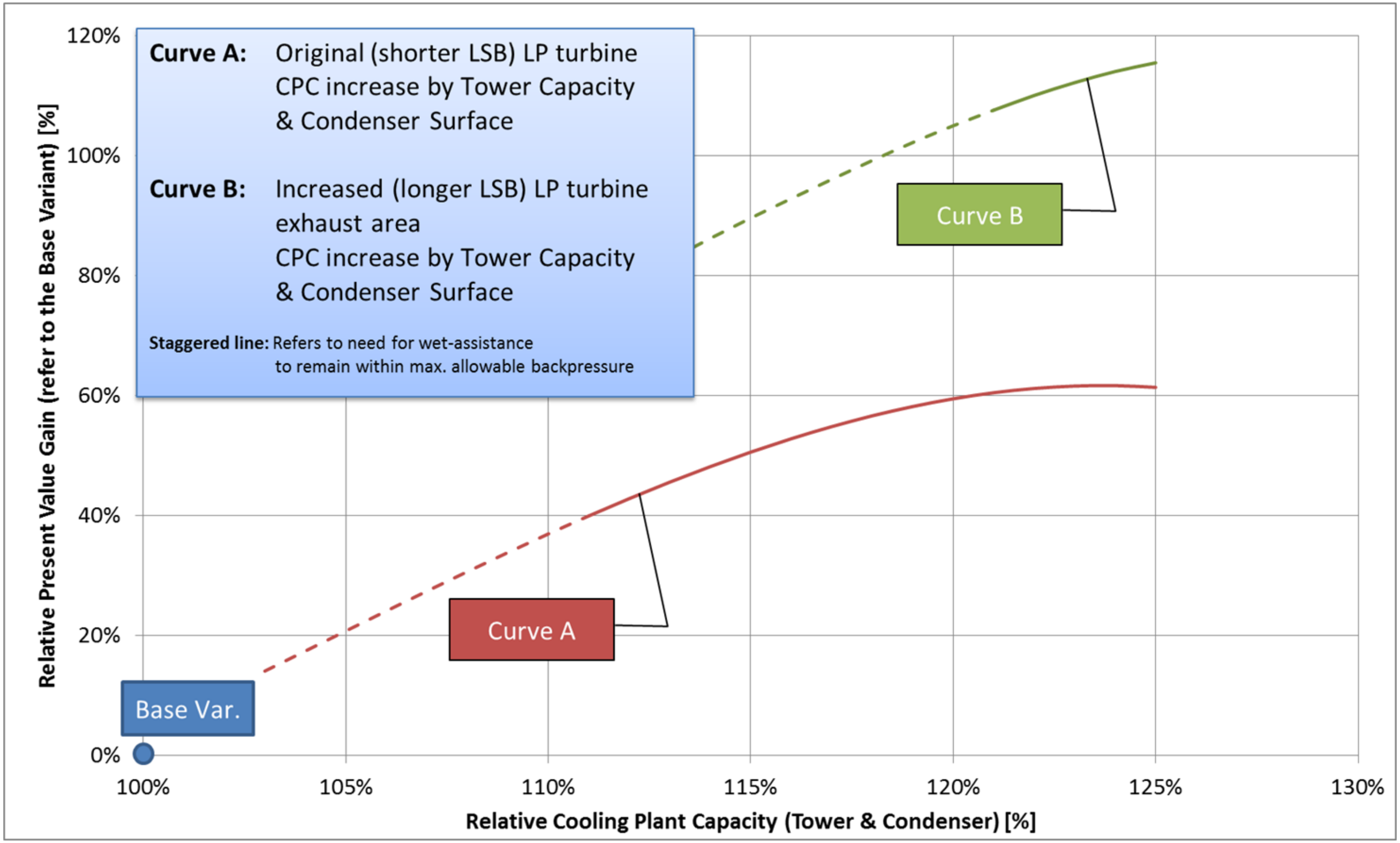


Fig 4.1 Relative Present Value gain for different dry (and dry & sprayed) cooling system capacities and at two LP turbine exhaust areas (Curve A for smaller and Curve B for larger exhaust area)

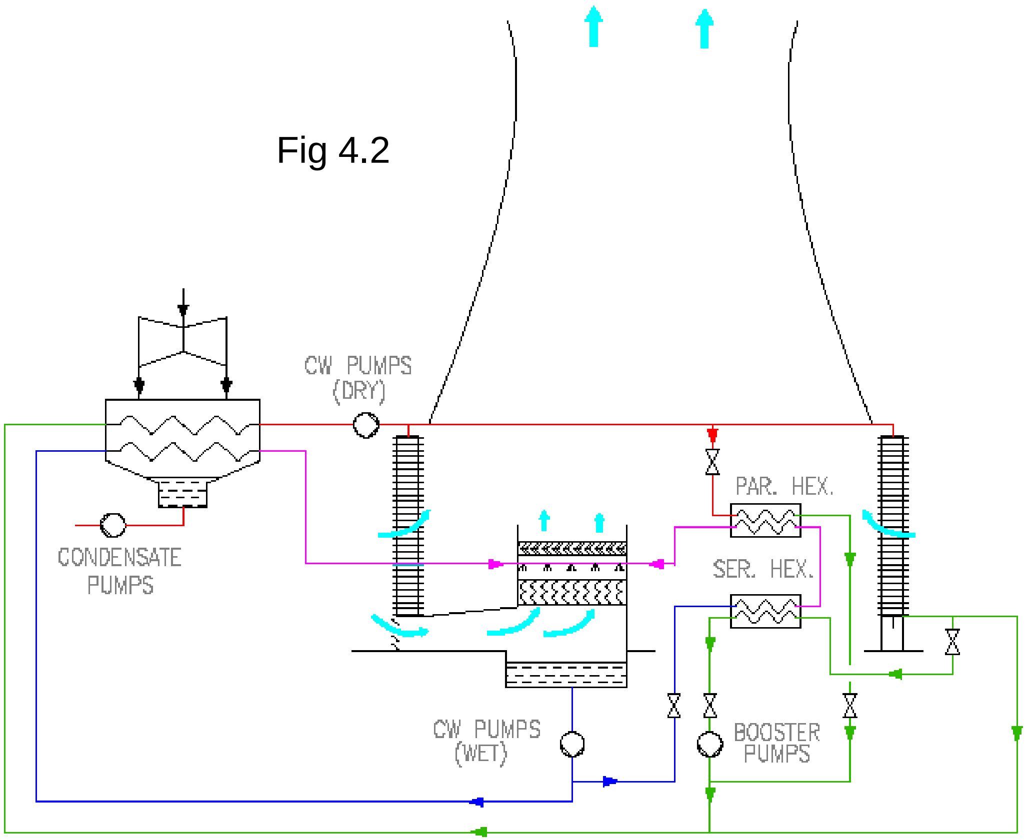
❖ **Case Study 2: Economic evaluation of water conserving cooling systems serving a 1200 MW_e class NPP** (planned for a warm climate)

- ✓ The site has a relatively warm climate characterized by a high make-up water cost (1 $/m^3).
- ✓ A number of water conserving variants were investigated, and compared to wet cooling:
  - dry HELLER System with supplemental spraying, with < 1% annual make-up water consumption (compared to the all-wet cooling system;
  - single circuit serial dry/wet system with < 16% annual make-up water consumption;
  - different separate circuit dry/wet systems with < 16% annual make-up water consumption.
- ✓ All variants were investigated with both, natural and mechanical draft. Variants with natural draft dry part proved to be more economic than the mechanical draft ones.
- ✓ The dry/wet variants were investigated with the same LP turbine as applied for all-wet cooling (6F) and with a smaller exhaust turbine (4F). The 4F turbine was more economic only at the dry cooling with supplemental spraying, whereas at all the other dry/wet cooling systems the same 6F LP turbine (as used for all-wet cooling) was the more economic option.

- ✓ Fig 4.3 introduces a sensitivity diagram (showing the present value gain/cost differences in function of the variation of specific electricity selling price) for some of the selected variants. The electricity selling prices with bold numbers refer to the yearly average specific prices, under each of these values a pair of assumed off-peak and peak price value is shown (keeping a ratio of 1.83 : 1 between them). The dry part of all variants shown in Fig 4.3 is with natural draft.
- ✓ The best scoring variant among the dry/wet ones is a separate circuit dry/wet system at which the integration is made through both: the condenser and water-to-water heat exchangers. All the enhancing wet cells are located inside the tower (see Fig 4.2).

At the given specific site both, the separate circuit dry/wet system and the sprayed dry system (4F) represent a good economic viability against the all-wet one under a wide range of conditions.

Fig 4.2



Note: compared to the solution introduced in para 3.2 (Fig 3.6) the dry/wet cooling system in Fig 4.2 saves more water, though the electricity production of the NPP unit equipped with it will differ with higher value from the wet cooled one.

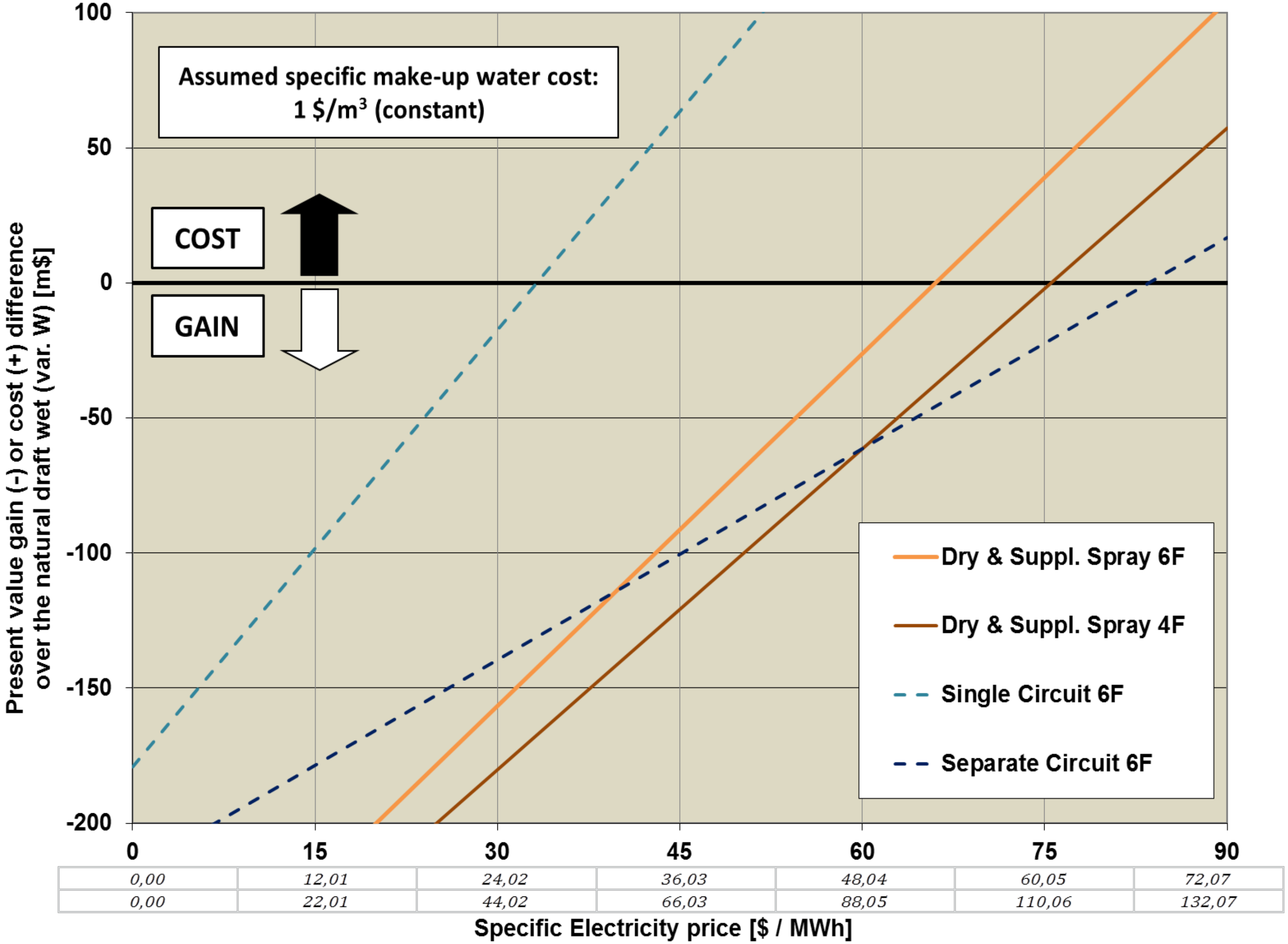


Fig 4.3 Present Value gain (-) or cost (+) differences referred to the all-wet cooling - in function of the specific average electricity price (divided for off-peak and peak values; the peak period is considered when DBT ≥ 77°F)

Enclosure: Concepts Embodied – Project References

- **GEA EGI (the center of excellence for indirect HELLER Systems) has six decades of experience - resulting in a total of 38,000 MW_e power plant capacity in service and under construction with the HELLER System and its derivatives**

- **GEA EGI's references located in 20 countries, cover all types of power cycles and climatic conditions:**

  ♦ units operating under extreme ambient conditions: *air temperature as cold as -62°C or as hot as +50°C (incl. areas over the arctic circle and in desert belt) and sites located at sea shore or at high altitudes (up to 2000 m)*

  ♦ indirect dry cooling plants either with DC or surface condenser

  ♦ the largest dry cooled Combined Cycle Power Plant in the world (set the highest availability record in the world in 2011)

  ♦ **the only dry-cooled nuclear power plant in the world**

  ♦ natural draft dry cooling towers through which flue gases are exhausted

  ♦ cost efficient, environmentally compatible dry/wet derivatives of HELLER System: *2200 MW_e equipped with supplemental spraying (incl. units under constructions) and 4300 MW_e with parallel wet assisting or delugable cooler cells*

The only one dry cooled nuclear power plant in the world:

Bilibino Nuclear Power Plant 4×12 MW$_e$ Russia (located over the Arctic Circle) **– cooling system supplied by EGI**

The plant has been operating successfully since mid. of 1970s.

- The design minimum temperature considered for the complete plant, thus also for the cooling system was: - 62 ºC

- The mechanical draft HELLER Systems have:

  ✓stainless steel surface condensers

  ✓triangular shape vertically arranged Forgó-type all-aluminum air coolers

  ✓ warm air re-circulation possibility is applied to protect the air coolers against extreme low winter temperatures

photo's source: http://foto.chukotken.ru

✓since the ambient temperature in July and August may exceed 30-33°C, after a period of operation a supplemental spraying system has been installed to be used for this short period (approx. 100 hours/year).

Air Moving: either natural (concrete or steel) or mechancal draft

3 × 220 MW_e Al Zara TPP, Syria; EPC: MHI

2 × 600 MW_e Yangcheng TPP
HELLER System with surface condenser

800 MW_e Modugno CCPP, Italy; EPC: ALSTOM
Induced draft, low noise, near sea shore

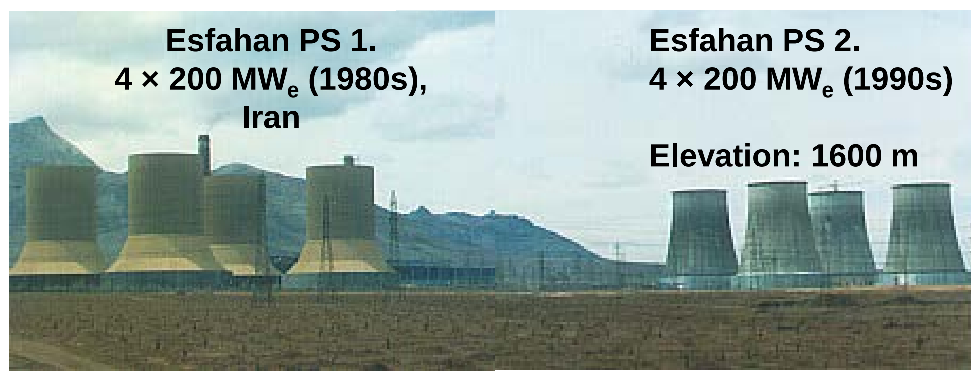
260 MW_e Moscow City 2. Co-gen CCPP
winter proof up to -42°C

HELLER Systems for any climate: Extreme Cold or Sizzling Deserts

2 × 180 MW_e Pervomajsk CHP, Russia
freeze proof up to -42°C

540 MW_e Nasserieh CCPP, Syria, EPC: Siemens

2 × 310 MW_e & 4 × 200 MW_e Razdan PS, Armenia
Elevation: 1760 m



Esfahan PS 1.
4 × 200 MW_e (1980s),
Iran

Esfahan PS 2.
4 × 200 MW_e (1990s)

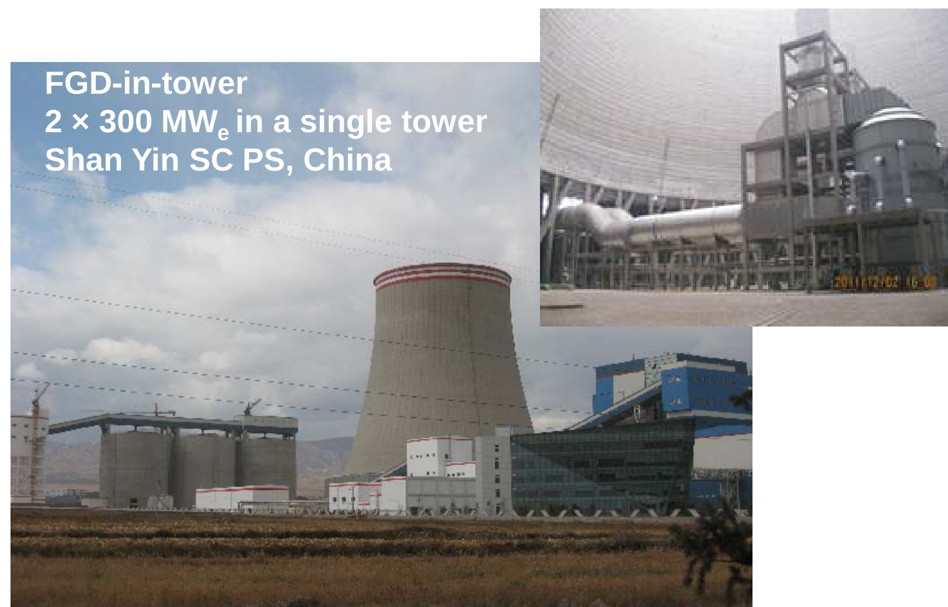
Elevation: 1600 m

World’s largest dry cooled combined cycle power plant

Cool for Coal – a greener & cheaper flue gas exhausting

2 × 700 MW_e BaoJi SC PS, China, FGD-in-tower

Stack-in-tower in the 320 MW_e Can PS, Turkey

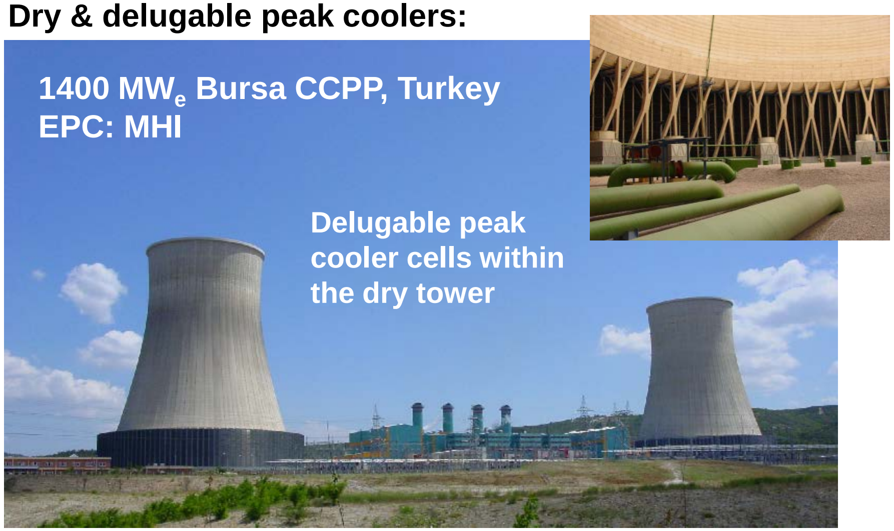


FGD-in-tower
2 × 300 MW_e in a single tower
Shan Yin SC PS, China

Dry/wet HELLER System Derivatives

Dry with supplemental spray:

Dry & delugable peak coolers:



Separate circuit dry/wet HELLER System

Assisting wet cells located outside the dry cooling towers

860 MW_e lignit fired Mátra PS, Hungary – of which 2×230 MW_e dry/wet units

Literature

[1] Balogh, A., Szabó, Z., Dry & Dry/Wet Cooling May Enhance Economy and Realize Ultimate Environmental Compatibility for Nuclear Power Generation, Paper presented at the 8th Annual China Nuclear Energy Congress, May 2012, Beijing, China

[2] Szabó, Z., Grégász, A., Mezey, Z.: Water Conservation Type Cooling Systems for Nuclear Power Plants, Paper at 3rd Annual Meeting of ACC Users Group, September 2011, San Francisco, CA

[3] Szabó, Z., No Green Nuclear Power without Green Cooling Systems, Paper presented at the China nuclear Power Leadership Summit, September 2010, Guangzhou, China

[4] Jones, N., Kaplan, C., Narula, R., Appraising Our Future Cooling Water Options, June, 2010, Power

[5] Balogh, A., Szabó, Z., Heller System: The Economical Substitute for Wet Cooling, November 2009, Power Plant Chemistry

[6] Hogan, M., The Secret to Low-Water-Use, High-Efficiency Concentrating Solar Power, Climate Progress, April 2009, http://www.worldchanging.com/archives/009802.html

[7] Balogh, A., Szabó, Z., Heller System: The Economical Substitute for Wet Cooling – to avoid casting a shadow upon the sky, EPRI Workshop on Advanced Thermal Electric Power Cooling Technologies, July 2008, Charlotte (NC)

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