

MODULAR HIGH TEMPERATURE GAS-COOLED REACTOR HEAT SOURCE FOR COAL CONVERSION

R.W. SCHLEICHER, JR. and A.C. LEWIS

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MODULAR HIGH TEMPERATURE GAS-COOLED REACTOR HEAT SOURCE FOR COAL CONVERSION*

ROBERT W. SCHLEICHER, JR.
ALAN C. LEWIS
General Atomics

1. INTRODUCTION

In the industrial nations, transportable fuels in the form of natural gas and petroleum derivatives constitute a primary energy source nearly equivalent to that consumed for generating electric power. Nations with large coal deposits have the option of coal conversion to meet their transportable fuel demands. But these processes themselves consume large amounts of energy and produce undesirable combustion by-products. Therefore, this represents a major opportunity to apply nuclear energy for both the environmental and energy conservation reasons. Because the most desirable coal conversion processes take place at 800°C or higher, only the High Temperature Gas-Cooled Reactors (HTGRs) have the potential to be adapted to coal conversion processes.

Ever since the inception of the High Temperature Gas-Cooled Reactor (HTGR) the U.S., Germany and other countries have been investigating the different methods to utilize this high temperature for various processes. In the 1979-1980 time period General Atomics performed a comprehensive study to investigate the possibilities for various large HTGR Cogeneration applications. Of these potential applications, cogenerating an HTGR to supply heat energy to a synthetic fuel plant for coal liquids and coal gasification processes was determined to be an appropriate candidate.

Displacement options for petroleum fuels include natural gas (compressed or liquified), synthetic gasoline, biomass fuels, electric vehicles, hydrogen, and methanol. Although no alternative

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vehicle technology, methanol has often been cited as a good compromise and is perhaps the best coal derived fuel (See Ref. 1).

A main criticism leveled at methanol is whether it can be produced economically in sufficient quantities to significantly displace petroleum-derived fuels. Although methanol can be manufactured from biomass, natural gas or coal feedstocks, only coal offers the potential for a substantial long term indigenous feedstock in nations which have large coal deposits.

A privately funded study was recently carried out at General Atomics to investigate the use of a Modular High Temperature Gas-Cooled Reactor (MHTGR) for the production of methanol from coal without producing CO₂. This study compared two alternative conversion processes, steam-coal gasification and hydro-gasification (Ref. 2), both of which require nuclear generated heat in the range of 850°C core outlet temperature.

2. COAL TO METHANOL REACTIONS

The conversion of coal to methanol can be approximated roughly by the reaction:



where coal is represented by CH_x, where "x" is the ratio of non-aqueous hydrogen to carbon atoms. For typical U.S. coals, "x" varies from about 0.8 for high volatility bituminous to 0.3 for anthracite (Ref. 3). However, this hydrogen content range is insufficient to produce methanol without a CO₂ by-product. For a stoichiometric reaction, every mole of product methanol results in 0.43 to 0.74 moles of by-product CO, which ultimately becomes CO₂.

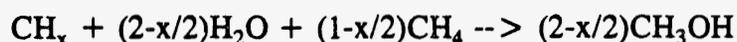
The coal-to-methanol reaction also requires substantial quantities of heat. If the heat were supplied by coal through a standard gasification reaction, about 80% more coal feedstock would be required along with oxygen for combustion (Ref 4). Thus, production of methanol using the burning of coal for the heat input of a gasification reaction results in the release of from 1.0-1.4 moles of CO₂ for every mole of methanol produced. Further, for every mole of gasifier-produced methanol that is ultimately combusted, approximately 2.0-2.4 total moles of CO₂ would have been released to the environment.

The role of atmospheric CO₂ emissions to the global warming phenomena is the subject of world-wide study. With few exceptions, the scientific community is in agreement that significant additional warming can be expected if substantial heat-absorbing CO₂ and other greenhouse gases are added to the atmosphere (Ref. 5). The impact of the more severe estimates of warming would be devastating to many regions of the world.

In order to produce methanol from coal without producing CO₂, two process inputs, in addition to coal and steam, are required: a supplemental hydrocarbon feed with a H/C ratio well above 2 and a non-combustion source of high temperature heat.

The ideal supplemental hydrocarbon feed is H₂. Although small quantities of inexpensive H₂ are available as process by-products, a large-scale methanol economy would require enormous quantities of H₂ which would have to be produced specifically for methanol production. With current production techniques, this H₂ would be prohibitively expensive. However, future technologies, such as thermo-chemical water splitting hold promise of cheaper H₂ which would make H₂ supplemental feed economically viable.

In lieu of a cheap H₂ source, CH₄ from natural gas can be an interim feedstock. The stoichiometric non-CO₂ producing reaction is:



With "x" in the range of 0.3 to 0.8, from 0.85 to 0.6 moles of CH₄ are required per mole of carbon from coal to make methanol without CO₂.

The above reaction is endothermic and requires heat in the range of 1,200-1,400°F (650-760°C). The only practical non-combustion source of such heat is a nuclear reactor. Even though this temperature range is well beyond the capability of most nuclear reactors, it is well-suited to the temperature range of the MHTGR.

3. PROCESS ARRANGEMENT FOR MHTGR METHANOL SYNTHESIS

The principal challenge to configuring a MHTGR Process Heat (MHTGR-PH) system for methanol production is the method of transporting heat to drive the coal to methanol reactions.

Conventional coal conversion technologies introduce oxygen into the steam-coal gasifier to provide the reaction heat via direct coal combustion. Nuclear heat must be generated separately and then supplied indirectly to the process stream by a heat exchanger.

Two possible configuration arrangements have been recognized for nuclear coal conversion schemes: steam-coal gasification and hydro-gasification (Ref. 2). Both are amenable to methanol synthesis without CO₂ production, as illustrated in Fig. 1. In the steam-coal gasification process, excess H₂

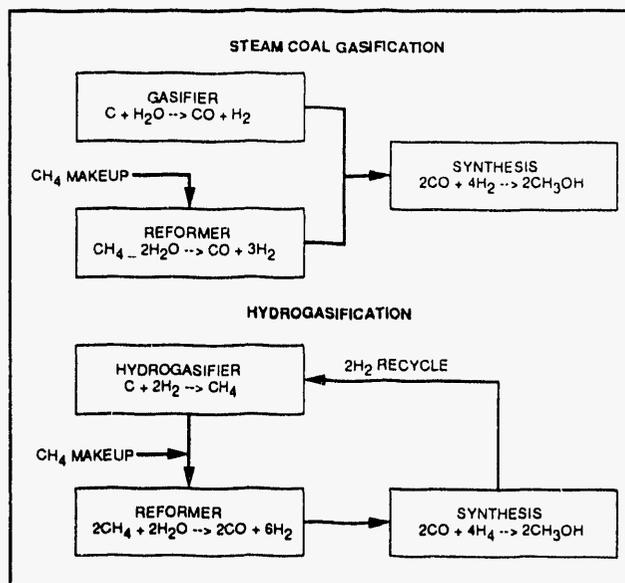


Fig. 1. Reactions for coal to ethanol by hydro-gasification

from the steam-methane reforming reaction compensates for the lack of H₂ in the steam-coal gasifier. The combined reformer and gasifier outputs constitute the necessary feed for stoichiometric methanol synthesis. Both the reformer and gasifier reactions are endothermic, requiring heat at high temperatures for efficient production rates.

The indirectly heated steam-coal gasifier is particularly challenging because the heat must be transferred into the coal solids through a barrier which isolates the primary system, viz. heat exchanger tubes. Remarkably, a steam-coal gasifier was demonstrated by Lurgi utilizing an electrically heated helium loop and a circulating fluidized-bed gasifier. Heat exchanger tubes containing the high temperature helium flow dipped into the bed for transfer of heat (Ref. 6).

The steam-coal gasification process for CO₂-less methanol production has the disadvantage of requiring two heat exchangers for introducing nuclear heat into the process. Furthermore, despite being demonstrated, the helium-heated fluidized-bed remains technically difficult and costly. Therefore, the initial process investigation was focussed on hydro-gasification in which only the reformer requires heat from the reactor.

In the hydro-gasification process, nuclear generated heat is introduced directly through the reformer, which converts CH₄ and steam to CO and H₂. For efficient reaction rates, the reformer requires heat at temperatures up to 1450°F (788°C), which is achievable with an

MHTGR-PH with 1550°F (850°C) core outlet helium temperature. In addition, feed steam is required at approximately 900°F (482°C) in at least a 2-to-1 ratio with CH₄. This high temperature steam can be conveniently supplied by a MHTGR steam generator in series with the reformer. In fact, excess steam is typically produced, which enables cogeneration of significant electric power.

The reformer equipment has been standardized for process industries and a variety of reformer heat exchanger configurations and materials have been studied for application in HTGR's in the late 70s and early 80s (Ref. 7).

The hydro-gasifier itself is strongly exothermic and does not require a heat source to produce CH₄ from coal feed and H₂. The hydro-gasifier concept, illustrated in Fig. 2, is a two-stage vertical arrangement, operating at conditions of 1800°F (982°C) and 1060 psia (72 atm). Even though this concept was studied by several organizations in the 1970s, it is still largely a developmental piece of equipment.

Development studies carried out by Rockwell have demonstrated efficient carbon conversion (Ref. 8).

The process arrangement for MHTGR-PH methanol production via coal hydro-gasification is shown in block diagram form in Fig. 3. The reformer would interface directly with the reactor primary system and would constitute part of the primary pressure boundary.

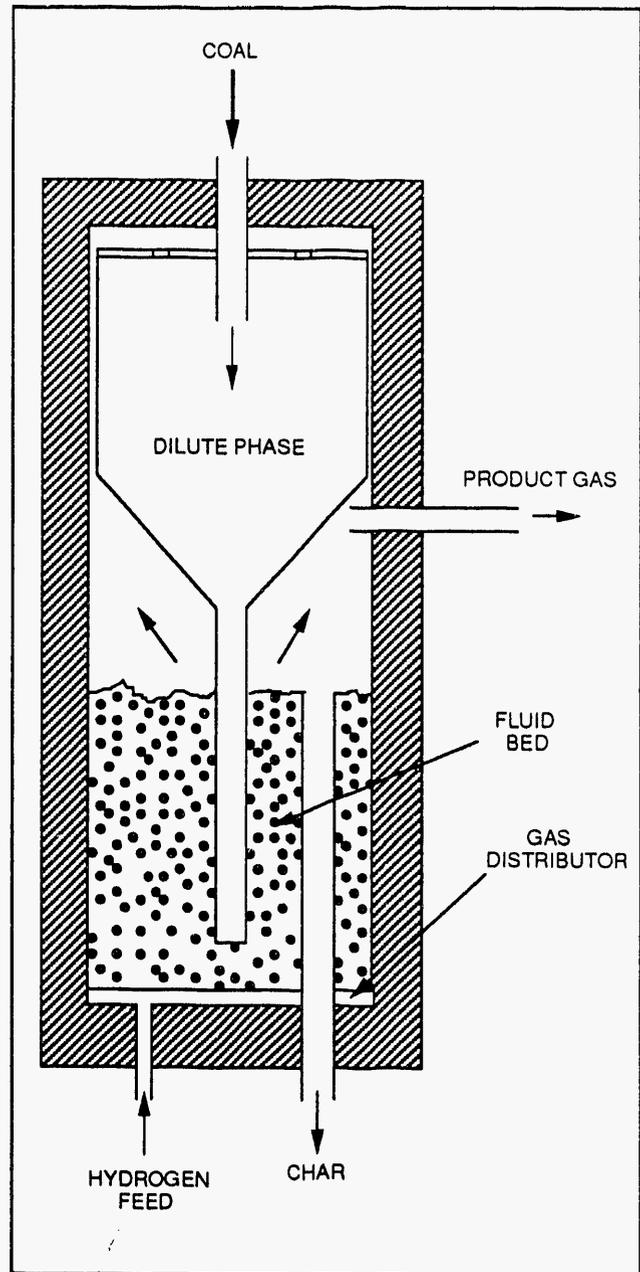


Fig. 2. Hydrogasifier

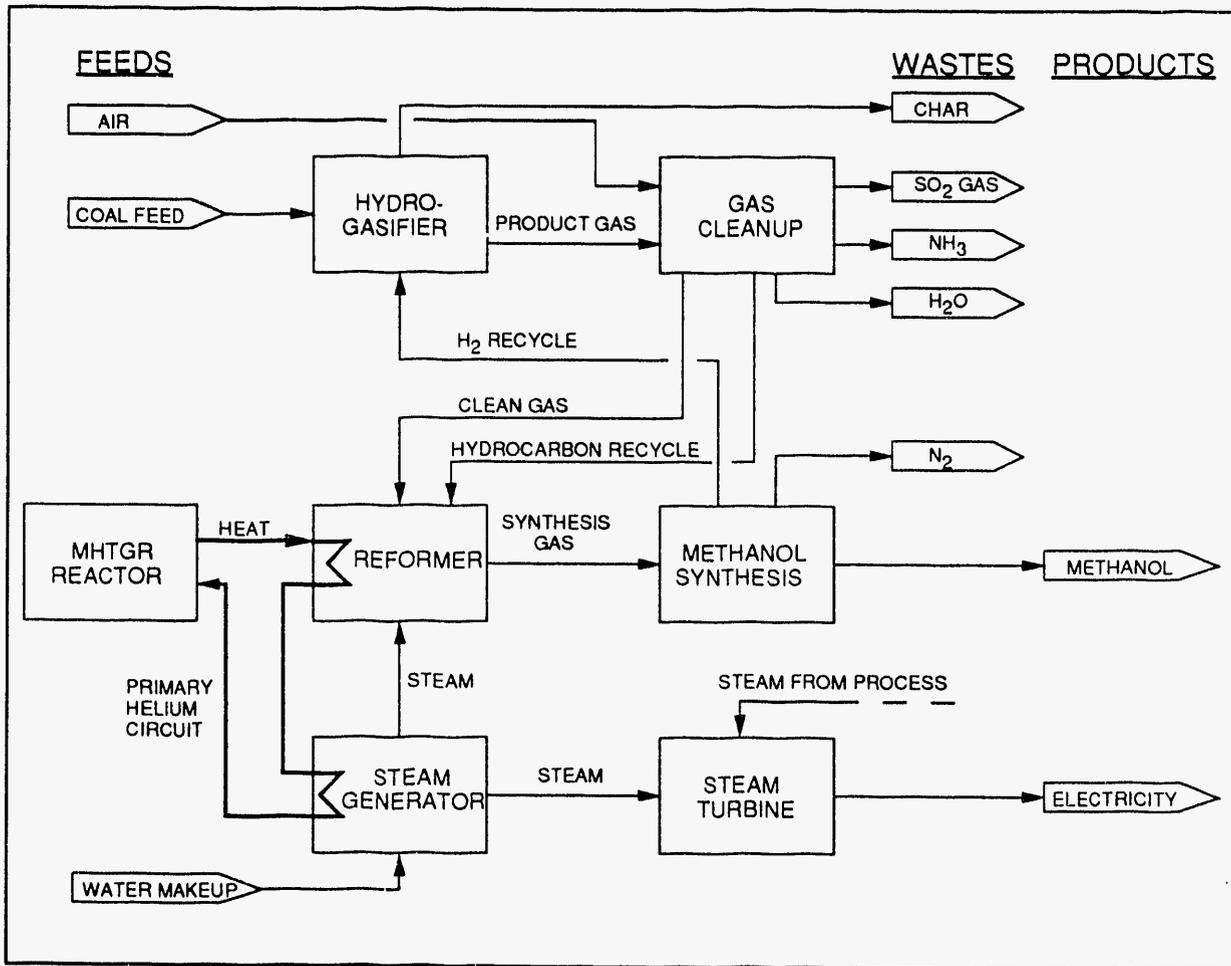


Fig. 3. MHTGR methanol process arrangement

Prepared coal feed is delivered to the hydro-gasifier which supplies the product gas to the gas clean up system. After removing unwanted byproducts in the gas cleanup system, the clean gas is combined with supplemental CH₄ feed and then delivered to the reformer. The synthesis gas, which is rich in H₂, is delivered to the methanol synthesis unit with the excess H₂ from the synthesis reaction diverted to the hydro-gasifier. The product gas from the hydro-gasifier contains a fair amount of hydrocarbons. These are cracked in a catalytic pre-reformer to further increase synthesis gas production.

Table 1 presents the expected operating parameters for the three major processes. The actual parameters will vary from these values dependant on coal type and equipment performance characteristics.

A summary of the process results for three case studies are presented in Table 2.

TABLE 1
PROCESS OPERATING
CONDITIONS

	Temp. (°F)	Press. (psia)	Catalyst
Hydro-gasifier	1800	1060	None
Reformer	1440	176	Ni on Al ₂ O ₃
Methanol Synthesizer	460	1060	CU/Zn

The performance of each process component was based on published experimental or manufacturers data. The hydro-gasifier performance was based on tests by Rockwell (Ref. 8) which showed a 60% carbon conversion at 1800°F (982°C) with the following fractional yields at H/coal ratio of 0.32:

Carbon Monoxide	0.043
Methane	0.40
Liquid (as Benzene)	0.11
Ethane	0.37
Carbon Dioxide	0.26

TABLE 2
CASE STUDY PROCESS RESULTS

	Coal Type	% Carbo n In Coal	% Conversio n
Case A:	Anthracite	80	56
Case B:	Bituminous	60	56
Case C:	Bituminous	60	80
	Case A	Case B	Case C
Coal feed, lb/hr	342,800	538,700	357,000
CH ₄ feed, lb/hr	171,928	127,310	153,028
Methanol, lb/hr	759,597	739,351	764,913
Net power, MWe	292	306	300
Ash, lb/hr	150,791	193,630	76,826
Thermal eff., %	56	54	61

The reformer performance is highly dependent on temperature, catalyst type and steam-to-CH₄ ratio. This work was based on 90% yield at a peak temperature of 1440°F (782°C) and a 2-to-1 steam/CH₄ ratio.

A host of gas cleanup processes are available for control of solid particulates, sulfur compounds, nitrogen compounds, etc. Initial work assumed a Phosam ammonia

(nitrogen) removal unit and an iron-oxide dry-bed sulfur removal unit for primary pollutant removal steps.

Methanol synthesis units are currently used in process applications. Typical methanol synthesis yields are 98% for CO and 50% for CO₂ in the feed gas. Yields are increased considerable

when excess H_2 is present as in this case. After condensing the product methanol along with water, the non-condensable H_2 and unreacted synthesis gas may be recycled (in unspecified quantity) to the synthesis reactor or pumped back to the hydro-gasifier as H_2 supply.

Calculations of overall process performance were performed using a spreadsheet calculation which performed material balances, reaction equilibria, heat and energy balances, power consumption and net power generation.

4. MHTGR-PH HEAT SOURCE DESCRIPTION

The reactor system envisaged for this application would be an adaptation of the Nuclear Island design developed by General Atomics and others under the U.S. Department of Energy sponsored MHTGR-NE Program for steam cycle electric power generation. This takes advantage of substantial work performed on the design of the MHTGR, and it extends the versatility of the MHTGR as a universal heat source. The MHTGR-PH primary system design shown in Fig. 4 features two side by side vessels.

The MHTGR design is based on generic, gas-cooled reactor experience and specific HTGR programs and projects, including the 53 carbon dioxide-cooled reactors developed in the United Kingdom and built around the world (including Japan), and the 5 helium-cooled reactors built in Western Europe and the United States. The MHTGR is being designed to meet the rigorous requirements established by the Nuclear Regulatory Commission (NRC) and the electric utility-user industry for a second-generation power source for the late 1990s. The

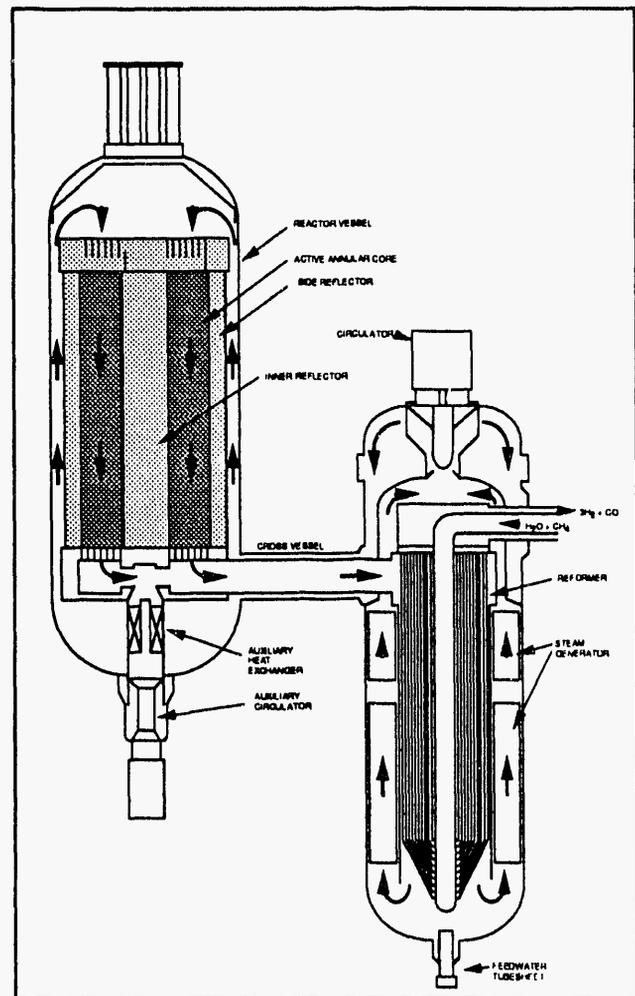


Fig. 4. MHTGR-PH primary system

plant is expected to be equally attractive for deployment and operation in the United States, other major industrialized nations, and the developing nations of the world. A description of MHTGR-SC is given in Ref. 9. Both 350 MWt and 450 MWt reactor sizes have been developed, although current emphasis is on the 450 MWt because of better economy. A typical plant may consist of any number of reactor modules but a convenient, economical configuration is four reactor modules (i.e. 4 x 450 MWt) coupled to multiple process trains.

The reactor module components are contained within three steel pressure vessels; the uninsulated reactor vessel, a steam generator vessel, and a connecting cross vessel. The reactor core and the surrounding graphite neutron reflectors are supported on a steel core support plate in the lower portion of the vessel. The annular, active core is composed of hexagonal graphite fuel blocks containing fuel compact material in sealed vertical holes. The heat transport system (HTS) provides heat transfer during normal operation and normal shutdown conditions using high pressure, compressor driven helium that is heated as it flows down through the core. The main circulator is electric motor driven, two-stage axial compressor with active magnetic bearings. For availability and maintenance requirements, a separate shutdown cooling system (SCS) is provided as a backup the primary HTS. The shutdown heat exchanger and shutdown cooling circulator are mounted on the bottom of the reactor vessel. These heat removal systems allow hands-on module maintenance to begin within 24 hours after plant shutdown.

The ensuing discussion of the MHTGR-PH reactor system focuses on the distinguishing features relative to the 450 MWt MHTGR-SC concept. Figure 4 shows the configuration of the 450 MWt MHTGR-PH primary system with the reactor in one vessel and the heat exchangers and circulator in a second vessel viz. the MHTGR-SC arrangement. The primary coolant exiting from the core at 1560°F (850°C) flows through the inner duct in the concentric cross duct to the heat exchanger vessel which contains the steam methane reformer and the steam generator. The primary coolant gives up its heat in series to the reformer and steam generator. The reformer provides CO and H₂ to the methanol synthesizer, and the steam generator provides high temperature steam for the process and excess steam for electric power generation. The circulator, which is located at the top of the heat exchanger vessel, returns the cold helium at 650°F (343°C) to the core inlet via the outer concentric duct in the cross-vessel and the outer annulus of the reactor vessel for the purpose of maintaining the vessel below the operating temperature limit of 700°F (371°C) during operation.

The MHTGR-SC reactor with an annular graphite core can be adapted to process heat application with an outlet temperature of 1550°F (850°C) with very little modification. The reactor vessel, core, fuel, internals and supports remain unchanged. The salient primary system design parameters for the MHTGR-PH are given in Table 3.

The significant fuel cycle difference between the MHTGR-PH and MHTGR-SC is that the fuel cycle is changed from a staggered reload scheme where half of the core is replaced every 1.5 years to a batch reload in which the entire core is replaced every 3 years. The effect of the batch core is to reduce the age component of the radial peaking factor and thereby reduce

both peak fuel temperatures and peak helium outlet temperatures. The fuel temperature profiles for both the MHTGR-PH and MHTGR-SC core remains below 2280°F (1,250°C), the practical normal operating limit for standard silicon carbide (SiC) TRISO fuel. This has the major advantage of enabling SiC-TRISO fuel which has a substantial irradiation data base for the MHTGR-SC to be used for the MHTGR-PH.

The effect of higher operating temperatures in the MHTGR-PH core was evaluated for its impact on the important core design features including temperature defect, uranium loading, shutdown margin, negative temperature coefficient, graphite conductivity, graphite dimensional change, graphite expansion coefficient, graphite modulus, graphite strength, and graphite creep relaxation. In all cases, the design margins were found to undergo little change relative to the MHTGR-SC and remain more than adequate for operation in the MHTGR-PH temperature regime.

The heat exchanger vessel contains the reformer, steam generator and circulator. The conceptual vessel arrangement is shown in Fig. 4. The circulator is located at the top of the heat exchanger vessel as is the case with the MHTGR-SC. The heat exchanger/reformer arrangement is unique

TABLE 3
MHTGR-PH PRIMARY SYSTEM

Design Parameters	
Reactor thermal power, MWt	450
Core inlet pressure, psia (MPa)	1025 (7.066)
Helium flow, 10 ³ lbs/hr (kg/s)	1374 (173.5)
Core inlet temperature, °F (°C)	650 (343)
Core outlet temp., °F (°C)	1550 (850)
Steam gen. inlet temp., °F (°C)	1248 (676)
Steam gen. outlet temp., °F (°C)	644 (340)

in that the straight tube reformer is located in the center of the helical steam generator. The hot helium from the core outlet flows down through the reformer and then up through the steam generator. Regenerative heating between the two units is limited by two shrouds and an annular gap. The vessel is internally insulated to maintain its metal temperature below 700°F (371°C).

The straight-tube reformer bundle is headered on the top by a tubesheet and on the bottom by a cylindrical manifold which is an extension of the central return duct. The large tubes, 3 inch (7.6 cm) OD, contain a nickel impregnated aluminum oxide catalyst in the form of 0.5 inch (1.3 cm) spheres for catalyzing the steam-methane reaction.

The helical steam generator surrounds the straight tube reformer. The steam generator is a down-flow unit which represents the only major deviation from the MHTGR-SC. Downflow helical bundles have been successfully built and operated in gas-cooled reactors (viz. THTR in Germany) but they place restrictions on the minimum flow and method of shutdown. In view of its process application, the MHTGR-PH plant will be essentially based-loaded and, therefore, limitations of a downflow unit should not be a significant concern.

5. REACTOR SYSTEM SAFETY CONSIDERATIONS

The MHTGR-PH is required to meet the same safety and licensing requirements as the MHTGR-SC including satisfying the intent of all Federal and NRC regulations. The plant design precludes the need for off-site emergency drills for sheltering or evacuation, because all design basis events with frequency $\geq 5 \times 10^{-7}/\text{yr}$, meet the lower limit of the EPA's Protective Action Guidelines (PAGs), i.e. 1 rem whole body and 5 rem thyroid. The MHTGR meets these requirements by relying solely on passive and inherent safety features without requiring electric power or operator actions.

There are two important safety issues specific to the MHTGR-PH. The first concerns the effect of higher core operating temperatures on the ability of the MHTGR-PH to adequately reject core afterheat in the same passive manner as the MHTGR-SC. The second is whether tritium, a radioactive contaminant in the primary system will readily diffuse into the product stream via the reformer tubes. Both of these issues have been evaluated and shown not to be a serious concern for the MHTGR-PH.

The MHTGR-PH with 1550°F (850°C) outlet temperature can sustain the design basis pressurized and depressurized cooldown events without exceeding fuel or component safety limits. The analysis for both events assumes that the reactor is shut down from full power with no active cooling systems available. In the passive shutdown cooling mode, core afterheat is conducted radially outward through the core and reflector and through the reactor vessel wall. It is then radiated and convected to the air-cooled panels in the reactor cavity. These panels, which are part of the Reactor Cavity Cooling System (RCCS), have continuously circulating air, driven by natural convection, and ultimately reject the heat to the environment. Sufficient heat can be removed by this mechanism to prevent damage to the fuel or reactor components including the reactor vessel.

Despite higher operating temperatures than the MHTGR-SC, the peak MHTGR-PH temperatures during shutdown cooling are within safety limits. This is due to two reasons. First the cooldown transients are long term so the effect of initial conditions becomes secondary to afterheat levels which are identical for both concepts. Second, the limiting heat transport mechanism is the radiation from the vessel to the cooling panels which is a highly non-linear (T^4) relation. Higher temperatures result in significantly higher heat transfer rates, thereby suppressing peak internal temperatures.

The second safety issue for the MHTGR-PH is the potential for tritium to diffuse through the reformer tubes. H_2 diffuses readily through many alloys and the rate is enhanced with temperature. Tritium is present in the MHTGR primary system as a result of fission product release through defective fuel and reaction products from neutron capture in boron present in control rods and lumped burnable poison. Under worst case assumptions, the annual release of tritium into the process stream was estimated at less than 90 Ci. However, due to the large product throughput, the concentration in methanol would be less than 4×10^{-11} Ci/cc. This is nearly two orders less than the 10CFR20 Appendix B limit of 3×10^{-9} Ci/cc for liquid effluent releases.

Although a more thorough examination of MHTGR-PH safety is needed, based on the results of these two feasibility issues, it is fully anticipated that the MHTGR-PH will retain the same degree of benign passive safety characteristics as the MHTGR-SC.

6. ECONOMIC EVALUATION

The economic analysis of the MHTGR-PH methanol cogeneration plant was based on a revenue requirements methodology which involves the determination of the year-by-year revenue required for the return of capital, fuel, feed and operating expenses. Table 4 presents a summary of the projected methanol production costs for an equilibrium 4 x 450 MWt MHTGR-PH assumed to start up in the year 2010. The estimate is for the above Case C production rates, which is based on bituminous coal feed and 80% carbon conversion in the hydro-gasifier. The estimated output for this plant is 95 Kg/sec of methanol and 300 MWe net electrical power, given feeds of 63 Kg/sec of bituminous coal and 16 Kg/sec of methane. Product costs are quoted in 30-yr. levelized constant \$-1991. MHTGR capital and operating costs were derived from DOE MHTGR program data and methanol plant cost were derived from Ref. 10 using escalation per the Whitman-Handy Index and applying a 25% contingency. Capital costs include owner's

cost, contingency and interest during construction. A constant dollar fixed charge rate of 12.2% was used based on ownership by a private enterprise. Additional marketable products include sulphur and ammonia.

The product methanol price of \$12.50/MBTU is high compared to current wholesale gasoline prices which are equivalent to \$5.27/MBTU without taxes. This corresponds to \$18 per barrel crude oil. However, gasoline is expected to experience real escalation during the period from 2010-2040, the assumed plant operating life. Based on an assumed 4% real price escalation, the levelized wholesale gasoline price (without taxes) for this period is \$15.90/MBTU

TABLE 4
METHANOL PRODUCTION
COST ESTIMATE

Methanol Plant Cost, \$M	1,045
MHTGR-PH Cost, \$M	1,770
Total Capital Cost, \$M	2,815
Coal Feed Cost, 1991-\$/MBTU	1.60
Coal Real Escalation, %	1.0
Methane Feed Cost, 1991-\$/MBTU	2.50
Methane Real Escalation, %	4.0
Annual Capital Cost, \$M	343
Annual O&M Cost, \$M	36
Annual Feedstock Cost, \$M	207
Annual Electrical Credit, \$M	(188)
Methanol Price, \$/MBTU	12.50

In conclusion, the MHTGR represents an important option for nations with large coal deposits for achieving independence from foreign fuels by utilization of coal reserves without further threatening the environment with large CO₂ releases.

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