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PRIMARY-LOOP HEAT EXCHANGER FOR HTGR PLANT RESIDUAL HEAT REMOVAL AND AUXILIARY COOLING SYSTEM

by
E. J. HURN and D. P. CAROSELLA

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ABSTRACT

For several years design studies have been under way in the U.S. on high-temperature process heat and steam applications utilizing a high-temperature gas-cooled reactor (HTGR) plant. Plant designs have incorporated safety-class core auxiliary cooling systems (CACSs). These systems differ from comparable light water reactor (LWR) systems in that they are additional to, and separate from, the reactor main coolant loops. The CACS, therefore, provides an independent means of cooling the reactor core and is designed to maintain the prestressed concrete reactor vessel (PCRV), core, and component temperatures within safe limits.

Each CACS primary loop includes an auxiliary helium circulator, a shutoff valve, and a water-cooled core auxiliary heat exchanger (CAHE), which transfers heat from the primary coolant helium to secondary system water. This function may be for normal or plant accident conditions and is completely independent of the main heat exchanger loops. Due to the high heat capacity of the HTGR graphite core/moderator structure, which means a slower heatup than for the LWR, more time is available to initiate CACS safety measures in the event of an accident. The cooling modes include pressurized cooldown, depressurized cooldown, and cooldown for maintenance, refueling, and tests. This paper addresses the design criteria, design configuration, performance, and safety aspects of the CAHE design.

INTRODUCTION

A revised design has been engineered for the CAHE for the 2240-MW(t) HTGR plant (Fig. 1). The safety function of the CACS of an HTGR power plant is the removal of residual and decay heat from the reactor core following any postulated accident that disables the power-producing main reactor heat transfer loops. The core auxiliary cooling water system (CACWS) is a pressurized water circuit that takes heat from the reactor primary coolant (helium) through the CAHE and transfers it to the atmosphere by means of air-cooled heat exchangers external to the reactor containment building. Each reactor unit has three CACS loops. Electric-motor-driven compressors circulate the helium from the reactor core through the CAHEs, conventional pumps move the water, and electrically driven fans force air over the external heat exchangers. The speed of the compressors is controlled to maintain CAHE water outlet subcooling. The pumps and fans operate at constant flow.

It is a consequence of the CACS function that the heat transfer surface of the CAHE is part of the primary coolant pressure boundary. As such, the CAHE must be demonstrated to meet the highest criteria for integrity.

In normal plant operation, the CAHEs are not used. The three CACS loops are normally maintained in a standby mode of operation with circulating water flowing through the CAHE at a rate lower than that required for operation to remove reactor core heat in an accident. Helium circulation is shut off to the CAHE, but there is a small backward flow of core inlet ("cold") helium past the

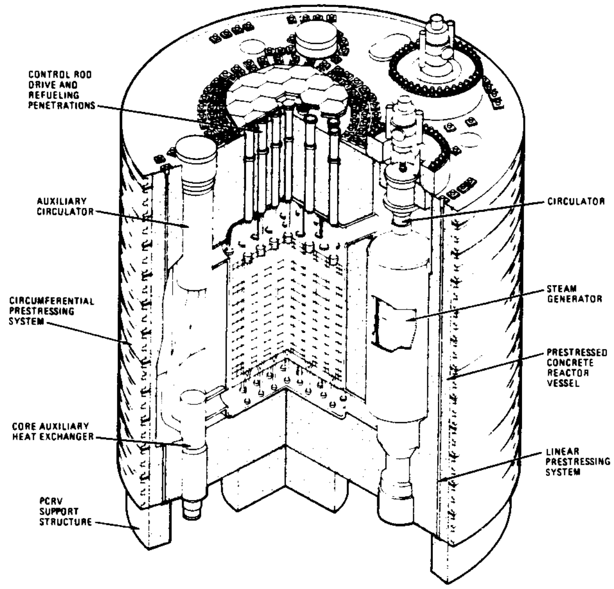

Fig. 1. Cutaway view of HTGR nuclear steam supply system

CACS compressor and its shutoff valve. Continuous water circulation is of benefit to the CAHE in potentially minimizing thermal shock in the "startup" transient (phasing from CACS standby to core cooling mode). It is also fundamental to the CACS design philosophy of simplicity of initiation and predictability of operation. The standby mode operation results in parasitic heat removal from the reactor primary coolant system. Thus, the lost heat reduces plant output by reducing heat and power transfer through the steam generators, turbine, and generator. Therefore, the lost heat should be minimized. However, flow stability considerations necessitate a minimum standby water flow, which effectively establishes a minimum parasitic loss.

In addition to the safety function of core heat removal, the CACS is intended for removal of core afterheat in plant shutdown and refueling modes. This service does not directly relate to system performance criteria. The refueling duty does, however, affect CACS circulator motor life, CAHE tube corrosion and erosion, and system maintenance options.

DESIGN BASIS

The design basis for the CAHE consists of three transients. All components of the CAHE are designed to perform in accordance with these transients, and other steady-state or transient operations impose less severe requirements on the CAHE. The three transients are:

1. Depressurized Cooldown with Pure Helium. For this transient the reactor core is cooled with two CACS loops. The primary coolant inventory is initially depressurized to equilibrium pressure with the containment volume, and all flow is assumed to be out of the reactor vessel.

2. Design Basis Depressurization Accident (DBDA). In the DBDA the reactor core is cooled with two CACS loops. The primary coolant inventory is initially depressurized to equilibrium pressure with the containment volume, and it is postulated that the vessel and containment volume communicate through a 0.06 m^2 (100-in.^{2}) breach between the reactor inlet plenum and the containment. Helium and air mix through convection via that breach.

3. Loss of Main Loop Cooling. This transient is the cooldown of the reactor core with one CACS loop following ingress of 4,536 kg (10,000 lb) of water with the primary coolant pressure at the PCRV relief valve setpoint value. In this transient the primary coolant flow through the core will be maintained at a level 10% greater than the value required to suppress reverse flow in all core regions.

The case of depressurized cooldown with pure helium as the primary coolant is the situation with the least effective heat transfer conditions, and it establishes the minimum CAHE surface area. The second accident, depressurized cooldown with air ingress, is the case requiring maximum helium circulator pumping power and thus governs CAHE helium flow resistance. The third case of pressurized cooldown with helium and moisture ingress from a steam generator leak sets the maximum heat duty and the water-side flow rate, resulting in the highest mean CAHE water temperatures. As water in the CAHE tubes approaches subcooled boiling, buoyancy forces can become significant and lead to tube-to-tube flow instability. Since the pressurized case is the operating condition of least exit water subcooling, it is closest to water-side stability limits. For this case, analysis has shown that the nominal exit enthalpy is 154 J/g (66 Btu/lbm) below the enthalpy where instability is initiated. The enthalpy rise required to cause unstable operation would require 27% additional heat input beyond the maximum expected value.

In each design basis event it must be assumed that in addition to the initiating event, one of the available CACS loops suffers an independent single active failure, thus disabling that loop. This design basis is imposed by the general plant safety criteria. Therefore, no more than two CACS loops must meet the performance requirements and accommodate the resulting condition in the design basis events.

CAHE SIZING

The surface area of each heat exchanger is 335 m^2 (3611 ft^2). This is required to meet the peak depressurized reactor cooldown heat duty of 25.6 MW (87.3 x 10^6 Btu/hr) for the case of pure helium coolant and two CACS loops functioning. In the case of depressurization and air ingress, each loop is to remove 21.9 MW (74.6 x 10^6 Btu/hr). The pressurized cooldown with moisture ingress to the primary coolant requires 78.5 MW (268.0 x 10^6 Btu/hr) heat removal with one CACS loop functioning. This case sets a water flow rate of 142 kg/s (1.12 x 10^6 lb/hr). Table 1 shows the principal design parameters for each of these design basis accidents.

The resulting water-side pressure drop for the CAHE is 0.7 bar (10 psi). While not insignificant, the water pumping power is only about 10% of the safety class power required for CACS operation. The helium compressor and the air fans on the external heat exchangers consume 90% of the safety class power.

In the standby operation of the CAHE, the incentive to minimize parasitic heat loss to the CACS leads to low flows such that static stability is also of concern in this mode of operation. Orificing would increase water-side pressure drop and the required CACS safety class power needed in the core cooldown mode. A minimum flow rate of 28.7 kg/s (2.24 x 10^5 lb/hr) ensures stability, and at this rate the calculated parasitic heat loss to the entire plant is 6.0 MW (20.5 x 10^6 Btu/hr). The standby mode design parameters are also shown in Table 1.

DESCRIPTION

The basic CAHE mechanical arrangement is shown in Figs. 2 and 3 and the major design data are given in Table 2.

The CAHE is a straight-bayonet-tube configuration comprising 721 bayonet tube assemblies. Each bayonet tube assembly consists of an outer or sheath tube (sealed at the upper end) and a concentric double-walled inner or bayonet tube. Each sheath tube is supported at the lower end by a sheath tube tubesheet, which is welded to the PCRV liner to form the primary coolant pressure closure. Each bayonet tube is supported at the lower end by a bayonet tube tubesheet, which also forms the seal between the water inlet and outlet.

The entire tube bundle is laterally spaced and supported at one location by a support grid. Tube loads are transmitted to the PCRV liner via an outer shroud, which also controls gas flow over the tube bundle.

Hot helium, the reactor primary coolant, exits the bottom of the core cavity and feeds radially through a round duct to the top of the CAHE cavity. The gas then flows downward through the tube bundle parallel to the tubes. At the lower end of the bundle, the gas turns 90 deg and flows radially outward through windows in the shroud into an annulus formed by the shroud and

TABLE 1
CAHE DESIGN BASIS PARAMETERS
(DATA PER CAHE)

	Design Basis Accident Transients			Standby Mode (Normal Plant Operation)
	Depressurized Vessel Helium Coolant	Depressurized Vessel Air Ingress	Pressurized Vessel Moisture Ingress	
Peak helium flow, kg/s (lbm/hr)	7.3 (59,069)	17.6 (140,185)	35.9 (284,384)	-2.0[a] (-15,500)
Helium pressure, bar (psia)	1.6 (23.6)	1.6 (23.6)	72.4 (1,050)	72.4 (1,050)
Maximum helium inlet temperature to CAHE, °C (°F)	952 (1,746)	952 (1,746)	860 (1,580)	322 (611)
Water flow, kg/s (lbm/hr)	142 (1.12×10^6)	142 (1.12×10^6)	142 (1.12×10^6)	28.7 (224,000)
Water pressure, bar (psia)	103 (1,500)	103 (1,500)	103 (1,500)	34.0 (500)
Maximum water outlet temperature from CAHE, °C (°F)	122 (250)	116 (244)	284 (544)	80 (170)
Peak heat duty, MW (Btu/hr)	25.6 (87.3×10^6)	21.85 (74.6×10^6)	78.5 (268×10^6)	2.0 (6.8×10^6)

[a] Backward leakage flow.

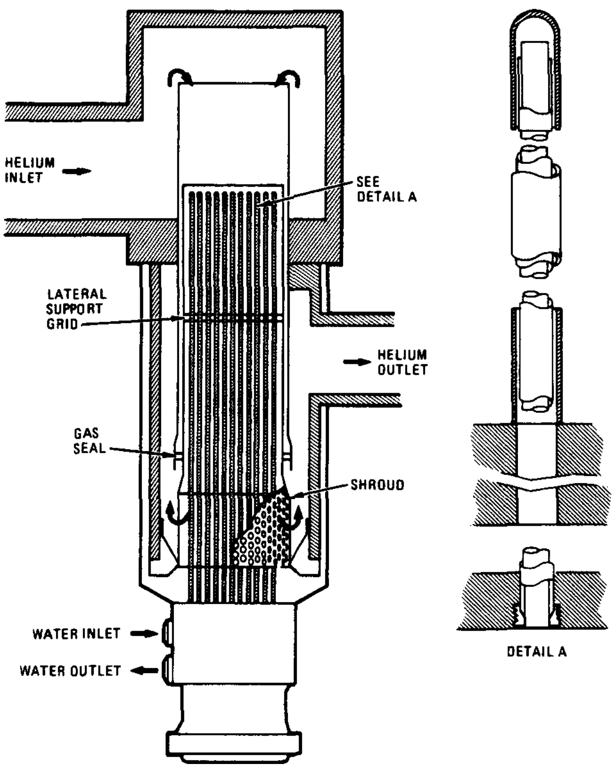

Fig. 2. Section through bayonet tube CAHE for HTGR

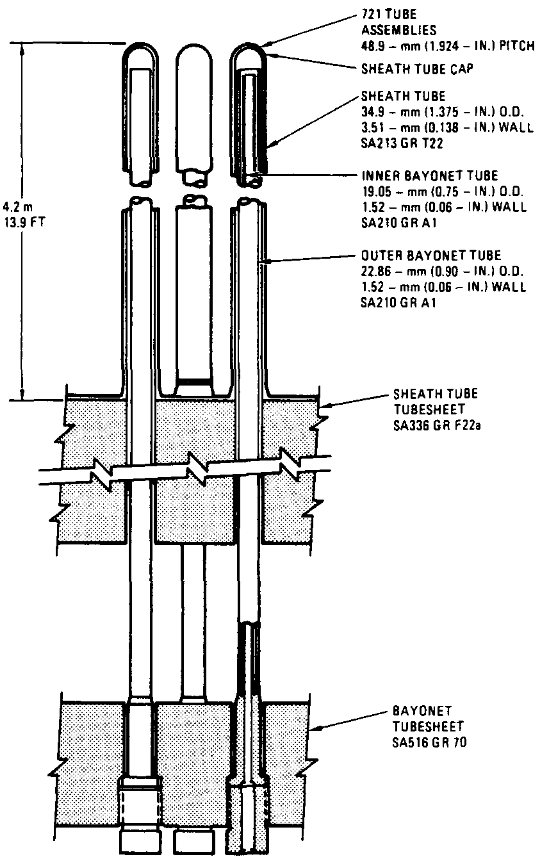

Fig. 3. Typical tube assembly

TABLE 2
MAJOR CAHE DESIGN DATA

Overall length	6.48 m (21 ft 3 in.)
Number of tubes	721 bayonet assemblies
Sheath tube	34.9-mm (1.375-in.) o.d.; 3.51-mm (0.138-in.) wall
Bayonet outer tube	22.86-mm (0.90-in.) o.d.; 1.52-mm (0.06-in.) wall
Bayonet inner tube	19.05-mm (0.75-in.) o.d.; 1.52-mm (0.06-in.) wall
Surface area	335.51 m^2 (3611 ft^2)
Materials of construction	
Sheath tubes	2-1/4Cr - 1Mo
Bayonet outer tubes	Carbon steel
Bayonet inner tubes	Carbon steel
Tube sheets	2-1/4Cr - 1Mo
Tube grids	Alloy 800H
Shrouds	Alloy 800H and 2-1/4Cr - 1Mo
Shroud (hexagonal)	
Total frontal area	1.49 m^2 (16.055 ft^2)
Distance across flats	1313.2 mm (51.70 in.)
Exit window height	0.85 m (2 ft 10 in.)
Support grid	1.37 m (4 ft 6 in. from top)

liner thermal barrier. From this annulus the gas returns to the helium circulator via a circulator duct.

Water enters the sheath tube tubesheet and travels upward in the annuli formed by each sheath and bayonet tube. The water is heated by the downward flowing gas and by regeneration from the bayonet tube. This regeneration is reduced by the double wall construction of the bayonet tube. When the heated water reaches the top of the annuli, it turns 180 deg and flows downward through the bayonet tubes to the bayonet tube tubesheet.

Primary Closure

The reactor coolant primary boundary is effected by the sheath tube and the sheath tube tubesheet. The tubesheet has a short straight cylindrical section, which is field welded to the PCRV liner. This cylindrical section is used as a thermal sleeve between the hot tubesheet and the cool concrete. Attached to this primary support is the lower cylindrical head, which forms the pressure boundary for the water system.

Support System

All the dead weight and pressure loads are transmitted to the liner through the primary closure. A single tube support grid maintains the tube spacing and transmits seismic loads to the shroud. The unit is sufficiently short to eliminate the need for seismic stops external to the CAHE.

Maintenance and Inservice Inspection

The overall height of the CAHE has been minimized to enable installation and reinstallation from below the PCRV.

A major feature of the design presented herein is its good access for tube leak detection/plugging and inservice inspection (without exposure to high radiation fields). Currently inservice inspection is required for welds in the primary boundary and the heat exchanger tube support structure. The only major weld in the primary boundary is the tubesheet-to-liner weld, which is directly accessible for volumetric examination. The tube support is provided by the tubesheet itself; the bulk of this tubesheet is available for a visual examination through the manway by removing the blind flange.

The heat transfer tubing is fully inspectable. To perform an inspection, the blind flange is removed. This provides access to the bayonet tubes and tubesheet. Individual bayonet tubes are withdrawn from the sheath tube and an ultrasonic or leak detection probe may now be inserted for full-length inspection of the primary boundary sheath tube.

COMPARISON WITH PREVIOUS HTGR BAYONET TUBE CAHE

A bayonet tube CAHE for the HTGR has been described and compared with other heat exchanger types in Ref. 1. This modified design retains many of the advantages of the originally reported version while providing improvement, particularly in the areas of manufacture and maintenance, as follows:

1. The overall tube bundle length has been reduced by packing tubes closer, i.e., reducing tube pitch. This reduced bundle height enables installation and reinstallation of the unit from below the PCRV and, in addition, eliminates the need for all but one tube support grid. Elimination of the tube supports and the associated helium pressure losses compensates for additional losses resulting from the tighter tube pitch.
2. The primary boundary tubesheet configuration was revised from spherical to flat, thereby improving manufacturing requirements.
3. The shorter unit allowed for hot helium inlet at the top of the bundle, thereby locating the tubesheet at the cold helium end of the CAHE and eliminating the need for a heat trap required for minimizing natural convection heat transfer during the nonoperating mode.
4. The shorter unit eliminated the need for a seismic stop between the CAHE and liner.

CONCLUSIONS

Comparison studies with helical straight-tube and U-tube bundle configurations in the past (1) indicated that the bayonet tube CAHE has a significant number of advantages in an HTGR application. The major ones are as follows:

1. Capability for complete inservice inspection of the primary boundary, including the heat transfer tubing.
2. Elimination of subheaders.
3. Reduction of tubing expansion stresses.
4. Fully drainable.
5. Increased tube plugging allowance.
6. Minimum of unheated heat transfer surface.
7. Elimination of congestion with associated auxiliary circulator and valve.
8. Low water-side pressure drop.
9. Removal and reinstallation from below the PCRV, thus minimizing delays normally associated with reinstallation in congested areas such as the PCRV top head.

ACKNOWLEDGMENT

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REFERENCE

1. Thurston, G. C., and Allen, D. T., "Core Auxiliary Heat Exchanger Design for HTGR," ASME Paper No. 78-NE-9, June 1978.