Enhancing VHTR Passive Safety and Economy with Thermal Radiation Based Direct Reactor Auxiliary Cooling System

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Enhancing VHTR Passive Safety and Economy with Thermal Radiation Based Direct Reactor Auxiliary Cooling System

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Abstract – One of the most important requirements for Gen. IV Very High Temperature Reactor (VHTR) is passive safety. Currently all the gas cooled version of VHTR designs use Reactor Vessel Auxiliary Cooling System (RVACS) for passive decay heat removal. The RVACS can be characterized as a surface-based decay heat removal system. It is especially suitable for smaller power reactors since small systems have relatively larger surface area to volume ratio. However, RVACS limits the maximum achievable power level for modular VHTRs due to the mismatch between the reactor power (proportional to the core volume) and decay heat removal capability (proportional to the vessel surface area). Besides the safety considerations, VHTRs also need to be economical in order to compete with other reactor concepts and other types of energy sources. The limit of decay heat removal capability set by using RVACS has affected the economy of VHTRs. A potential alternative solution is to use a volume-based passive decay heat removal system, called Direct Reactor Auxiliary Cooling Systems (DRACS), to remove or mitigate the limitation on decay heat removal capability. DRACS composes of natural circulation loops with two sets of heat exchangers, one on the reactor side and another on the environmental side. For the reactor side, cooling pipes will be inserted into holes made in the outer or inner graphite reflector blocks. There will be gaps or annular regions formed between these cooling pipes and their corresponding surrounding graphite surfaces. Graphite has an excellent heat conduction property. By taking advantage of this feature, we can have a volume-based method to remove decay heat. The scalability can be achieved, if needed, by employing more rows of cooling pipes to accommodate higher decay heat rates. Since heat can easily conduct through the graphite regions among the holes made for the cooling pipes, those cooling pipes located farther away from the active core region can still be very effective in removing decay heat. By removing the limit on the decay heat removal capability due to the limited available surface area as in a RVACS, the reactor power density and therefore the reactor power can be significantly increased, without losing the passive heat removal feature. This paper introduces the concept of using DRACS to enhance VHTR passive safety and economics. Three design options with different cooling pipe locations are discussed. Analysis results from a lumped volume based model and CFD simulations are presented.

I. INTRODUCTION

One of the important requirements for Gen. IV High Temperature Gas Cooled Reactors (HTGR) is passive safety. Currently all the HTGR designs such as GT-MHR ¹, PBMR ², NGNP ³, and GTHTR300 ⁴ use Reactor Vessel Auxiliary Cooling System (RVACS) for passive decay heat removal. The decay heat first is transferred to the core barrel by conduction and radiation, and then to the reactor vessel by thermal radiation and convection; finally the decay heat is transferred to a cooling air or water system driven by natural circulation. RVACS can be characterized as a surface-based decay heat removal system. Similar concepts have been widely used in sodium cooled fast reactor (SFR) designs such as General Electric’s PRISM and S-PRISM designs ⁵, and advanced light water reactors like AP600 and AP1000 ⁶. The RVACS is especially suitable for smaller power reactors since small systems have relatively larger surface area.

RVACS tends to be less expensive than the volume-based decay removal system. However, it limits the largest achievable power level for modular HTGRs due to the mismatch between the reactor power (proportional to volume) and decay heat removal capability (proportional to...
When the relative decay heat removal capability is reduced, the peak fuel temperature increases, even close to the design limit. Annular designs with internal reflector can mitigate this effect therefore further increase the power. Another way to increase the reactor power is to increase the power density. However, both options are also limited by the decay heat removal capability. Besides safety, HTGRs also need to be economical in order to compete with other reactor designs. The limit of decay heat removal capability set by using RVACS has affected the economy of HTGRs. Forsberg pointed out other disadvantages of using RVACS such as conflicting functional requirements for the reactor vessel and scaling distortion for integral effect test of the system performance.

A potential alternative solution is to use a volume based passive decay removal system, call Direct Reactor Auxiliary Cooling Systems (DRACS), to remove or mitigate the limitation on decay heat removal capability. DRACS has been widely used in SFR designs such as the EBR-II reactor, EFR, JSFR, and ABTR and in liquid salt cooled high temperature reactors. The containment cooling system in BWR is another example of volume based decay removal systems. DRACS composes of natural circulation loops with two sets of heat exchangers, one in reactor side and another is in environmental side. Fig. 1 shows one example of DRACS system for a SFR design. DRACS has the benefits of increasing the power as needed (scalability) and modularity. For example, GE was able to scale up the power of 600 MWe SBWR to 1500 MWe ESBWR design while Westinghouse can only increase the 600 MWe AP-600 design to 1100 MWe AP-1000 design mainly due to the limit of available containment surface area. This paper introduces the concept of using DRACS to enhance HTGRs passive safety and economy. Three design options are discussed in Section II. Preliminary analysis results are presented in Section III.

II. DESIGN DESCRIPTION

The DRACS for HTGRs will be similar to those used in SFRs with high-temperature liquid flowing in the loops. In the reactor side, thermal radiation will transfer heat to one or several rows of cooling pipes. Those small diameter pipes can be compared to water panels in a typical coal fired power plant boiler. During normal operation, a small amount of heat will leak into DRACS to keep the fluid from freezing. During accidents, elevated reactor temperature will rapidly increase thermal radiation heat transfer since it is proportional to the fourth power of temperatures.

Different high temperature fluids can be considered depending on operation temperature range, chemical inertness, natural circulation capability, and material compatibility. Fluoride salts are excellent high temperature coolants with potential operation temperature range from 400 to 1600°C. Liquid fluoride salts are stable and only slowly react with air or water. Therefore, use of liquid salts will not affect the safety of HTGRs. Lead can be considered as a potential coolant for the DRACS as well.

Fig. 1. DRACS for an advanced SFR design.

Fig. 2. DRACS cooling pipes arrangement options.
Depending on the locations of the cooling pipes, three different designs are proposed as shown in Fig. 2: Option A – cooling pipes located in the gap between the core barrel and the reactor vessel, Option B - cooling pipes in the permanent outer reflector, and Option C - cooling pipes in the inner reflector. Fig. 3 shows two potential cooling pipe designs. In order to facilitate the installation and removal of cooling pipe assemblies during maintenance, both the inlet and outlet of the cooling pipes should be located above the core as shown in Fig. 4. For the concentric cooling pipe design, the liquid coolant from the inlet joint (manifold) will flow into the inner pipe and turn up at the bottom to enter the annular space. The upward flow will absorb heat from the outer pipe wall and finally merge into the outlet joint (manifold) with flow from other neighboring pipes. During maintenance, the passive cooling assemblies can be temporarily removed from the top, similarly to the way of removing control rod drive mechanism. The concentric design is more difficult to manufacture than the U-tube pipe. However, the U-tube pipe needs non-circular holes in the graphite blocks for the design Options B and C. The penetrations for the DRACS piping through the reactor pressure vessel (RPV) can be minimized by combining groups of cooling pipes into few of DRACS loops. Due to the low total volumetric flow rate of the liquid coolant, the total cross section area is small and will be much smaller than control rod drive mechanism penetrations.

Although the concept is demonstrated here for a prismatic type of HTGRs, it also works for pebble bed HTGR designs. The following section will discuss three design options in detail.

II.A. Design Option A: Cooling Pipes near Reactor Vessel

One or two rows of cooling pipes are installed close to the inner surface of the reactor vessel. In this design, the total heat removal capability is still limited by the available surface area. But by being closer to the heating source and bypassing the reactor vessel wall compared to the RVACS, this design has slightly higher heating temperature, therefore better heat transfer, and the flexibility to eliminate the reactor vessel from the heat transfer path. This design may increase the decay heat removal capability slightly. In the region between the core barrel and the reactor vessel, fast neutron influence level is low and temperature can be controlled below 700°C. Less expensive high temperature alloys can be chosen as structure material.

II.B. Design Option B: Cooling Pipes in the Permanent Reflector

In this design, the cooling pipes will be inserted into the holes in the permanent reflector blocks. There will be gaps between these cooling pipes and their corresponding surrounding graphite hole surfaces. Graphite has an excellent heat conduction property. By taking advantage of this feature, we can have a volume-based method to remove decay heat. The scalability can be achieved, if needed, by employing more rows of cooling pipes to accommodate higher decay heat rates. Since heat can easily conduct through the graphite regions between the holes made for the cooling pipes, those cooling pipes located further away from the active core region can still be very effective in removing the decay heat. By removing the limit on the decay heat removal capability due to the limited available surface area as in a RVACS, we can significantly increase the reactor power and power density without losing the passive heat removal feature.
Certainly, we will need to examine fast neutron influence on the cooling pipe, but it is expected to be low due to the thick graphite reflector’s protection from the active core region. At this location, the temperature is still not too high so that high temperature alloys such as Alloy 617 can be considered as a potential pipe material.

The DRACS system will become almost thermally equilibrium with ambient graphite under normal operation condition since we do not wish excess heat leakage through DRACS. The potential asymmetric cooling and thus undesirable distortion effects like thermal stresses or temperature-dependent shrinkage/swelling of graphite therefore will only appear during major design basis accidents that are rare. Even without the DRACS system, graphite will still subject to a large temperature gradient along radial direction during those accidents. We believe these issues need to be considered during detailed design and analysis, but it is not a showstopper.

II.C. Design Option C: Cooling Pipes in the Inner Reflector

In this design, the cooling pipes are arranged inside the holes in the inner/central reflector blocks near the center of the reactor. Due to very high temperatures at this location, thermal radiation is so efficient that only very small amount of heat transfer area is needed to remove enough decay heat.

For a cogeneration plant such as hydrogen production, high temperature process heat can also be extracted from here by forced circulation loops with a similar liquid fluid. This process heat transfer loop design will greatly simplify the system arrangements and improve economy. No intermediate heat exchanger (IHX) is needed to transfer heat from the helium to process fluids. The largest challenge on the IHX design – high temperature and high pressure difference – will be removed. Increased temperature will also increase the quality of the process heat and therefore the efficiency of process heat utilization.

The feasibility of this design will depend on the availability of suitable structural material. At this location, very high temperature and high fast neutron influence exist at the same time. Refractory alloy or some advanced composite material such as SiC or carbon fiber composite material could be potential candidates. One potential candidate alloy is TZM (Mo-0.5Ti-0.08Zr), which has been considered as heat sink material for the ITER project. Mo-TZM has also been considered as an alternative material for the intermediate heat exchanger in the PBMR design, though it does form a brittle carburised layer in carburising atmospheres and costs three times more than the Ni-based alloys. TZM has extremely high melting point (2500°C) and can be readily manufactured into thin pipes. The damage effects in the stress-relieved TZM alloy after neutron irradiation to high influences at high temperatures were studied. Carbon fiber or SiC fiber based composite materials are currently being developed as LWR fuel clad and can be considered as an ideal cooling pipe material when the technology becomes mature.

Since the inner reflector must be replaced several times during the reactor life time, the cooling pipes need to be replaceable too.

III. PRELIMINARY ANALYSIS RESULTS

While detailed transient flow analysis has not been performed, simplified calculations that treat the reactor as a single-lumped mass can provide a first-order estimation for the transient response that follows a low-pressure conduction cool-down transient. 2-D steady state CFD analyses can show spatial temperature distribution and demonstrate the feasibility of this volume-based decay removal method.

III.A. Lumped Parameter Analysis

In the lumped parameter analysis, we assume that all the mass inside reactor vessel, including graphite, fuel block, and steel structures, behaves as one 0-D volume. The spatial distribution of temperature can be estimated by referring previous detailed system analysis. For the GT-MHR reactor design, the total active fuel block mass $m_f$ is about 93 t (metric ton) and total reflector block mass $m_r$ is about 424 t. Here we further assume that the active fuel has the same specific heat as graphite. Therefore we can combine all the fuel and reflector blocks together as graphite mass $m_g = m_f + m_r = 517$ t. The reactor vessel is the largest steel component within the reactor. The vessel mass $m_v$ is 1300 t. As an approximation, we add 30% more for the core barrel, metal support structure, and active cooling systems. Therefore the total steel mass $m_s = 1.3 \times m_v = 1700$ t.

The heat balance for the lumped volume is

$$\left( m_c c_{pc} + m_s c_{ps} \right) \frac{dT_s}{dt} = q_{decay}(t) - q_{DHX}(t) \quad (1)$$

Where $c_{pc} = 1800$ J/kg-K is the specific heat of graphite, $c_{ps} = 450$ J/kg-K the specific heat of steel, $T_s$ the average temperature for the lumped mass, $q_{decay}(t)$ the decay heat power curve, and, $q_{DHX}(t)$ the heat removal rate from the DRACS cooling pipes and can be estimated by the following equation:

$$q_{DHX}(t) = 5.67 \times 10^{-8} \cdot 0.9 \cdot A_{DHX} \left( T_b^4 - T_c^4 \right) \quad (2)$$

In Eq. (2), $A_{DHX}$ is the total outer surface area for all the cooling pipes except for Option A, $T_b$ the core barrel temperature for option A or the graphite temperature facing the cooling pipes for Options B and C, and, $T_c$ the DRACS cooling coolant temperature. For thermal radiation heat transfer, the heat transfer rate is mainly decided by the hot
side and is less sensitive to the cold side. Therefore we can assume $T_c$ to be constant. According to transient system analyses, the cooling pipe heating temperature can be estimated as

$$T_h = \begin{cases} T_a - 230K, & \text{for Option A} \\ T_a - 210K, & \text{for Option B} \\ T_a + 390K, & \text{for Option C} \end{cases}$$ (3)

The peak fuel temperature can be conservatively estimated:

$$T_{max} = T_a + 490K,$$ (4)

where 490K is the calculated maximum temperature difference between the peak and the average value during the low pressure cool down transient.

Fig. 5 shows the lumped parameter analysis result for the low-pressure conduction cool-down transient for Option A. In this case, we cannot increase the passive decay heat removal heat transfer area ($A_{DHX} = 200$ m$^2$, about same as the available reactor vessel inner surface area). The steady-state heat loss through the DRACS system is about 0.15%, which is much lower than 0.55% for the RVACS system. However, due to rapidly increasing of DRACS heat removal capability, the peak fuel temperature appears around at 21 hours instead at 50 to 60 hours for the designs with RVACS systems. The peak fuel temperature is about 1310 °C, which is much lower than the 1500 to 1600 °C values predicted by different analyses for GT-MHR design with RVACS system.

Fig. 6 shows the lumped parameter analysis result for the low-pressure conduction cool-down transient for Option B. In this case, we use two rows of cooling pipes inside the outer permanent reflector. The cooling pipe diameter is 1 cm. The number of cooling pipes is 1000 and $A_{DHX}$ is 300 m$^2$. The steady-state heat leak through DRACS system is about 0.3%, which is 100% higher than that in Option A. Due to the increased decay removal capability, the peak fuel temperature for Option B is about 40°C lower and occurs at 11 hours into the transient.

Fig. 7 shows the lumped parameter analysis result for the low-pressure conduction cool-down transient for Option C. In this case, we have freedom to use one or more rows of cooling pipes inside the inner permanent reflector. The result presented here shows the case with one row of 54 cooling pipes, which lead to a value of 16 m$^2$ for $A_{DHX}$. Due to excellent radiation heat transfer under high temperatures, the cooling pipes, even though limited in number, are sufficient to remove the decay heat. The steady-state heat leak through the DRACS system is about 0.4% of the normal power. If we need remove more decay heat, we can simply add more rows of cooling pipes. Since we only need a small number of cooling pipes in the inner reflector, we can afford to use more expensive high-temperature materials for the cooling pipes and to have more complex mechanical coupling mechanisms.
III.B. CFD Analysis

In addition to the lumped parameter analyses, 2-D steady-state CFD simulations have been performed to qualitatively estimate the decay heat removal capacity of the DRACS concepts described in Section II. All CFD analyses were performed in a one-sixth core region by taking advantage of the axisymmetric configuration of typical HTGR cores, as shown in Fig. 8.

All 2-D meshes were created using Cubit, with around 100k cells for each of the design options. All CFD analyses were performed using STAR-CCM+. In solid regions, heat conduction is the only heat transfer mechanism. In all gaps between the DRACS pipes and their surrounding graphite, thermal radiation is the dominant heat transfer mechanism. The pipe diameter used for the current preliminary study is set at 1 cm and the gap between the DRACS pipes to their surrounding graphite is set at 0.25 cm. Some further assumptions were made to simplify the mesh generation process as well as the CFD simulation. For example, the irregularly shaped active core was simplified as an annular shape. The heat transfer between the DRACS cooling pipes and the fluid inside was not included in all simulations, but it was assumed all DRACS pipes would maintain a constant wall temperature, e.g. 550 °C for design Options A and B and 850 °C for Option C. A convective heat transfer boundary condition was set on the outer boundary of the reactor vessel, assuming a constant convective heat transfer coefficient of 50 W/m²-K and a constant ambient temperature of 50 °C. A constant decay heat source, 0.05 MW/m³, which is equivalent to 1% of the nominal reactor power density, was used for the steady-state CFD simulations.

Figures 9 – 11 show the CFD results of core temperature distributions for the different DRACS design options described above. A summary of the design configurations and CFD results is listed in Table I.

### TABLE I

<table>
<thead>
<tr>
<th>Design Options</th>
<th>Heat source [MW/m³]</th>
<th>Number of pipes in 1/6th core</th>
<th>Pipe wall temperature [°C]</th>
<th>Maximum core temperature [°C]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Option A</td>
<td>0.05</td>
<td>240</td>
<td>550</td>
<td>1135</td>
</tr>
<tr>
<td>Option B</td>
<td>0.05</td>
<td>240</td>
<td>550</td>
<td>949</td>
</tr>
<tr>
<td>Option C</td>
<td>0.05</td>
<td>60</td>
<td>850</td>
<td>1060</td>
</tr>
<tr>
<td>Option C</td>
<td>0.1</td>
<td>60</td>
<td>850</td>
<td>1532</td>
</tr>
</tbody>
</table>

An observation of the maximum core temperature achieved in Options A and B leads to the conclusion that by moving cooling pipes into the outer reflector region from the gap between the graphite blocks and the vessel wall, the maximum core temperature drops dramatically from 1135 to 949 °C. In Option A, the DRACS cooling pipes are inserted in the gap between the core barrel and reactor vessel, so that the thermal radiation heat transfer capacity is still largely determined by the reactor vessel inner surface area. Therefore, adding more DRACS cooling pipes is not expected to affect the heat removal capacity significantly. However, in Option B, due to the excellent thermal conductivity of graphite, all cooling pipes work in means of volume-based heat removal mechanism. If necessary, more cooling pipes could be added to reduce the maximum core temperature further. The maximum temperature achieved in Option C, having cooling pipes inserted in inner reflector, was found to be larger than that in Option B but still lower than that in Option A. It however should be noted that the number of cooling pipes used in Option C (60 pipes in one-sixth core) is only one quarter of that used in Option B (240 pipes in one-sixth core). Option C still provides an acceptable result while this design will significantly reduce the system complexity by largely reducing the number of cooling pipes used.

As described in the previous paragraph, design options B and C are expected to achieve volume-based heat removal capacities. Fig. 12 shows the local temperature distributions in the region near the cooling pipes for design option C. It can be seen that in the small inner core reflector region surrounding the cooling pipes, the temperature varies by only about 23 °C, from 891 to 914 °C. As depicted in Fig. 12, three rings of cooling pipes were used in Option C. The surface area averaged heat flux on the graphite surfaces and total heat absorbed by cooling
pipes are summarized in Table II. It can be found that the most inner ring of the cooling pipes (Ring 3) could still achieve around 80% capacity of the most outer ring (Ring 1), which clearly proves the volume-based characteristics in the option C design.

A sensitivity case study was also performed to investigate the effect of the decay heat power density on the steady-state maximum core temperature. A constant decay heat source was set at 0.1 MW/m³, instead of 0.05 MW/m³ in the previous simulations, in the active core region. The core temperature distribution is shown in Fig. 13. The maximum core temperature was predicted to be 1532 ºC. While this value is significantly larger than the same Option C with a decay heat power density of 0.05 MW/m³, it is still smaller than the allowable peak fuel temperature 1600 ºC during design basis accidents. As a comparison, the results were also listed in Table I. As it can be seen, the maximum core temperature is very sensitive to the decay heat level. This strongly indicates that the reactor power will be largely limited by how fast the decay heat could be removed. If necessary, more cooling pipes could be added, or even a combination of Options B and C could be used to reduce the maximum core temperature. This is based on the observation of volume-based heat removal characteristics of the DRACS cooling concept. Doubling the decay heat level means doubling the reactor normal power. Therefore, just from the perspective of the decay removal capability, it is possible to increase the GT-MHR reactor thermal power from 600 to 1200 MW employing a DRACS for decay heat removal, without increasing the reactor size. Futher increasing the reactor power level beyond 1200 MW is possible by developing a design with more DRACS cooling pipes. However, due to the large uncertainty in the preliminary analyses presented here, we choose to delay this investigation to the future work when more detailed analysis models are available.

### TABLE II

<table>
<thead>
<tr>
<th>Number of pipes in one-sixth core</th>
<th>Area averaged heat flux [kW/m²]</th>
<th>Total power absorbed [kW/m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ring 1</td>
<td>20</td>
<td>8.753</td>
</tr>
<tr>
<td>Ring 2</td>
<td>20</td>
<td>7.584</td>
</tr>
<tr>
<td>Ring 3</td>
<td>20</td>
<td>6.992</td>
</tr>
</tbody>
</table>
Use of DRACS in HTGRs for passive decay heat removal is a new concept. This idea opens new opportunities to greatly improve HTGRs economy. However, to realize those potentials, further detailed investigations, such as coupling 3-D CFD transient simulation with RELAP5 system analysis are necessary to develop optimized designs and to assess the power limit that the HTGRs with DRACS can reach while still maintaining the passive cooling capability. Material related research and innovative mechanical designs are additional keys to realize the potential.

ACKNOWLEDGMENTS

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