SYSTEMS ENGINEERING REQUIREMENTS IMPACTING MHTGR CIRCULATOR DESIGN

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Abstract

At the initiation of the MHTGR program, an important task involved translating the plant users' requirements into design conditions. This was particularly true in the case of the heat transport and shutdown cooling systems since these embody many components. This paper addresses the two helium circulators in these systems. An integrated approach is being used in the development of design and design documentation for the MHTGR plant. It is an organized and systematic development of plant functions and requirements, determined by top-down design, performance, and cost trade-off studies and analyses, to define the overall plant systems, subsystems, components, and human actions. These studies, that led to the identification of the major design parameters for the two circulators, are discussed in this paper. This includes the performance information, steady state and transient data, and the various interface requirements. The design of the circulators used in the MHTGR is presented in Reference ..

1. MHTGR Overview

The MHTGR plant design consists of four reactor modules (Fig. 1), each rated at 350 MW(t), coupled to two steam turbines yielding at net output of about 550 MW(e) (Figs. 2, 3). The four module plant is divided into two major areas, the Nuclear Island comprising the reactor enclosures, reactor modules, and power generating systems. Each reactor module is housed in a vertical silo (Fig. 4).These silos also serve as an independent confinement structure having a vented and filtered exhaust system. The Nuclear Island also includes auxiliary structures that house a common system for fuel handling, radioactive waste storage, helium processing and other essential services.

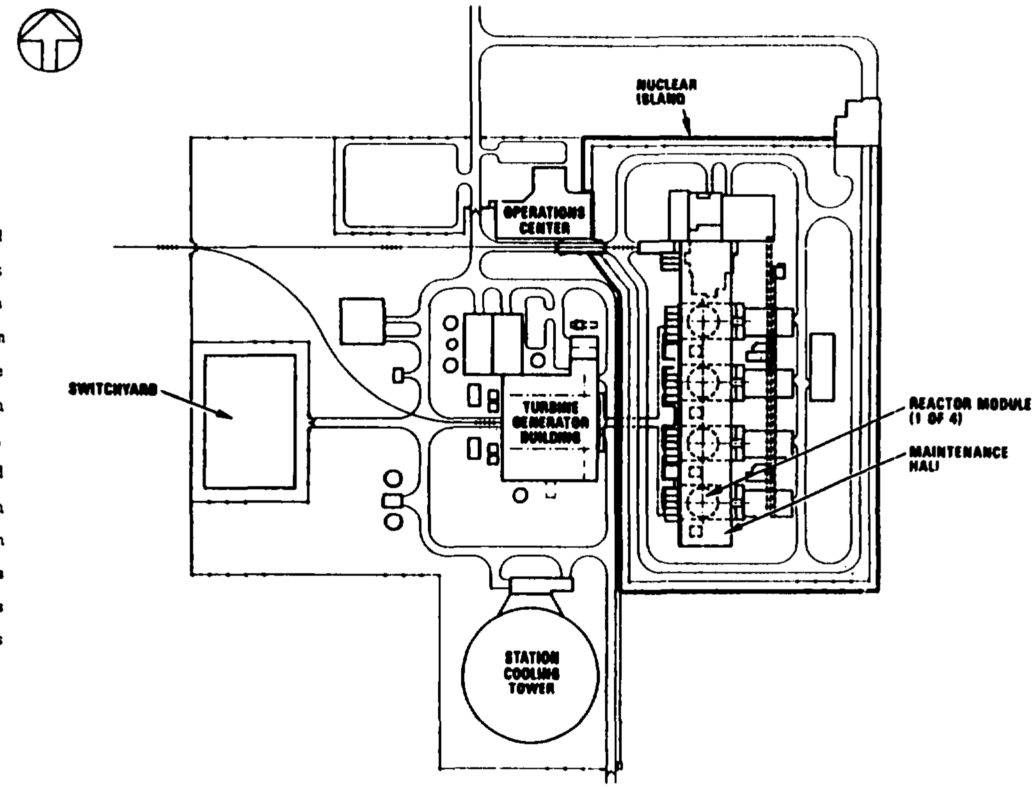

FIG. 1 MHTGR SITE PLOT PLAN

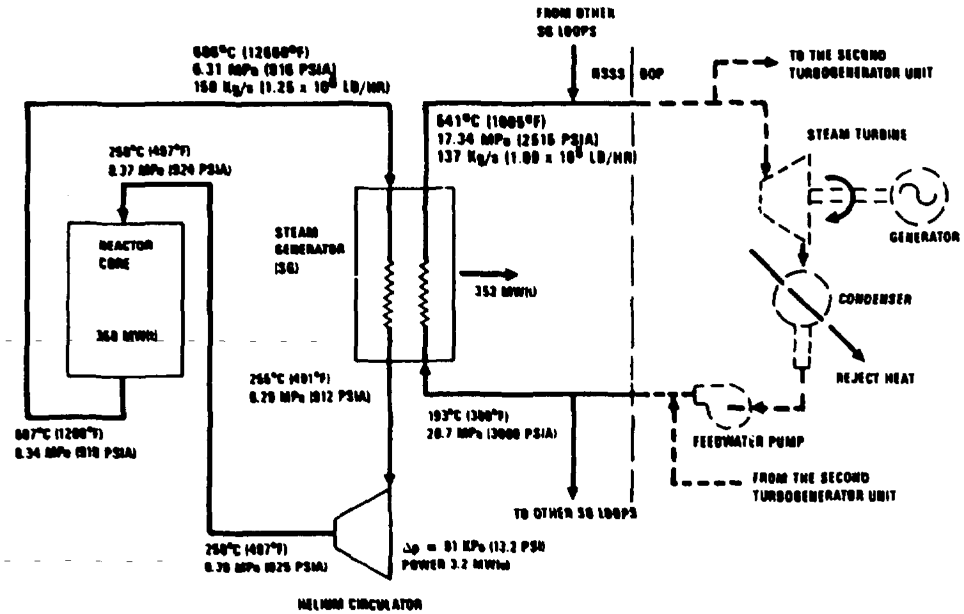

FIG. 2 HEAT BALANCE DIAGRAM FOR 350 MW(t) MODULE

NUCLEAR SYSTEM PARAMETERS

THERMAL POWER, MW(t)	1400
HELIUM PRESSURE, MPa (PSIA)	6.4 (925)
HELIUM TEMPERATURE, INLET °C (°F)	255 (491)
HELIUM TEMPERATURE, OUTLET °C (°F)	687 (1268)

POWER SYSTEM PARAMETERS

FEEDWATER PRESSURE, MPa (PSIA)	20.7 (3000)
FEEDWATER TEMPERATURE, °C (°F)	193 (380)
STEAM PRESSURE, MPa (PSIA)	16.6 (2415)
STEAM TEMPERATURE, °C (°F)	538 (1000)

PLANT PERFORMANCE

NET ELECTRICAL OUTPUT, MW(e)	540
NET THERMAL EFFICIENCY, %	~39

FIG. 3 MHTGR KEY PLANT PARAMETERS

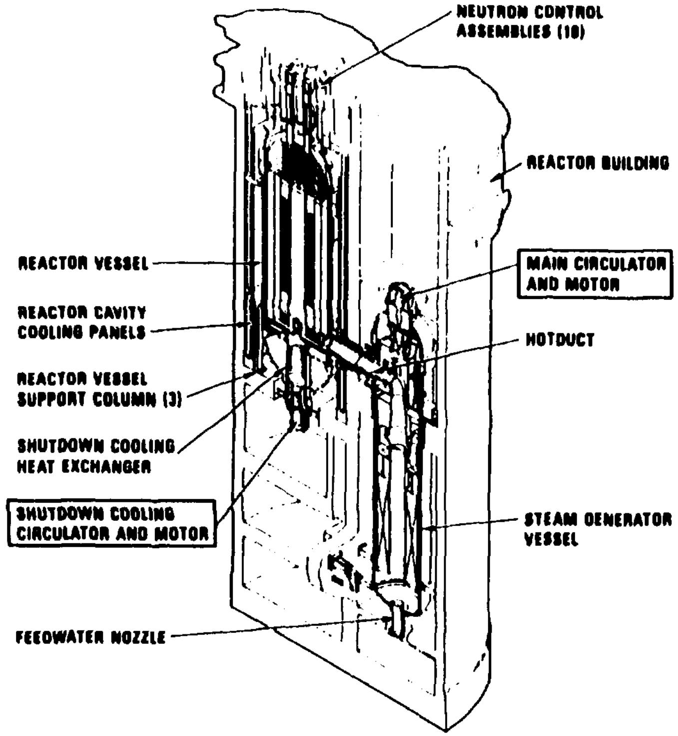

FIG. 4 350 MW(t) MODULAR HTGR ISOMETRIC

The reactor module components are contained within three steel vessels, a reactor vessel, a steam generator vessel and a connecting concentric cross-duct vessel. The reactor vessel contains the core reflector and associated supports. A shutdown heat exchanger and a shutdown circulator are located at the bottom of the vessel. The top mounted standpipes contain the control rod drive mechanisms and reserve shutdown hoppers. The steam generator, a helically wound once-through, uphill boiling unit and the main circulator are installed in the steam generator.

During normal operation (i.e., power production), the heat generated in the core is transferred to the power conversion system usinb the Heat Transport

System (HTS) consisting of the main circulator and the steam generator. The MHTGR is capable of maintaining conventional steam conditions of 16.6 MPa and 538°C throughout the load range between 100% and 25%.

The decay heat removal during shutdown or following an upset can be accomplished following the design philosophy of defense in depth by three different means. The decay heat removal using the HTS (Fig. 5) where the steam generated in the secondary circuit bypasses the turbine and condenses in the condenser. The decay heat can also be removed by the Shutdown Cooling System (SCS) (Fig. 6) located at the bottom of the reactor vessel. The heat

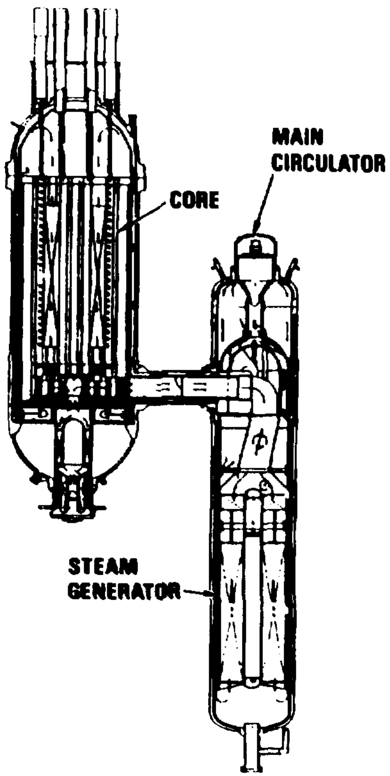

FIG. 5 PRIMARY COOLANT FLOW PATH DURING HEAT TRANSPORT SYSTEM OPERATION

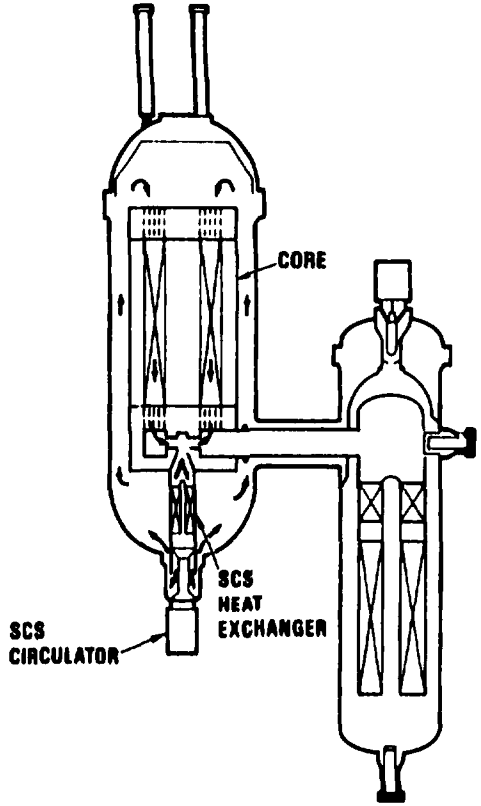

FIG. 6 PRIMARY COOLANT FLOW PATH DURING SYSTEM OPERATION

transferred to the shutdown heat exchanger is rejected to the ultimate heat sink via separate cooling water circuit. Decay heat may also be rejected to the environment by means of the totally passive Reactor Cavity Cooling System (RCCS) (Fig. 7). This system utilizes passive phenomena such as conduction natural convetion, conduction and radiation heat transfer to rejecte the decay heat. All these systems are capable of providing sufficient heat removal with the reactor primary coolant either pressurized or depressurized.

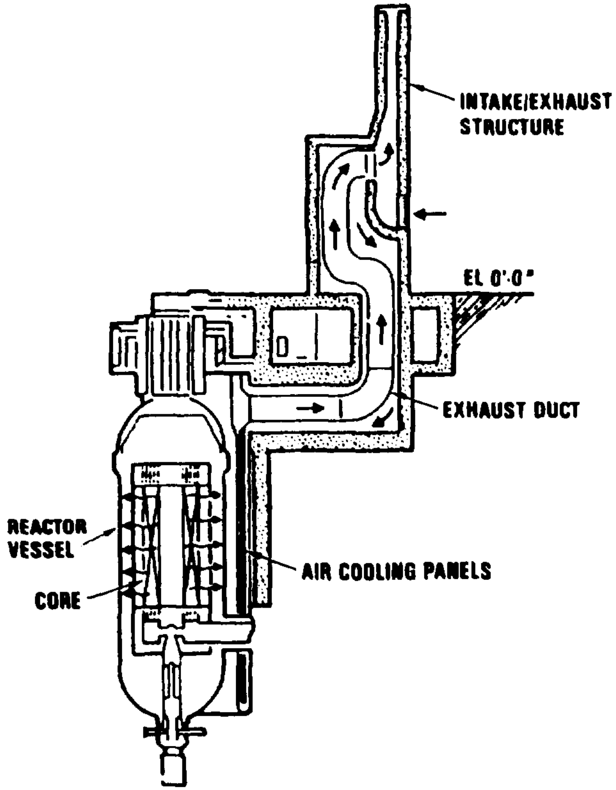

FIG. 7 RCCS (PASSIVE) DECAY HEAT REMOVAL

2. Requirements Development

The design approach for the Standard MHTGR has been applied in a "top-down" fashion as illustrated in Figure 8. The process begins with the quantification of top-level criteria pertaining to how well each Goal is to be achieved. Next, an integrated systems engineering approach is systematically applied to develop the functions, requirements, and specific design selections necessary to achieve, in a balanced fashion, all of the Top-Level Regulatory Criteria and user requirements.

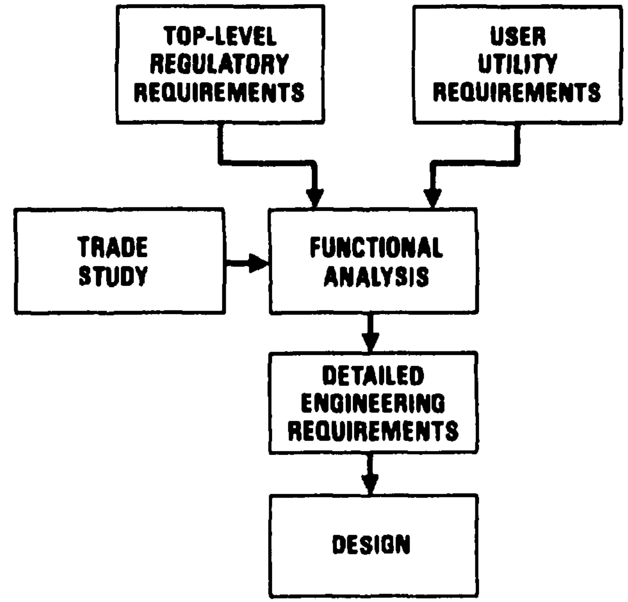

FIG. 8 DESIGN PHILOSOPHY AND METHODOLOGY

The analysis tools include the use of functional analysis, reliability evaluations, probabilistic risk assessments, trade studies, and engineering analyses. The product of the Integrated Approach is the plant design.

The top-level criteria and requirements are defined primarily from two sources: the regulator, whose concern is primarily public health and safety, and the user, whose concern is all encompassing (e.g., safety, performance, availability and economics). The Top-Level Regulatory Criteria are a necessary and sufficient set of direct quantitative statements of acceptable health and safety consequences (i.e., doses) or risks to the public that are indpendent of reactor type and site.

Figure 9 shows the top level Goal; namely safe, economical power by providing defense-in-depth through the pursuit of four goals:

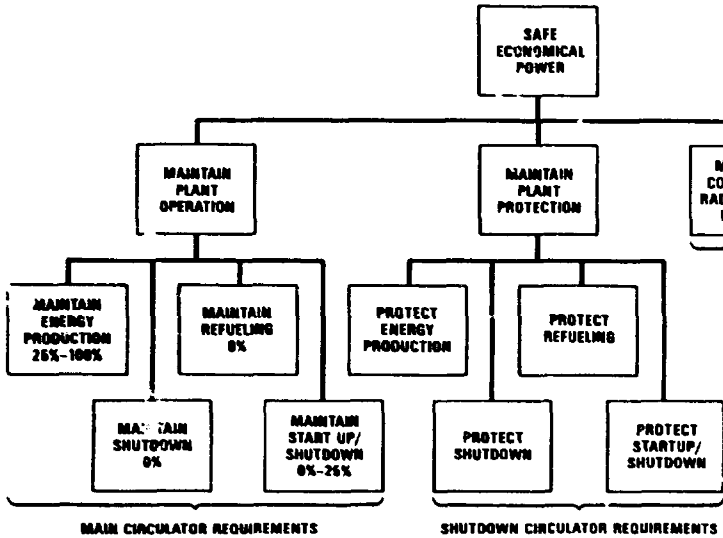

FIG. 9 PLANT GOALS AND STATES

Goal 1 encompasses normal plant operations, including the planned operating states of energy production, shutdown, refueling, and startup/shutdown. Goal 1 user requirements include that the plant be designed for an average equivalent unavailability due to planned outages not to exceed 10 percent and minimizing worker doses to less than an average of 10 percent of 10CFR20 allowables. The design lifetime is to be 40 years from start of plant operation.

Goal 2 is protection of the plant investment to ensure that economic losses associated with unscheduled events are limited. Top-level user requirements for Goal 2 include limiting average annual equivalent unscheduled unavailability to less than 10 percent and limiting the frequency for events resulting in reactor loss to less than 10^{-5} per plant year.

Goal 3 is to ensure that releases of radioactive materials remain within acceptable limits for transients or accidents having the potential for release of radionuclides. In addition to the Top-Level Regulatory Criteria which quantify this goal, it is a top-level user requirement that radionuclides be controlled to the extent that the emergency planning does not require provisions for the offsite sheltering or evacuation of the public.

Goal 4 assures emergency preparedness in the event an accident occurs in which radionuclide release is not controlled. As described above, the user has required that the design control radionuclide releases so reliably that measures should not be required for the offsite evacuation or sheltering of the public.

The latter two goals impose no requirements on the main or shutdown circulator designs.

Figure 9 shows the starting point for the functional analysis, namely the four Goals identified to achieve safe, economic power. Figure 10 shows expansion of Goal 1. As illustrated in this figure, each subsequent level of function is developed by examining the next upper level function and answering the question, "How is the function to be achieved?" In such a manner, a "tree" of increasing levels of detail is defined until a specific design selection results.

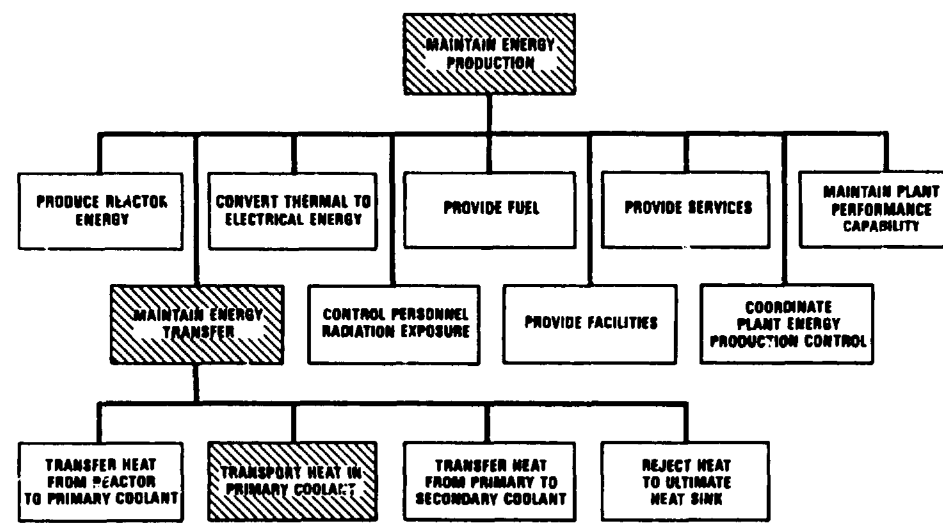

FIG. 10 CIRCULATOR FUNCTIONAL REQUIREMENT

Following this logic the general circulator requirements are obtained from plant level requirements and trade studies. The specific requirement for each circulator, i.e., main and shutdown circulator, is derived from the 4 states, namely:

1. Energy production,
2. Shutdown,
3. Refueling, and
4. Startup/Shutdown.

These are reflected in Figure 11 under performance requirements. The configurational and feature requirements shown in Figure 11 are not attributable to the various states.

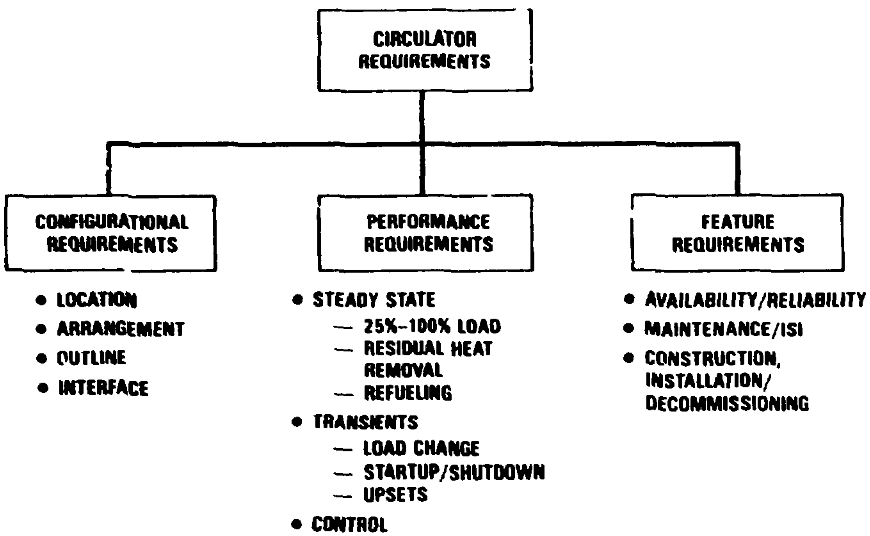

FIG. 11 SPECIFIC CIRCULATOR REQUIREMENTS

3. Helium Circulator Requirements

The heat transport system (HTS) shall consist of a single cooling loop per module. The HTS shall contain the steam generator in series with the helium main circulator and its associated shutoff valve assembly. The circulator assembly shall be located in the cold leg of the helium flow path in the top plane of the steam generator vessel (Fig. 12). The main circulator shall consist of a vertically oriented, single-stage axial compressor driven by an electric motor. The motor shall be submerged and shall be an integral part of the compressor rotor. The rotating assembly shall be fully floating on a set of active magnetic bearings. Backflow through the non-operating main loop shall be prevented by a helium shutoff valve attached to the main circulator assembly. Three service modules shall be provided for the necessary support to the main circulator.

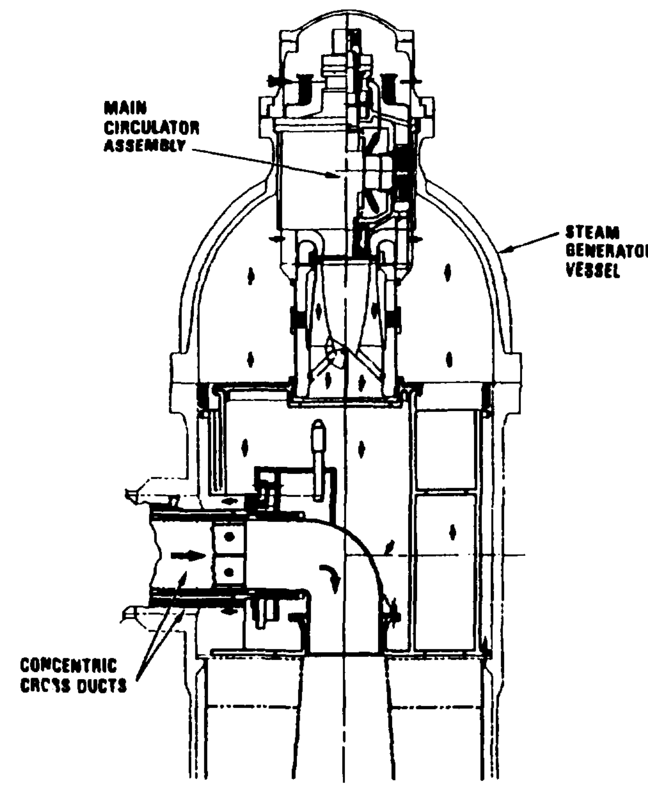

FIG. 12 MHTGR MAIN CIRCULATOR ARRANGEMENT

Helium shall be pumped by the main circulator to the top of the core through the outer annulus of the concentric crossduct, then downward through the core and back to the circulator through the steam generator. Heat shall be removed from the core and transferred to the secondary coolant through the steam generator. The main circulator is used to control the helium flow to match the heat generation with the heat removal.

The HTS shall have several operating modes depending on the operating conditions of the module. During steam production the module will be pressurized, the reactor will be critical and the operation of the main loop will range between 100% and 25% of rated feedwater flow. The main circulator will run at speeds corresponding to loop feedwater flow in order to produce the desired steam conditions. The loop shutoff valve will be wide open.

When the module is shutdown the HTS shall be used to remove the residual/decay heat from the core. When the HTS is not available, it shall be isolated and the SCS used. The HTS shall be able to remove the residual/decay heat under pressurized or depressurized helium conditions. Under these conditions the steam generator will be flooded and the main circulator will be run at speeds dictated by the heat generated by the core, the feedwater flow and the helium density. When the main loop is not available, the SCS is used to cool the core, the main loop will be isolated with the steam generator flooded and the main circulator shutdown. The main loop shutoff valve shall then be closed.

The design point for the main circulator shall be based on main loop operating conditions expected to occur at the middle of life. Under these design reference conditions, the best estimates of heat transfer and flow resistance were used, one percent of the steam generator tubes was assumed to be plugged, and 5% of the steam generator heat transferring surface was assumed to be unavailable because of under steam generator performance. The main circulator design point under these conditions is 91.0 KPa pressure rise for a helium flow of 158.0 Kg/s at an inlet temperature of 255°C and outlet pressure of 6.38 MPa.

The HTS design accounts for statistical uncertainties in predicting the performance of the components within each module and for measurement/instrumentation errors. These uncertainty ranges (±2 sigma) have been combined by statistical means considering the uncertainties associated with core, steam generator, lower plena, and outer and inner duct flow resistances, steam generator heat transfer coefficients, primary coolant flow distribution, and primary coolant heat losses. Operational envelopes including these uncertainties have been established for the HTS at 100% (Fig. 13) and 25% (Fig. 14) feedwater flow, and for refueling conditions (Fig. 15). Three operational envelopes (at 100% and 25% feedwater flow, and refueling conditions) have been developed specifically for the main circulator. In these envelopes the pressure drop is plotted against the circulator flow rate. The main circulator shall be designed to operate at any points within these envelopes.

The main circulator shall be designed for a 40 years service life in which it shall not contribute to the unplanned reactor module outage rate by more than

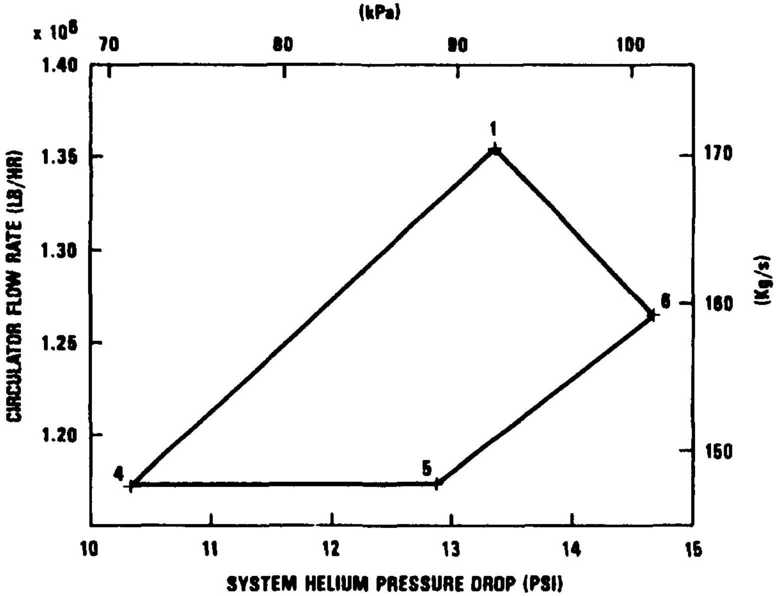

FIG. 13 MAIN CIRCULATOR OPERATING ENVELOPE AT 100% FW FLOW

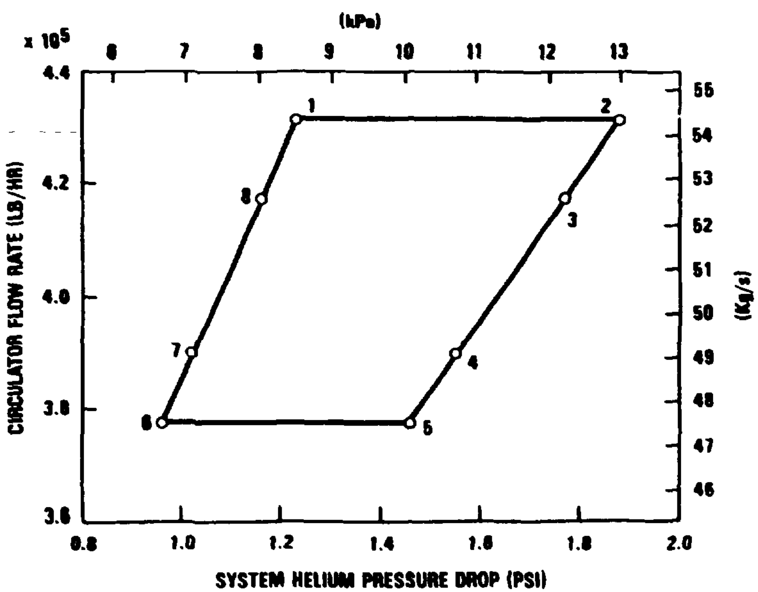

FIG. 14 MAIN CIRCULATOR OPERATING ENVELOPE AT 25% FW FLOW

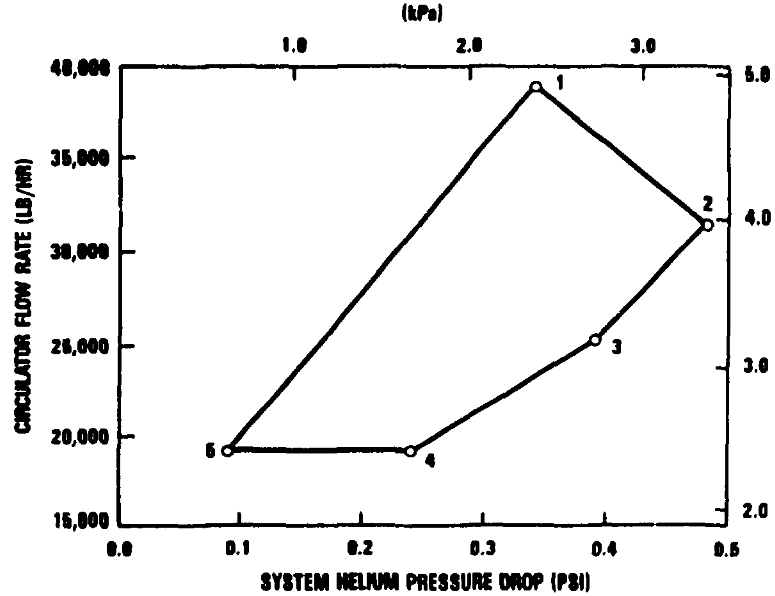

FIG. 15 MAIN CIRCULATOR OPERATING ENVELOPE DURING REFUELING

10.5 equivalent forced outage hours per module and per year, on the average. Stable primary coolant flow shall be provided over the main circulator speed control range from 5% to 110% of manual shaft speed with the HTS pressurized or depressurized.

The main loop shutoff valve shall be designed such that the bypass flow through the isolated main loop does not exceed 10% of the total SCS flow during core cooling operation with the SCS. This bypass flow has to be carefully controlled because an excessive flow will degrade the SCS performance and a too small flow will not provide adequate cooldown to the isolated main loop for inspection or maintenance.

Acoustically induced vibrations may originate from several noise sources inside a module. Among these, the main circulator is potentially the dominant source. A limit has, therefore, been imposed to the acoustic energy of the primary coolant entering/leaving the main circulator during normal steady state, rated reactor operations. This limit is 160 dB at the blade passing frequency.

The main circulator shall be designed to operate through the expected design transient evenly for the number of cycles specified by the design duty cycles. Also, the main circulator is expected to operate through the level A events of the design duty cycles without initiating any major protective action. During level D events in which forced cooling of the core is lost for a protracted period of time, the main circulator shall be designed to withstand, and be capable of restart after, a thermal soak of up to 371°C.

Interface requirements imposed by the main circulator include the requirement to be supported at its interfaces with the steam generator vessel and the hot duct assembly. Space also shall be provided for surveillance, on-line and in-situ maintenance. The main circulator interface requirements also include the measurement of the shaft rotation speed for the plant control system. For the plant protection system the main circulator shall provide redundant measures of the shaft rotation speed and the main loop shutoff vale plates position. The main circulator also shall provide for the plant protection system redundant contactors in the circulator motor control and power module to trip the circulator in less than 10 seconds upon demand.

The main circulator design shall include several additional features related to availability and maintenance. The main circulator shall be designed for remote removal and replacement and it shall be able to be disassembled with remote handling equipment and special tools. Portions of the main circulator within the primary coolant pressure boundaries shall be designed to function, through the life of the component, without maintenance requiring man access.

4. Shutdown Cooling Circulator Requirements

The shudown cooling system (SCS) shall consist of a single alternate cooling loop for each module. The SCS will include the shutdown cooling heat exchanger (SCHE), the shutdown cooling circulator (SCC), the shutdown cooling water system (SCWS), anda the shutdown cooling heat removal control system (SCHRCS). The SCS shall be located in the cold leg of the helium flow path at the bottom of the reactor vessel with the SCHE positioned above the shutdown circulator (Fig. 16). The circulator shall be a vertically oriented, radial flow type compressor which is driven by an electric motor that is contained within (submerged) the helium pressure boundary. The shutdown circulator shall include a shutdown loop shutoff valve (SLSV) assembly which will limit the helium backflow through the SCS. The SLSV shall be located in the SCC inlet duct between the SCHE and the SCC.

Helium flow shall be pumped by the shutdown circulator to the top of the core, the helium passes downward through the core and through the SCHE. Heat shall be transferred from the helium to the shutdown cooling water in the SCHE. This heat shall be rejected to the service water system via water-to-water heat exchangers in the SCWS. The SCWS shall include pumps to maintain water flow through the SCHE and a surge tank to maintain water pressure.

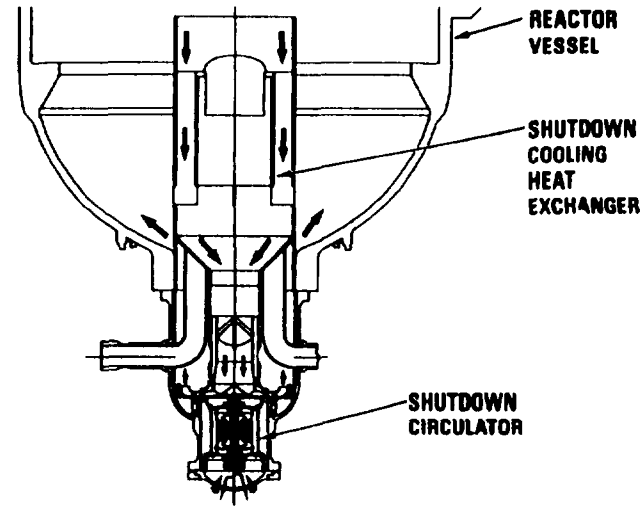

FIG. 16 SCS CIRCULATOR ARRANGEMENT

The SCS shall have two different operating modes depending on the operating condition of the module. During normal main loop (HTS) cooling the SLSV will be closed and the shutdown circulator will be operating. A small amount of cold leg helium will leak through (backflows) the closed shutoff valve and flow opposite normal flow direction over the SCHE tubes and through the shutdown circulator. To prevent heat up of the SCS components water will be pumped through the SCHE to remove core heat. This method of operation is called "standby mode."

When the HTS becomes unavailable and the reactor is shutdown, the shutdown circulator will be started up, water flow to the SCHE increased and reactor cooling obtained with the SCS. This method of operation is called the "cooldown mode." This mode of cooling can be performed with the primary system pressurized or depressurized. The SCS will also be used for cooling the reactor during refueling when the primary system is depressurized.

The design point for the shutdown circulator shall be based on the expected depressurized operating conditions of the SCS. The design point is 4.9 KPa pressure rise at a flow of 2.86 Kg/s. The design pressure rise includes margins for design evolution and hardware variations.

A pressure rise versus circulator flow operating envelope for the shutdown circulator is shown in Figure 17. The envelope encompasses the expected operating points for pressurized and depressurized operation in the cooldown mode. The envelope also includes margins on the flow and pressure rise to account for hardware variations and design evolution.

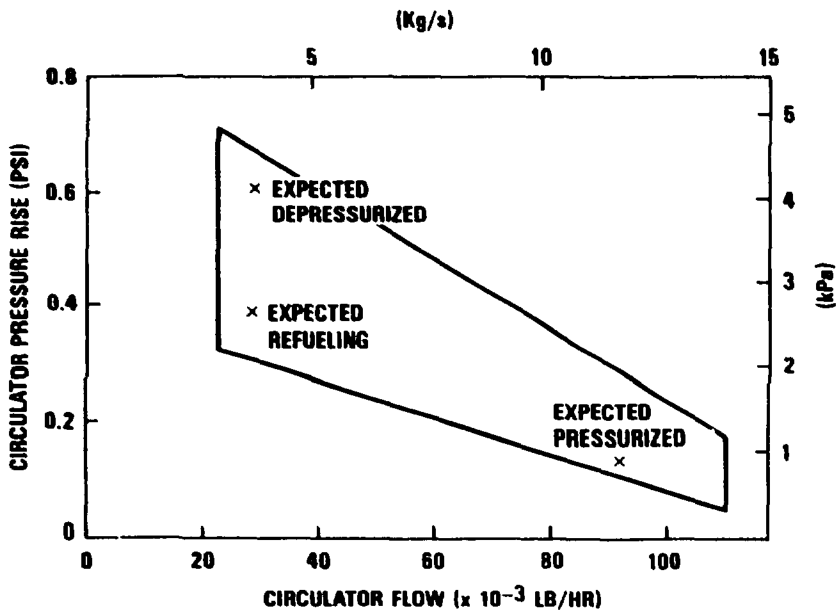

FIG. 17 SHUTDOWN CIRCULATOR OPERATING ENVELOPE

The shutdown circulator shall be designed to provide a stable helium flow over a speed range between 5% and 100% for a period of 40 years service life. The 5% speed represent the initial startup of the circulator in the pressurized cooldown mode. At this speed the circulator will provide more than the required helium flow (8.8 Kg/s) necessary to avoid core flow reversals.

The SLSV shall be designed to provide less than 0.4% leakage (backflow) when the valve is closed. This limit is necessary to minimize the primary coolant heat loss when the HTS is operating.

The shutdown circulator shall be designed to provide the necessary depressurized helium operating conditions required for refueling the core within *24 hours after module shutdown.* For refueling the cold helium temperature should be cooled down to less than 116°C.

The shutdown circulator shall be designed to operate through the expected design transient events for the number of cycles specified in the design duty cycle table. Also, the circulator is expected to operate through the level A events in the duty cycle table without initiating any major protective function.

Interface requirements imposed by the shutdown circulator include the requirements for a SCS support interface with the reactor vessel and space in the building for surveillance and maintenance. The shutdown circulator requirement also include the measurement of helium flow rate, circulator speed and helium outlet temperature which are necessary for assessing the compressor performance. Also, the SLSV valve position shall be measured to provide an indication when the shutoff valve is closed.

The main control for the SCS involves the measurement and adjustment of circulator speed (helium flow), to maintain a subcooled water temperature setpoint at the SCHE exit. The SCS controls also include a flow rate controller to maintain the required water flow to the SCHE.

For investment protection the shutdown circulator shall include trip logic which will shutdown the circulator upon loss of shutdown cooling water flow.

The shutdown circulator design shall include several additional features relating to availability and maintenance. The circulator shall be designed so that preventive maintenance activities including inspections, surveillance, and planned maintenance services should be minimized to limit the amount of reactor plant outage. Also, the circulator and the SLSV shall be designed for remote removal and replacement, and to facilitate on line maintenance as much as possible.

5. Conclusions

The utilization of the integrated approach resulted in the development of optimized requirements for the two circulators employed in the MHTGR. The most significant requirements are:

1. The non-safety related classification of the circulators, and

2. The performance envelope is well within today's technical knowhow.

It is therefore believed that the MHTGR can be designed with minimum technology development.

Acknowledgment

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REFERENCE

1. McDonald, C. F., M. K. Nichols, and J. S. Kaufman, "Helium Circulator Design Concepts for the Modular High-Temperature Gas-Cooled Reactor (MHTGR) Plant," paper presented at IAEA Circulator Specialists Meeting, San Diego, California, December 1, 1987.

HELIUM CIRCULATOR DESIGN CONCEPTS FOR THE MODULAR HIGH TEMPERATURE GAS-COOLED REACTOR (MHTGR) PLANT

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Abstract

Two helium circulators are featured in the Modular High-Temperature Gas-Cooled Reactor (MHTGR) power plant - (1) the main circulator, which facilitates the transfer of reactor thermal energy to the steam generator, and (2) a small shutdown cooling circulator that enables rapid cooling of the reactor system to be realized. The 3170 kW(e) main circulator has an axial flow compressor, the impeller being very similar to the unit in the Fort St. Vrain (FSV) plant. The 164 kW(e) shutdown cooling circulator, the design of which is controlled by depressurized conditions, has a radial flow compressor.

Both machines are vertically oriented, have submerged electric motor drives, and embody rotors that are supported on active magnetic bearings. As outlined in this paper, both machines have been conservatively designed based on established practice. The circulators have features and characteristics that have evolved from actual plant operating experience. With a major goal of high reliability, emphasis has been placed on design simplicity, and both machines are readily accessible for inspection, repair, and replacement, if necessary. In this paper, conceptual design aspects of both machines are discussed, together with the significant technology bases. As appropriate for a plant that will see service well into the 21st century, new and emerging technologies have been factored into the design. Examples of this are the inclusion of active magnetic bearings, and an automated circulator condition monitoring system.