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** Stone & Webster Engineering Corporation

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ENVIRONMENTAL ASPECTS OF MHTGR OPERATION*

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ABSTRACT

The Modular High-Temperature Gas-Cooled Reactor (MHTGR) is an advanced reactor concept being developed under a cooperative program involving the U.S. Government, the utilities and the nuclear industry. This plant design utilizes basic High Temperature Gas-Cooled Reactor (HTGR) features of ceramic fuel, helium coolant, and a graphite moderator. The MHTGR design approach leading to exceptional safety performance also leads to plant operation which is characterized by extremely low radiological emissions even for very low probability accidents. Coated fuel particles retain radionuclides within the fuel, thus minimizing material contamination and personnel exposure. The objective of this paper is to characterize radioactive effluents expected from the normal operation of an MHTGR. In addition, other nonradioactive effluents associated with a power generating facility are discussed.

Nuclear power plants produce radioactive effluents during normal operation in gaseous, liquid and solid forms. Principle sources of radioactive waste within the MHTGR are identified. The manner in which it is planned to treat these wastes is described. Like other reactors, the MHTGR produces nonradioactive effluents associated with heat generation and chemical usage. However, due to the MHTGR's higher efficiency, water usage requirements and chemical discharges for the MHTGR are minimized relative to other types of nuclear power plants.

Based upon prior operating HTGR experience and analysis, effluents are quantified in terms of radioactivity levels and/or emission volume. Results, quantified within the paper, demonstrate that effluents from the MHTGR are well below regulatory limits and that the MHTGR has a minimal impact upon the public and the environment.

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1. INTRODUCTION

Under sponsorship by the U.S. DOE and in cooperation with utility/users represented by Gas-Cooled Reactor Associates (GCRA) and the National Laboratories, several U.S. corporations (including Bechtel National, Inc., Combustion Engineering, General Atomics, and Stone & Webster Engineering Corporation) have designed an MHTGR plant, which will provide highly reliable, economic, and safe nuclear power. This advanced reactor design builds upon experience from operating High Temperature Gas-Cooled Reactors (HTGRs) incorporating the following standard HTGR features:

- refractory coated particle fuel capable of retaining radionuclides at high temperatures;
- graphite moderator which remains stable to high temperatures and has a high heat capacity; and
- helium coolant which is inert, non-corrosive, and remains as a gas under all operating conditions.

US operating experience with the 330 MW(e) Fort St. Vrain (FSV) and 40 MW(e) Peach Bottom - 1 reactors demonstrates that these standard HTGR features provide the capability to produce electricity more efficiently with lower personnel radiation exposure levels than LWR power plants (Ref. 1,2) Likewise, Federal Republic of Germany (FRG) operating experience with the 13 MW(e) Arbeitsgemeinschaft Versuchs Reaktor (AVR) and 300 MW(e) Thorium Hochtemperaturreaktor (THTR) confirm the positive attributes of Hochtemperaturreaktor (HTR) operation (Ref. 3). MHTGR design selections enhance these HTGR features to ensure that the plant meets stringent user/utility requirements for safety, investment protection, and environmental compatibility. Within this paper, MHTGR radioactive and nonradioactive effluents are quantified and compared with regulatory limits.

2. DESIGN DESCRIPTION

The reference MHTGR plant design shown in Figure 2-1 features four 350 MW(t) reactor modules coupled to two steam turbine generators that produce a net electrical output of 540 MW(e). The design draws upon proven technology in operating nuclear and fossil-fired plants. Table 2-1 summarizes key design parameters for the MHTGR.

As shown in Figure 2-2, the modular reactor components are contained within a steel vessel made up of a reactor vessel, a steam generator vessel and a connecting crossduct vessel. Each reactor module is housed in adjacent, but separate, reinforced concrete silos located below grade and enclosed by a common maintenance hall. Although operating and decay heat loads from the reactor are normally removed through the steam generators or shutdown cooling heat exchangers utilizing helium gas circulators, a passive, air-cooled system is also available to remove decay heat loads via natural convection of outside air through the cooling panels located in each reactor silo cavity.

TABLE 2-1

MHTGR DESIGN PARAMETERS

	MHTGR 4 X 350 (Ref. 4)
Core Thermal Power, MW(t)	1400
Plant Electric Output, MW(e)	540
Plant Efficiency, %	38
Core Power Density, kW/liter	5.9
Fuel/Moderator Volume Ratio	1.0/5.0
Design Fuel Burnup, MWd/Te	98000
Refueling Cycle	1/2 core per 20 months

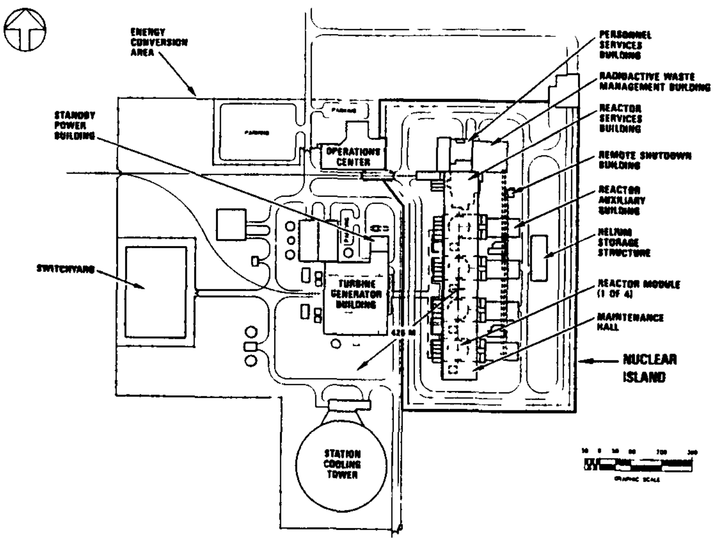

Fig. 2-1 Four Unit MHTGR Reference Design

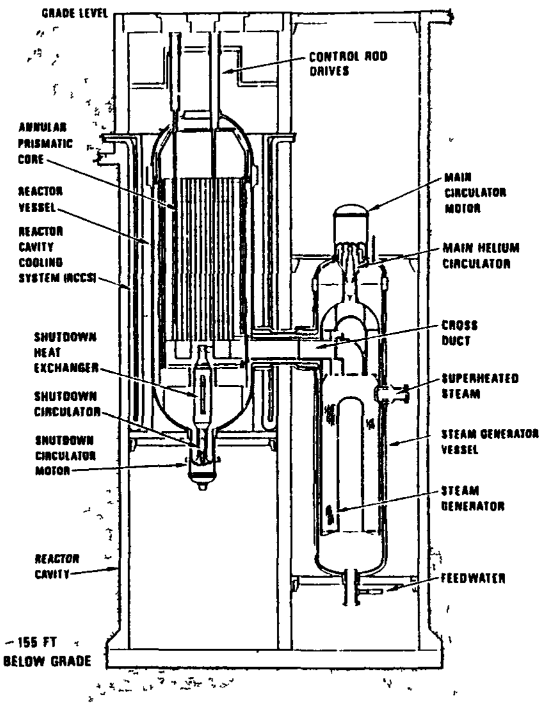

Fig. 2-2 Nuclear Steam Supply Module

Auxiliary structures that house common systems for fuel handling, helium processing and other essential services, complete the Nuclear Island portion of the plant. Waste treatment systems utilize conventional designs proven effective in operating LWRs and gas cooled reactors, including the FSV plant. Remaining plant facilities are similar to those found in a modern fossil-fired plant. The turbine generator plant employs a nonreheat steam cycle to provide a plant overall efficiency of 38% (which is higher than LWR or scrubber-equipped coal-fired plant efficiencies). For the reference MHTGR plant design, a mechanical draft cooling tower rejects the condenser heat load to the atmosphere.

3. RADIOACTIVE EFFLUENTS

Criteria utilized in developing the MHTGR provide for the protection of the public and the environment. For routine operation, this includes meeting regulations specifying limits for liquid, gaseous, and solid releases of radioactive materials to the environment as embodied in 10CFR20, 10CFR50, and 10CFR61 (Refs. 5,6, and 7).

Routine plant operation results in small quantities of radionuclides being released into the environment. FSV operating experience has demonstrated that gaseous and liquid effluents are typically over an order of magnitude lower than the average of the US nuclear power industry (Ref. 1). Preliminary studies indicate that volumes of low level solid wastes and spent fuel from the MHTGR are comparable to volumes generated by LWR plants.

3.1 LIQUID EFFLUENTS

During routine operation, radioactive liquid wastes from the MHTGR are segregated into two categories based upon electrical conductivity, which is a measure of dissolved impurities. The bulk of the waste, which is low in electrical conductivity (less than 50 mho/cm) and varied in radioactivity level, is collected in a receiver tank. On a batch basis, low conductivity liquid waste is processed through a filter/demineralizer. Although higher decontamination levels may be achieved with evaporators, LWR experience indicates that demineralizers are easier to operate and are less subject to operational upset. Treated liquid from the demineralizer is collected in a test tank for monitoring prior to discharge. The high conductivity waste stream is collected in a separate receiver tank and consists of highly tritiated waste and wastes from decontaminating equipment.

Expected radioactive liquid effluent releases for the MHTGR are calculated in Ref. 8 to be five to eight orders of magnitude lower (depending upon the radionuclide) than the maximum permissible concentration limits of 10CFR20. These calculations assume a 20 to 1 dilution of the liquid effluent by a cooling tower blowdown flow prior to discharge to the environment. Although utilization of a cooling tower results in lower effluent flows and higher effluent concentrations than use of a cooling reservoir, the reference MHTGR design includes cooling towers for siting flexibility.

In the US, effluent releases from nuclear power plants meet offsite doses specified in the design objectives of 10CFR50, App I. Table 3-1 provides the expected annual releases of dominant radionuclides contained in MHTGR liquid releases. Lower radiation levels in MHTGR releases permit equipment design selections which improve plant availability (such as the increased reliability associated with demineralizers) and increase siting flexibility (since a large body of water is not required for an MHTGR site).

TABLE 3-1

EXPECTED ANNUAL LIQUID RELEASE FROM THE MHTGR

Nuclide	MHTGR Releases (Ci/yr)
I-131	4.9(-6)[(a)]
Cs-137	2.2(-4)
Ba-140	3.1(-7)

(a) Read as 4.9×10^{-6}.

3.2 GASEOUS EFFLUENTS

During routine operation, sources of radioactive gaseous releases from the MHTGR include: reactor building ventilation, helium purification, gaseous radioactive waste system, and neutron activation of air circulating through the Reactor Cavity Cooling System (RCCS).

Utilizing redundant high efficiency particulate/charcoal filtration assemblies and redundant waste gas exhaust blowers, the MHTGR Gaseous Waste System filters, monitors, and subsequently releases nonradioactive or low-level activity gases to the environment as an elevated release. In the event of a high activity alarm, the flow stream is diverted to the waste gas vacuum tank for treatment until the high-activity source is isolated. Radioactive gases or gases potentially above a preset activity limit are accumulated within the waste gas vacuum tank, compressed by diaphragm compressors. Surge tanks retain these gases for 30 days to allow for radioactive decay prior to release to the environment. Helium and noble gases from the waste gas surge tanks are not recycled as the cost savings do not appear to justify the additional capital costs for equipment, controls, piping, valves, and building space required to recover the helium.

It is demonstrated within Ref. 8 that the maximum expected radionuclide concentration from gaseous effluent releases for all MHTGR sources are a small fraction of 10CFR20 limits. In the US, concomitant doses associated with gaseous effluent releases must also meet 10CFR50, App. I limits. Using conservative site meteorology parameters, it has been shown that the concomitant doses for MHTGR releases are over an order of magnitude below 10CFR50 App I limits (Ref. 8). Table 3-2 provides a tabulation of the gaseous releases of dominant dose-contributing radionuclides generated by the MHTGR.

TABLE 3-2

EXPECTED ANNUAL GASEOUS EFFLUENT RELEASE FROM THE MHTGR

Nuclide	MHTGR Releases (Ci/yr)(a)
H-3	10
Kr-85	40
Kr-88	---(b)
Xe-133	10
Xe-135	---(b)
Ar-41	20(c)

(a) Quantities from Ref. 4 have been adjusted to include a 30 day holdup of gaseous radionuclides from regeneration of the helium purification dryer.

(b) Negligible (i.e. less than 10^{-5} Ci).

(c) Primarily generated by activation of air circulating through the RCCS.

3.3 SOLID WASTE

Solid radioactive waste materials from the MHTGR include solidified wet wastes, spent resin from liquid waste process demineralizers, spent filter cartridges, high-temperature filter units, low-level compressible wastes, High Efficiency Particulate Absorber (HEPA) and charcoal filtration units, and miscellaneous solid materials which become radioactive during plant operation or maintenance. Wet wastes, such as high conductivity decontamination solutions, highly tritiated liquids, spent resins, and noncompactible wastes such as contaminated tools, incore devices or small components that have become contaminated are stabilized utilizing cement solidification to meet stabilization requirements of 10CFR61 for disposal of radioactive wastes. A compactor, which includes a ventilated shroud for dust control, provides volume reductions of 50 to 85% for dry compressible wastes such as rags, paper, or clothing. Large noncompactible waste items are cut utilizing an industrial robot.

Spent graphite reflector blocks are also classified as low level solid radioactive waste. The used reflector blocks are placed in drums and stored in a shielded area prior to shipping.

The volume of solid radioactive waste expected to be generated from the four-unit reference MHTGR plant is estimated as 90 m^3/yr. This waste volume is primarily comprised of used reflector blocks, but includes other material as discussed above. The quantity of radioactivity contained in the solid radioactive waste is estimated at 470 Ci/yr. The great majority of this activity is from decontamination operations and contained in solidified chemical solutions utilized in decontamination operations.

3.4 SPENT FUEL

Although beneficial for safety and investment protection reasons, certain MHTGR design features (such as low power densities in a solid moderator), increase the rate at which spent fuel is generated. However, if volume reduction techniques are employed, MTHGR spent fuel volumes are more comparable to LWR values. Activity release from spent fuel elements is low since the radionuclides are retained within the fuel particles.

The MHTGR fuel cycle utilizes a forty-month fuel residence time, replacing approximately one-half of the vertical fuel columns every 20 months. Six spent fuel storage pools provide interim fuel storage. Decay heat is removed from the spent fuel storage pool until the fuel element heat generation rate decreases sufficiently to allow shipment to permanent storage offsite (storage is provided on site in the spent fuel storage pools for up to 1 year before shipment).

The provisions of the Civilian Radioactive Waste Management Program (Ref. 9) designate the responsibility for shipment and disposal of spent fuel to the DOE. Although preliminary analyses indicate that fully exposed fuel elements may be shipped offsite after 100 days of storage, the MHTGR design provides for additional onsite storage facilities to offset potential delays in implementing the Civilian Radioactive Waste Management Program. If spent fuel must be placed in expanded onsite storage facilities, the requirements for decay heat removal and gamma shielding are significantly reduced from the requirements for the fuel storage pools which must accept spent fuel within a few hours after reactor shutdown. For example, the nominal heat load from a spent fuel element one year after shutdown is about 5% of the heat rate for a nominal element 30 hrs after shutdown (Ref. 10).

Table 3-3 lists expected MHTGR spent fuel volumes. Wastes from a fossil-fired plant with the same net electrical output as the MHTGR are provided in this table to emphasize that the waste volumes from any nuclear reactor are orders of magnitude smaller than the waste volumes associated with a coal fired plant. The MHTGR fuel volumes are more comparable to volumes from equivalent LWRs if the volume is reduced utilizing fuel rod pushout, which is simply removing the fuel rods from the fuel block (Ref. 10). An important factor in evaluating the benefits of this volume reduction approach is the classification of waste level for the residual graphite block with the fuel rods removed. Preliminary measurements of a FSV spent fuel-element graphite sample indicate that after rod pushout, the remaining activity within the element's graphite is below 10CFR61 limits for low level waste (Ref. 10). Successful hot and cold cell demonstrations of HTGR fuel processing techniques confirm that additional methods may be utilized to further reduce HTGR fuel volumes (Ref. 11).

TABLE 3-3

SPENT FUEL VOLUMES GENERATED BY THE MHTGR AND A COAL-FIRED PLANT

	Volume (m^3/GW(e)-yr)
MHTGR	
(w/o volume reduction)	130
(with fuel rod pushout)	30
Fossil-Fired	7.7(+4)(a)

(a) Read as 7.7 x 10^{+4}.

4.0 NONRADIOACTIVE EFFLUENTS

As with any nuclear power plant, the MHTGR produces effluents not immediately related to its heat source and, therefore, nonradioactive in nature. Water usage associated with meeting power cycle heat dissipation requirements are also important in assessing the environmental impact associated with power plant operation. Furthermore, nonradioactive effluents may contain industrial toxins and chemicals whose release must be closely controlled. Preliminary results indicate that the characteristics of the MHTGR are such that these nonradioactive effluents will be lower than those produced by existing LWR plants and some fossil-fired facilities.

4.1 HEAT REJECTION IN COOLING WATER

Waste heat from MHTGR plant components and internal closed cooling water is removed by several systems. The Service Water System removes heat from the Nuclear Island process systems using two 100% capacity service water pumps. The Circulating Water System removes waste heat from the condenser and the turbine building component cooling water heat exchangers. In normal operation, circulating water is pumped from the cooling tower basin through the condenser and heat exchangers and back to the cooling tower. In the reference design, the condenser heat load is rejected to the atmosphere by means of mechanical draft wet cooling towers.

The overall efficiency of the MHTGR is 38.4%. Overall efficiencies for operating HTGR plants, such as the FSV (39%) and THTR (41%) plants, demonstrate the ability of HTGRs to achieve higher efficiencies than other nuclear or some fossil-fired plants. Power plants with higher overall efficiencies reject less waste heat to the environment. The four 350 MW(t) MHTGR modules will collectively reject approximately 860 MW(t) of waste heat to the environment. For purposes of this study, waste heat rejected by LWR and fossil-fired plants were calculated assuming overall efficiencies of 33% and 35%, respectively. Results show that the MHTGR rejects approximately 23% less waste heat to the environment than LWRs and 16% less waste heat than coal-fired plants. Hence, the higher plant efficiency for the MHTGR is beneficial for economic and environmental reasons.

4.2 INDUSTRIAL BIOCIDES AND CHEMICALS

In the operation of steam electric power plants, chemicals and biocides are added to water systems and eventually discharged to the environment. Additions of chemicals or biocides are made for purposes such as control of biofouling or corrosion. Similarities in operating characteristics of MHTGR and LWR water systems suggest that no significant differences exist in the chemical concentration in their effluent streams. Hence, the primary difference in the quantities of chemicals and biocides released would be due to the difference in the magnitude of the effluent flow rate. Since the MHTGR dissipates less heat than LWR or coal-fired plants, the MHTGR requires less cooling water for equivalent electric production at the same site. Therefore, an MHTGR would be expected to release less chemicals than an LWR or a fossil-fired plant.

The nonradioactive effluents produced from components within the reactor modules and related auxiliary structures are limited to collected equipment and floor drainage and equipment cleaning wastes generated during start-up and following equipment maintenance. Only a small amount of the drainage must be treated or disposed of as oily waste.

Other significant effluents are reduced or completely eliminated in the MHTGR design as summarized below:

- The once-through MHTGR steam generator eliminates significant steam generator blowdown and wet layup wastes (Ref. 12);
- Chemical additives in effluents associated with active safety-related heat removal or cooling water systems are excluded;
- Elimination of a need for an active safety related heat sink facility precludes associated wastes;
- Combustion emissions associated with tests to satisfy safety-related requirements for emergency electrical generating capabilities are eliminated.

Coal-fired power plants also release significant quantities of substances to the atmosphere from the combustion process. The quantities released from a specific plant are dependent on the type of coal, installed equipment and local regulations. However, to comply with the New Source Performance Standards of 40CFR60 (Ref. 13) a plant of similar size to the MHTGR could release 10500-16800 tons NO_x/yr, 630 tons particulates/yr and 12600-25200 tons SO_2/yr.

Beyond this, coal-fired plants produce significant quantities of liquid waste effluent from such processes as flue gas desulfurization, fly ash flushing, and coal yard dust suppression. While some modern coal-fired plants, such as Utah's Warner Valley Plant (500 MWe net, twin turbine), maximize water recycle and direct non-re-usable water to evaporation ponds so that there is zero discharge of liquid waste, they must dedicate considerable land area to these liquid disposal facilities (e.g. approximately 485 hectares (1,200 acres) in the case of Warner Valley) (Ref. 14).

5. CONCLUSIONS

Building upon HTGR operating experience, an MHTGR plant has been designed to provide highly reliable, economic, and safe nuclear power. As discussed within this paper, MHTGR characteristics, such as low radioactive effluents and high thermal efficiency, combine to provide a means of meeting the world's energy needs in an environmentally acceptable manner. In addition, these MHTGR characteristics allow equipment design selections which further enhance the plant's availability and increase its siting flexibility.

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