SC-HTGR Performance Impact for Arid Sites

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Abstract – The SC-HTGR provides high temperature steam which can support industrial process heat applications as well as high efficiency electricity generation. The increased generating efficiency resulting from using high steam temperature provides greater plant output than lower temperature concepts, and it also reduces the fraction of waste heat which must be rejected. This capability is particularly attractive for sites with little or no water for heat rejection. This high temperature capability provides greater flexibility for these sites, and it results in a smaller performance penalty than for lower temperature systems when dry cooling must be used.

The performance of the SC-HTGR for a conventional site with wet cooling is discussed first. Then the performance for arid sites is evaluated. Dry cooling performance is evaluated for both moderately arid sites and very hot sites. Off-design performance of the dry cooling system under extreme conditions is also considered. Finally, operating strategies are explored for sites where some cooling water may be available but only in very limited quantities.

Results of these assessments confirm that the higher operating temperatures of the SC-HTGR are very beneficial for arid sites, providing significant advantages for both gross and net power generation.

I. INTRODUCTION

In many parts of the world water is in short supply. This includes both traditional arid regions as well as regions where increasing water use is exceeding the supply. This problem is only expected to worsen as increasing populations and economic growth place greater and greater demands on both water supplies and power supplies.

In such locations where the fresh water supplies are limited and demand is increasing, water is simply too valuable to be used in large quantities for evaporative cooling in power plants. In some arid locations, once-through seawater cooling can be used. However, for inland sites and sites with restrictions on seawater cooling, options are very limited.

For such locations, non-evaporative or dry cooling must be employed. Moreover, even in some locations where water is more readily available, dry cooling systems are being adopted due to environmental issues and associated regulations.

As a result, many markets will require power plants using dry cooling. However dry cooling has significant impacts on power plant performance and economics. The objective of this paper is to provide an initial evaluation of the relative impact of dry cooling on AREVA’s SC-HTGR (steam cycle – high temperature gas-cooled reactor).

II. BACKGROUND

Before discussing the detailed performance of the SC-HTGR system with dry cooling, it is worthwhile to discuss possible heat rejection options available for sites with limited cooling water and the general impact of dry cooling on power plant performance. Then SC-HTGR design concept is also
briefly described. More details of the SC-HTGR concept are discussed in [1] and [2].

II.A. Cooling Options for Arid Sites

All thermal power plants must reject a significant quantity of waste heat. But power plants in hot, arid locations face greater challenges. The air temperature to which the waste heat must be rejected is higher. More importantly, evaporative or “wet” cooling, which is typically the most effective mode of heat rejection, cannot be used due to the lack of water.

One option for a high temperature heat source such as the SC-HTGR would be to switch to an alternate power generation cycle. In particular, an HTGR coupled directly to a recuperated Brayton cycle can be an attractive option due the high temperature capability of the HTGR. This system can offer higher thermal efficiencies if properly optimized. More importantly, since the Brayton cycle rejects waste heat over a wider temperature range, it typically faces a smaller penalty in arid environments.

However, the Brayton cycle option is largely limited to electricity generation. While it could theoretically supply low temperature waste heat for other applications such as district heating, it is not appropriate for high temperature process heat cogeneration applications. Such applications are a major segment of the SC-HTGR target market. In addition, the Brayton cycle has greater developmental challenges.

For the conventional Rankine cycle, there are two main cooling options for arid sites:
- Closed circulating water system with dry cooling towers
- Air-cooled condenser

This study focuses on the circulating water system with dry cooling towers for the SC-HTGR. This option maintains greater commonality with the plant configuration for non-arid sites with wet cooling towers (or once-through water cooling). It also avoids the challenges typically associated with direct air cooling of the condenser such as maintaining the large vacuum boundary over the large surface area required for air cooling. It also simplifies the plant arrangement in the vicinity of the turbine plant, since the dry cooling towers can be located apart from the condenser.

II.B. General Dry Cooling Considerations

The selection of dry cooling leads to important optimization tradeoffs which have a strong impact on plant performance, heat rejection system initial and operating cost, and overall plant economics. In situations where wholesale power costs are low and capital costs are a major concern, the optimized system will likely have smaller dry cooling towers and reduced fan power, at the expense of plant thermal performance. On the other hand, in markets with high wholesale power prices, the optimized plants will likely have increased cooling area and fan power to maximize plant output.

But no matter how the system is optimized, use of dry cooling typically results in a higher condenser temperature. This is due first of all to the fact that the local dry bulb temperature will be higher than the concurrent wet bulb temperature (particularly in arid locations). In addition, the dry cooling tower heat transfer will generally not be as effective as the direct contact heat transfer in a wet cooling tower.

This results in a higher turbine backpressure for the plant with dry cooling, reducing the plant efficiency and the gross power generation. Dry cooling also results in an increase in auxiliary electrical load for cooling tower fans, further reducing the net electrical output of the plant.

There are typically three main impacts of dry cooling: reduced power generation, increased plant equipment cost, and higher parasitic power consumption within the plant. These impacts combine to reduce the net electric production of the plant and to increase the resulting cost of electricity.

The magnitude of the dry cooling impact is strongly dependent on the operating temperature of the plant. The higher the temperature at which energy is provided in the power generating cycle, the greater the usable energy and the smaller the fraction of waste heat that must be rejected and the less the impact of dry cooling on plant performance. This gives a high temperature system such as AREVA's steam cycle high temperature gas-cooled reactor (SC-HTGR) a significant advantage in dry cooling environments. Less heat needs to be rejected, and there is less impact on plant equipment and overall plant performance.

This concept is illustrated in the Figure 1 which shows simplified thermodynamic cycles for three different systems: one with 566°C superheated steam, one with 288°C saturated steam, and one with 232°C saturated steam. For each cycle, the area between the upper curve (energy into the cycle) and the lower curve (rejected waste heat) represents the useful energy obtained. The energy lost due to the increase in heat rejection temperature (e.g., due to dry cooling) is indicated by the shaded area at the bottom edge of the figure. This simple diagram indicates that the impact of dry cooling is more than 50% more severe for the 232°C cycle compared to the 566°C cycle.

A more detailed look at the performance of the SC-HTGR plant operating in arid sites where dry cooling must be used is provided in the remainder of this paper.
II.C. SC-HTGR Description

The SC-HTGR is being developed by AREVA in collaboration with the NGNP Industry Alliance. It is a high temperature graphite-moderated gas-cooled nuclear heat source that is capable of supplying safe nuclear energy to a variety of applications including process heat, electricity generation, and cogeneration of electricity and high temperature steam. Each power plant would typically include multiple reactor modules, each of which would be a 625 MWt prismatic block reactor. Helium coolant carries heat from the reactor outlet (750°C) to the steam generators where high temperature superheated steam is produced (566°C, 16.7 MPa main steam). These conditions make the SC-HTGR well suited to many applications which cannot be served by lower temperature steam from light water reactors, and it also provides high electricity generating efficiencies.

The concept has significant inherent safety characteristics that make it particularly well suited to colocation with large industrial facilities. These characteristics include inert helium coolant which cannot change phase or react with other reactor materials, graphite core structure which cannot melt, coated particle fuel which retains fission products for all operating and accident temperatures, and natural passive cooling characteristics that maintain acceptable fuel temperatures in spite of the failure of the active cooling systems or the loss of all electric power and even with the loss of all coolant. The reactor core is inherently self-regulating, shutting itself down if temperatures increase unexpectedly, and the system has large thermal inertia, so that any events will develop gradually.

As was already mentioned, the high steam temperature and pressure operating conditions provided by the SC-HTGR are a particular advantage for arid sites. The use of high temperature steam means that an increase in the condenser pressure at the turbine outlet has a relatively smaller impact on the cycle performance compared to lower temperature concepts.

In addition, since the basic thermodynamic efficiency of the system is higher, that means that less heat must be rejected for each unit of electricity produced. For the SC-HTGR nominal system, with a base efficiency of 43%, about 1.3 MWt of waste heat would be rejected for each MW of electric energy produced. This compares very favorably to a modern light water reactor with an efficiency of about 34%, in which case 1.9 MWt must be rejected for each MWe produced.

So, over 30% less waste heat has to be rejected from the SC-HTGR cycle than from a comparable modern light water reactor. One benefit of this is that the SC-HTGR heat rejection system will be smaller than for a similar reactor providing lower temperature steam. Moreover, any necessary modifications to the heat rejection system for arid conditions will be less costly for the high temperature SC-HTGR system.

III. PERFORMANCE EVALUATION APPROACH

The thermal performance of the SC-HTGR plant is modeled using a Microsoft Excel™ steady-state heat balance model. Steam properties are computed using Excel functions from [3]. This is based on the same model used for previously reported AREVA steam cycle HTGR results [4], but some enhancements to the model were included. The main enhancements include:

- Individual component efficiencies have been included in the model (e.g., turbine, pumps, generator).
- The plant house load has been expanded to explicitly consider circulating water and cooling tower fan power.
- Explicit modeling of the circulating water system and cooling towers was developed.

These enhancements were necessary to examine the dry cooling impact. The parameters such as circulating water flow and cooling tower fan power vary significantly in changing from wet cooling to dry cooling configurations.
IV. PERFORMANCE EVALUATION

The impact of hot arid sites and the need for dry cooling on the thermal performance of the SC-HTGR generating system was considered by evaluating system performance under three different conditions:

- Wet Cooling – Traditional moderate temperature site with evaporative cooling towers
- Arid Site Dry Cooling – A hot arid site requiring the use of closed dry cooling towers
- Extreme day hot arid site – Extreme conditions at a hot arid site using dry cooling

Each of these cases is described briefly below.

There are two basic types of dry cooling systems for steam cycle generating plants. One option uses an air-cooled condenser without an intermediate circulating water loop. The second approach uses a more conventional water-cooled condenser with closed, non-evaporative cooling towers to cool the circulating water. This study uses the second dry cooling approach.

IV.A. Reference Case – Wet Cooling

The base or nominal performance of the system provides an initial reference point. This is the performance of the standard system for a typical site using traditional wet cooling where temperatures are not extreme. This evaluation assumes a wet bulb temperature of 16°C and a corresponding dry bulb temperature of 36°C. This leads to a condenser temperature of 34°C, which sets the turbine backpressure and plays a key role in determining the plant efficiency.

The calculated performance takes into account preliminary efficiency estimates for the helium circulators, feedwater pumps, turbine, and generator, as well as electrical loads of the circulating water pumps, cooling tower fans, and other plant electrical loads. Considering the specific electrical loads provides a more detailed breakdown of the house load than that previously estimated for SC-HTGR performance evaluations. This was necessary, in anticipation of the more detailed evaluation of dry cooling, since dry cooling has a strong impact on the parasitic electrical loads associated with the cooling towers and circulating water system. The resulting house load for the nominal wet cooling case is provided in Table 1.

The gross electrical output from each 625 MWt reactor module is 293 MWe. After accounting for the 21 MWe house load, the net output is 272 MWe, giving a net efficiency of 43.5%. This is Case 1.

Table 1: Nominal house load (wet cooling).

<table>
<thead>
<tr>
<th>Description</th>
<th>Load (MWe)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main helium circulators (both loops)</td>
<td>8.0</td>
</tr>
<tr>
<td>Feedwater/boost pumps</td>
<td>7.7</td>
</tr>
<tr>
<td>Circulating (tertiary) water pumps</td>
<td>2.0</td>
</tr>
<tr>
<td>Cooling tower fans (wet tower)</td>
<td>1.4</td>
</tr>
<tr>
<td>Miscellaneous loads</td>
<td>2.0</td>
</tr>
<tr>
<td><strong>TOTAL HOUSE LOAD</strong></td>
<td><strong>21.1</strong></td>
</tr>
</tbody>
</table>

IV.B. Dry Cooling - Hot Arid Site

The second case is a plant located at a hot arid site. The plant is assumed to be designed for a typical “hot” day at the site. The nominal design dry bulb temperature is assumed to be 45°C based on conditions at potential future plant sites.

Optimization of the plant configuration for dry cooling will involve important tradeoffs between the benefits of increasing the cooling tower size and fan power to lower condenser pressure and improve gross cycle efficiency versus the increased capital costs of the larger cooling tower (and the increased house load of larger fans). In the real world, each plant will be optimized for the unique local conditions considering expected seasonal and daily temperature extremes, the daily variation in electrical demand, and the local value of electricity.

The case evaluated provides an initial compromise in cooling tower area and fan power pending more detailed design work.

The higher ambient temperature and the use of dry cooling result in a condenser temperature of 67°C. This lowers the gross cycle efficiency. The gross electricity generation is reduced to 264 MWe.

In addition, the use of dry cooling compels the use of higher cooling tower surface area and higher cooling tower fan power, resulting in a 4.4 MWe increase in house load. As a result, the net plant efficiency is reduced to about 38.2%. This is Case 2.

IV.C. Extreme Day - Arid Site Dry Cooling

The third case shown is for the same plant in Case 2, but now operating at an extreme condition for the hot arid site.

The usual approach is to design the plant for a "typical" hot day, since this is the most common demanding condition the plant will face. This provides the best overall performance, since the plant is usually operating relatively close to the design point. Operating at the design point generally gives the optimum performance for the site conditions, since all equipment is optimized for that point.

However, this means that on the extreme hot day (e.g., hottest day per year or hottest day per several years), then the plant will be slightly “off-design”. Its performance under the extreme conditions will be...
degraded slightly compared to what it would have been if it had been optimized for that point. Nonetheless, this is still usually the best approach. It is better to have the plant optimized to perform at the conditions it will encounter frequently, than to optimize for conditions it will almost never encounter at the expense of the more typical conditions.

So, this case considers the dry-cooled plant optimized for operation at a dry bulb temperature of 45°C but now operating with the dry bulb temperature increased to 55°C.

This off-design operation has several ramifications. The most significant is the direct increase in condenser temperature corresponding to the increase in heat sink temperature. This reduces the cycle efficiency which has a secondary effect of increasing the heat rejected to the dry cooling towers. This increase in heat load results in a slight further increase in condenser temperature. The efficiency for major plant components also degrades slightly, since they are no longer operating at their optimum design points. Most important of these is the steam turbine which is assumed to drop in efficiency from 93% at the design condition (previous case) to 92.5% in this extreme condition.

The house load is assumed to remain constant, since the cooling tower fans were sized for the design point at a 45°C dry bulb temperature. They still are operating at their design flow condition in the extreme case, so fan power is not affected significantly.

This off-design condition results in an increase in condenser temperature to 78°C. This further lowers gross electric generation to 254 MWe for gross efficiency of 40.6%. The net generation is 228 MWe for a net efficiency of 36.5%. It is noteworthy that even for these extreme conditions the net efficiency is still higher than a lower temperature reactor would achieve even under ideal wet cooling conditions. The extreme day performance case is Case 3.

The results of these three cases are summarized and compared in Table 2.

Table 2: SC-HTGR performance comparison.

<table>
<thead>
<tr>
<th>Case</th>
<th>Type of site and heat rejection mode</th>
<th>Cooling tower type</th>
<th>Wet bulb temperature</th>
<th>Dry bulb temperature</th>
<th>Condenser temperature</th>
<th>Reactor power (MWt)</th>
<th>Gross electricity generation (MWe)</th>
<th>Gross cycle efficiency</th>
<th>Total house load (MWe)</th>
<th>Net electricity output (MWe)</th>
<th>Condenser heat load rejected (Mwt)</th>
<th>Net efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Nominal Hot Arid Site</td>
<td>Wet</td>
<td>16°C</td>
<td>36°C</td>
<td>34°C</td>
<td>625</td>
<td>293</td>
<td>46.9%</td>
<td>21</td>
<td>272</td>
<td>340</td>
<td>43.5%</td>
</tr>
<tr>
<td>2</td>
<td>Extreme Day for Hot Arid Site</td>
<td>Dry</td>
<td>NA</td>
<td>45°C</td>
<td>67°C</td>
<td>625</td>
<td>264</td>
<td>42.3%</td>
<td>26</td>
<td>239</td>
<td>369</td>
<td>38%</td>
</tr>
<tr>
<td>3</td>
<td>Extreme Day for Hot Arid Site</td>
<td>Dry</td>
<td>NA</td>
<td>55°C</td>
<td>78°C</td>
<td>625</td>
<td>254</td>
<td>40.6%</td>
<td>26</td>
<td>228</td>
<td>380</td>
<td>36.5%</td>
</tr>
</tbody>
</table>

As a result, it is reasonable to expect that the economic impact of dry cooling on the SC-HTGR system will be less significant than for lower temperature systems. The reduction in plant output (i.e., revenue) will be less, and the increase in relative plant cost will also be smaller. Both of these factors minimize the economic impact of dry cooling.

V. HYBRID COOLING WITH LIMITED WATER

In semi-arid environments where limited fresh water for evaporative cooling might be available, combined wet-dry cooling systems offer significant advantages. There are two general approaches to combined wet-dry cooling:

- In one approach, limited water is used on a continuous basis for improved performance throughout the year.
- In the other approach, dry cooling is used most of the time, and the limited available water is reserved for use at the periods of highest temperature or peak demand in order to maximize the benefit of the limited resource.

Again, this discussion considers plant configurations using a conventional condenser with circulating water cooled with some combination of dry and wet cooling towers. These could either be dry towers in series with a wet tower or hybrid wet-dry towers which can accommodate both cooling modes. Or, as discussed later, they might be dry towers for normal use combined with wet towers for intermittent use.
V.A. Continuous Hybrid Cooling

For continuous cooling with limited water, a variety of system configurations are possible. Such systems usually place dry cooling and wet cooling in series. High temperature heat is first rejected using dry cooling, and then remaining low temperature heat rejection is performed using wet cooling. This combination is particularly attractive, since the dry cooling heat rejection is far more efficient at rejecting the high temperature heat than at the final lower temperature stages of heat rejection. And the wet cooling heat rejection is still very efficient in the final stage of the cooling as the circulating water approaches the ambient wet bulb which is often quite low in arid locations. This configuration might also require a split condenser in which different parts of the condenser are cooled in series. The coldest part of the condenser cooled with cold return water from the wet tower would operate at one temperature/pressure and subsequent condenser segments cooled by warmer water prior to returning to the dry tower would operate at higher temperatures/pressures.

Detailed performance of such a hybrid cooling system has not yet been performed for the SC-HTGR. However, the performance of the system would be expected to fall between Cases 1 and 2 in Table 2. The precise performance would depend on the actual configuration, which would be optimized on a case by case basis considering the expected range of wet bulb and dry bulb ambient temperatures, the plant turbine and condenser design, the amount of cooling water available, and the demand for peak versus non-peak power.

V.B. Intermittent Hybrid Cooling

For many situations with limited water availability, intermittent wet cooling may offer the best approach. This configuration relies solely on dry cooling most of the time and reserves the wet cooling for only the hottest ambient conditions and the periods of peak demand. This is analogous to current practice in open cycle gas turbine plants where chilled water is stored and then used to directly cool the compressor inlet air at times of peak demand (which usually occur at the hottest time of day).

The detailed configuration for a plant with intermittent wet cooling would again depend on a number of situation specific factors. Typically the dry cooling heat rejection system would be sized for full power operation during the normal range of conditions. The number of cooling tower cells required for wet cooling is usually much smaller than required for dry cooling, so either a limited number of additional wet cooling tower cells would also be provided or some of the dry cooling towers would be configured for hybrid wet-dry cooling.

If one considers the plant configuration used in Cases 2 and 3 of Table 1, the performance can be reestimated for the extreme conditions of Case 3 but with wet cooling instead of dry cooling. For the site conditions considered, a wet bulb temperature of 28°C offers the same level of conservatism as the 55°C dry bulb temperature used in Case 3. For wet cooling with a wet bulb temperature of 28°C, the net plant efficiency would be over 41%. This corresponds to an increase in plant output of over 13% compared to the dry cooling scenario for the same extreme ambient condition. This illustrates the large benefit of even small quantities of water that might enable the use of wet cooling during critical periods.

Of course, if no cooling water is available, the performance of the SC-HTGR system with dry cooling still provides an attractive alternative as a non-fossil fueled heat source with relatively high thermal efficiency.

Table 3: Benefit of wet cooling on extreme day.

<table>
<thead>
<tr>
<th>Type of site and heat rejection mode</th>
<th>Case 1</th>
<th>Case 2</th>
<th>Case 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cooling tower type</td>
<td>Wet</td>
<td>Dry</td>
<td>Wet</td>
</tr>
<tr>
<td>Wet bulb temperature</td>
<td>16°C</td>
<td>NA</td>
<td>28°C</td>
</tr>
<tr>
<td>Dry bulb temperature</td>
<td>36°C</td>
<td>55°C</td>
<td>55°C</td>
</tr>
<tr>
<td>Condenser temperature</td>
<td>34°C</td>
<td>78°C</td>
<td>47°C</td>
</tr>
<tr>
<td>Reactor power (MWt)</td>
<td>625</td>
<td>625</td>
<td>625</td>
</tr>
<tr>
<td>Gross electricity generation (MWe)</td>
<td>293</td>
<td>254</td>
<td>280</td>
</tr>
<tr>
<td>Gross cycle efficiency</td>
<td>46.9%</td>
<td>40.6%</td>
<td>44.8%</td>
</tr>
<tr>
<td>Total house load (MWe)</td>
<td>21</td>
<td>26</td>
<td>21</td>
</tr>
<tr>
<td>Net electricity output (MWe)</td>
<td>272</td>
<td>228</td>
<td>259</td>
</tr>
<tr>
<td>Condenser heat load rejected (Mwt)</td>
<td>340</td>
<td>380</td>
<td>353</td>
</tr>
<tr>
<td>Net efficiency</td>
<td>43.5%</td>
<td>36.5%</td>
<td>41.4%</td>
</tr>
</tbody>
</table>

VI. CONCLUSIONS

The use of dry cooling in a hot arid environment imposes a performance penalty on any thermal power plant. Fortunately, the penalty is not as severe for the SC-HTGR due to its higher steam supply temperature. This reduces the loss in generation resulting from an incremental increase in condenser temperature and it reduces the quantity of waste heat which must be handled by the dry cooling system.

The nominal SC-HTGR concept operating with wet cooling for a conventional site achieves a net efficiency of over 43%. For a hot arid site requiring...
the use of dry cooling, this drops to about 38%. For extreme conditions with an ambient temperature of 55°C, this is reduced further to just over 36%.

Thanks to the high temperature of the SC-HTGR steam supply system, switching from conventional wet cooling to dry cooling only results in a loss of 12% of the electric generation output (for the hot arid case). This compares to a drop of almost 20% of the plant output for a light water reactor under similar conditions. Moreover, the resulting efficiency of the SC-HTGR with dry cooling is still better than the net efficiency of a light water reactor even with wet cooling at a non-arid site.

The economic penalty associated with dry cooling is less severe for the SC-HTGR than for lower temperature generating systems.

The reduced sensitivity of the SC-HTGR system to increased heat rejection temperatures also makes it well suited to coupling with cogeneration and thermal desalination systems. The impact of lost electricity generation is much smaller than for other lower temperature power generating systems.

The SC-HTGR high temperature steam supply system not only offers the flexibility to serve a variety of process heat and electric applications, but also offers the flexibility to efficiently serve under a wide variety of site conditions including sites requiring collocation with a process application and arid sites requiring dry cooling.

REFERENCES


