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GAS-COOLED REACTOR PROGRAMS

NEW APPROACHES IN THE USA FOR HIGH-TEMPERATURE GAS-COOLED REACTORS

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Presented by
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ABSTRACT

Several concepts are being evaluated in the U.S. HTR† Program to explore designs which might improve the commercial viability of nuclear power. The general approach is to reduce the reactor power and increase the ability to use inherent features for removing heat following extreme accidents. The unit size and design of these concepts are constrained so that extreme accidents do not result in significant release of radioactivity from the reactor plant. Through the greater reliance on inherent safety features in small HTRs, it should be possible to minimize the amount of nuclear grade components required in the balance-of-plant, which could lead to an economic system. Four HTR concepts are presently being evaluated within the U.S. Program, and these concepts are briefly summarized. A modular HTR using a steel pressure vessel, which is very similar to one of the four HTR concepts being evaluated within the U.S. National program, is presented as an example of a specific concept to illustrate the features and performance of HTRs having a high degree of inherent safety.

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1. INTRODUCTION

The development of high-temperature gas-cooled reactors (HTRs) in the United States has in the past emphasized large reactor systems [2240-MW(t)] having relatively high core power densities (7 to 8

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†HTR is a generic term applying both to prismatic-fueled (HTGR) and pebble bed fueled (PBR) reactors.

W/cc). These systems have a high degree of inherent safety* following loss of cooling accidents because of their large core heat capacity and high temperature capability. However, they do depend upon the startup of auxiliary heat removal systems following extreme accident conditions to maintain fuel temperatures sufficiently low to prevent any significant failure of the coated fuel particles and to prevent plant damage. The use of such engineered features is a valid approach for high power units. However, one key to the future economic viability of nuclear power may be development of nuclear plants with safety features based on inherent heat removal mechanisms to remove decay heat and to protect the reactor plant. Together with a regulatory framework for addressing reactors with these advanced safety features, this could lead to a reduction in the number of nuclear safety grade systems relative to those of current-generation nuclear plants, and thereby result in an economically competetive system.

An important factor in reducing plant costs is the amount of nuclear grade equipment required in the balance-of-plant (BOP) which is directly related to the number and sophistication of the engineered systems needed to assure the safety of the nuclear steam supply system (NSSS). Through the incorporation of inherent safety features in the NSSS, it is hoped that the BOP outside the nuclear island can be constructed to fossil plant standards with attendant savings in cost and schedule.

In general, the present very high investment costs and long construction times of current nuclear plants in the United States clearly influence the future use of nuclear energy. Thus within the National HTR Program new approaches are being evaluated that could contribute to improved economic viability for HTRs; these new approaches involve lower-power density and lower-power concepts that rely on a high degree of inherent plant characteristics to achieve safety.

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*The term "inherent safety" is associated with reactor concepts that do not require operator action or action of mechanical devices (such as valves or control-rod systems) to limit the release of fission products to the environment.

The degree of inherent safety achieved is a function of the specific design. The HTGR large plant design [2240-MW(t)] has a significant degree of inherent safety, with several hours available for activation of auxiliary heat removal systems. Accident studies have indicated that the public radiation risk from the 2240-MW(t) HTGR is less than from existing LWR units.[1]

By reducing the core power level to about 1200-MW(t), reducing the core power density, and utilizing redundant cooling systems which can act in a passive mode, the time available for activating auxiliary heat exchange units after loss of primary cooling can be significantly increased without leading to component damage. These changes may be sufficient to permit economic construction of HTGR power plants if they lead to simpler licensing and plant construction practices.

Other design concepts are also being studied, which decrease the distance over which heat transfer has to take place under postulated accident conditions, and extends the time available for action to protect components to very long times. In these concepts, fission products are to be nearly completely contained within the coated fuel particles under postulated accident conditions as long as necessary, with this retention not depending on an active auxiliary heat removal system. For relatively high-power reactor units having this feature, i.e., about 1200-MW(t), annular geometry cores are employed rather than the cylindrical geometry employed in the more conventional units.

Another way to obtain the desired characteristics is to cluster modular units to make up a power plant. These modular HTR units would be designed so that under postulated accident conditions there is sufficient heat transfer from the reactor core to a natural circulation heat sink to maintain the integrity of nearly all coated fuel particles.

The general design features of the 2240-MW(t) HTGR nuclear steam supply system will first be discussed to serve as a reference "conventional" design against which the new design approach can be compared.

2. GENERAL FEATURES OF A CONVENTIONAL HTGR STEAM SUPPLY SYSTEM

The general features of a 2240-MW(t) [860-MW(e)] HTGR are given in Fig. 1. This design was developed by GA Technologies, Inc. (GA) as part of the National HTR Program sponsored by the U.S. Department of Energy (DOE). As shown, the reactor core is contained within a prestressed concrete reactor vessel (PCRV), with the core in the center cavity and the steam generators and auxiliary heat exchangers in pods surrounding the core. The reactor core is cooled with pressurized helium, moderated and reflected with graphite, and fueled with a mixture of uranium and thorium. It is constructed of prismatic hexagonal graphite blocks with vertical holes for coolant channels, fuel rods, and control rods. Helium coolant flows from four electric-motor-driven circulators downward through the core, through four steam generators, and back to the circulators. Superheated steam (17.3 MPa, 541°C) produced in the once-

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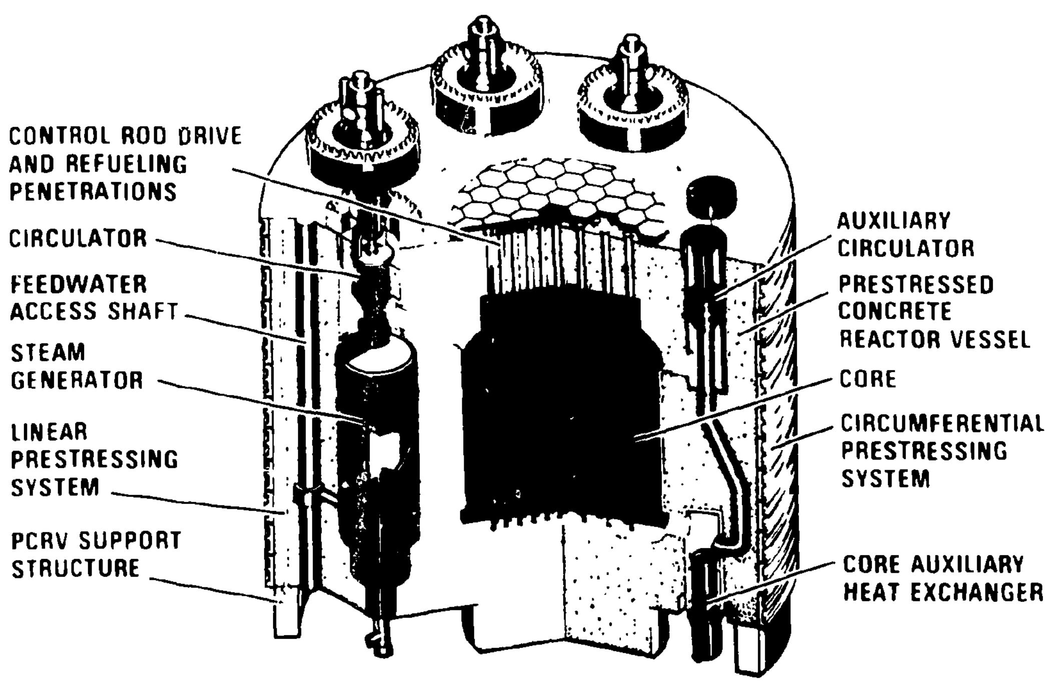

Fig. 1. 2240-MW(t) HTGR Nuclear Steam Supply System.

through steam generators is expanded through a tandem compound turbine generator. Steam is condensed in a water-cooled condenser, and waste heat is rejected to the atmosphere in a wet cooling tower. In addition to the four primary coolant loops, three core auxiliary heat removal system (AHS) loops are also provided. Each consists of a gas/water heat exchanger with an electric-motor-driven circulator located in a cavity in the PCRV wall. Should the main loops not be available, coolant is circulated from the reactor core through the AHS heat exchangers where heat is transferred to the core auxiliary cooling water system for eventual rejection from cooling towers to the atmosphere.

The average core power density is about 6 W/cc and the operating pressure is about 7 MPa. The coolant gas exits the core at about 690°C. The PCRV and ancillary systems are housed inside a reactor containment building, which is a conventional steel-lined reinforced secondary containment structure. Typically, BOP systems and equipment are arranged and housed in separate buildings depending on function and service.

The advantageous safety characteristics of HTGRs are based on the high heat capacity of the graphite core, the high temperature capability of the fuel and moderator, the use of a coolant which does not change phase and has no reactivity effect associated with density changes, the inherent shutdown mechanisms associated with a negative temperature coefficient, and the use of a PCRV which is a redundant structure and precludes catastrophic failure of the pressure vessel. The low core power density in combination with the graphite moderator leads to relatively slow fuel temperature rises following loss-of-cooling accidents; the graphite moderator and the ceramic fuel are stable to very high temperatures, providing a high degree of fission product retention within the fuel coatings up to about 1600—1800°C, with limited release up to about 2000°C. The helium coolant does not undergo chemical reactions within the reactor circuit, and the use of a gas coolant provides unambiguous coolant conditions. Further, the large negative temperature coefficient of reactivity for the fuel makes fast-acting shutdown systems unnecessary. Nonetheless, if there is a complete loss of forced convection under depressurized conditions, the afterheat generated in the core would eventually cause plant damage and significant fuel particle coatings to fail, since fuel temperatures would rise to values greater than 2000°C. As a result, engineered safety systems are used to supplement the inherent characteristics of the reactor and include the independent auxiliary cooling systems, independent and emergency reactivity shutdown systems, and a reactor containment building. The 2240-MW(t) HTGR design provides up to two hours following an extreme accident for the operators to evaluate conditions and respond with corrective action prior to onset of physical damage to the plant. Further, there is a longer time — 10 hours or more — available following loss of core cooling before extensive failure of fuel coatings takes place. Significant additional times would be required to transport radioactive materials to the environment. With such advantageous safety characteristics, large HTGRs are still considered to be a viable approach for generating commercial power.

3. POSSIBLE NEW APPROACHES WITH INCREASED INHERENT SAFETY FEATURES

During 1983 there were a number of studies concerning the future of the nation's power industry. A recurring message obtained from the results was the need for smaller, simpler nuclear power plants that would serve to ease regulatory, construction, and financing difficulties that were being experienced by the utilities. Also, a survey of U.S. utilities identified a relatively high level of interest in capacity additions within the 400—700 MW(e) and 200—400 MW(e) ranges.

In response to the above and to the associated interest of the Congress, the U.S. HTR Program was realigned in May 1984 to evaluate the potential for small reactor concepts. To guide the evaluation, design requirements for small HTRs were developed which incorporated specific requirements for plant investment protection and for safety. In particular, the plant design should be such that there would be no requirement for emergency sheltering or evacuation of the public as a consequence of licensing-basis events. The approach used to accomplish the above was to reduce the power density and unit power level of the reactor core and thereby maintain fuel temperatures below levels where fuel particle coatings would release significant quantities of fission products.

By decreasing the core power and power density, it is possible to design a system such that even in extreme accidents, significant release of radioactive materials to the environment could be prevented by natural heat removal processes alone. In such cases, the decay heat is removed by radiation, conduction, and/or convection from the regions of the core and reflector to a water-cooled heat exchange system, which can dissipate energy by natural convection processes (passive mode). When a steel pressure vessel is employed, the afterheat energy passes through the pressure boundary to a water-cooled system outside the reactor vessel. With use of a prestressed concrete reactor vessel (PCRV), the afterheat energy is transferred to a PCRV liner cooling system which can operate in the passive mode. With PCRV systems, annular type cores would be employed to decrease the distance through which heat transport would need to take place.

3.1 Modular Steel-Vessel HTR Design Approach

Modular steel-vessel HTR development began initially in West Germany. Concepts have been developed by Interatom, a subsidiary of Kraftwerk Union and by Hochtemperatur Reaktorbau (HRB).[2,3] Kernforschungsanlage (KFA), the Nuclear Research Center at Jülich, has been very active in concept development and evaluation. The approach taken in both the Interatom and the HRB efforts has been to utilize several units to obtain a large power output [for example, 1000-MW(t)] by utilizing several small, independent reactor modules of approximately 250-MW(t) each to supply steam to a single turbine generator. This approach obviously reduces the fission product inventory in any single reactor and reduces the amount of heat which must be removed from a reactor core in the event of an accident thereby contributing to inherent safety. Design parameters (such as core size and power density) for these modules were judiciously combined with generic HTR features (such as the large heat capacity of the core and reflector) so that in extreme accidents public safety is assured even without the operation of active heat removal equipment. Engineered systems are employed, but their role is largely for investment protection.

The Interatom concept places the core and steam generator in separate steel vessels in a side-by-side configuration, while in the HRB concept the steam generator is located above the core in the same vessel. For both concepts, the reactor vessel is housed in a reinforced concrete cavity, the concrete serving as both the confinement boundary and the biological shield. A vessel cooling system, mounted on the inside surface of the concrete confinement, is normally in operation cooling the concrete, and is capable of providing decay heat removal by heat radiation from the uninsulated vessel. Failure of this system results in damage to (but not failure of) the vessel, but not in excessive fuel temperatures. The core diameter is limited by the requirement to achieve cold shutdown with control rods in the reflector only. Thereby, the control rods are never in the hot core during heatup events, eliminating concerns about failure of control rod materials. The fuel element heavy metal loading is selected to provide a moderating ratio for which there is very little (<1 to 2%) reactivity insertion in the event of water ingress.

These modular HTR concepts have many features in common with the AVR,[4] a small [15-MW(e)] HTR in Jülich, West Germany, which was designed and constructed by HRB; the AVR has been operating successfully since 1967. The AVR employs a steel vessel, helium coolant, a pebble bed core, and on-line refueling.

3.2 Concept Evaluation Studies in the United States

At the present time, four HTR concepts are being evaluated in a process which is to lead to a reference concept for further detailed studies. The design and evaluation process is being guided by a Concept Evaluation Plan; this plan includes programmatic logic and specific criteria against which proposed plant concepts are to be evaluated.

The four concepts were the result of a preliminary screening process addressing a large number of alternatives, and are as follows:

1170-MW(t) HTGR Cylindrical Core Concept;
1260-MW(t) HTGR Annular Core Concept;
250-MW(t) PBR Vertical-In-Line Steel Vessel Concept;
250-MW(t) PBR Side-By-Side Steel Vessel Concept.

These are briefly described below.

A. 1170-MW(t) HTGR Cylindrical Core Concept. This unit has features very similar to that of the 2240-MW(t) HTGR discussed above. Primary differences are that the 1170-MW(t) unit employs more extensive heat exchange systems to remove afterheat under postulated accident conditions. In particular, auxiliary heat removal systems are added which can remove afterheat under natural-circulation pressurized conditions (1 loop), as well as under forced-circulation unpressurized conditions (2 loops); also, a more extensive PCRV liner cooling system is utilized. Further, a confinement rather than a containment building is employed. Figure 2 gives a schematic of this concept.

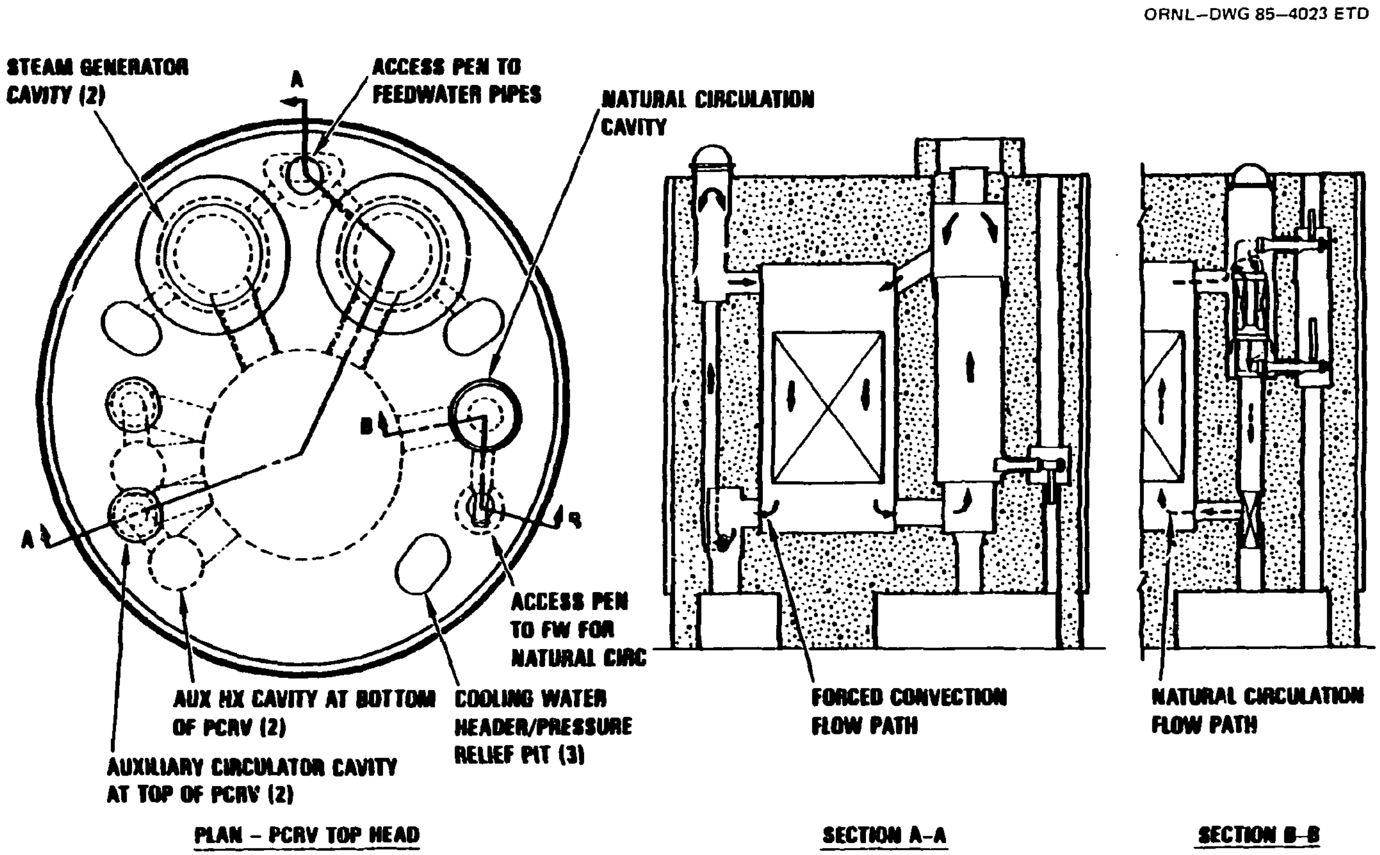

Fig. 2. 1170 MW(t) integrated HTGR concept multi-cavity PCRV, prismatic core, enhanced safety.

B. 1260-MW(t) HTGR Annular Core Concept. This unit employs an annular core within a PCRV, and in general has plant design features similar to those for concept A above. The core has prismatic fuel elements arranged in an annular geometry, with graphite moderator blocks filling the central region. Control rods enter the graphite reflector outside the core annulus. Heat removal systems to dissipate afterheat under postulated accident conditions consist of PCRV liner cooling systems (two loops) which can operate in a natural circulation mode; two separate shutdown-cooling-system loops can dissipate afterheat under forced-circulation pressurized conditions. A confinement building is employed with this concept. Figure 3 gives a schematic of this concept.

C. 250-MW(t) PBR Vertical-In-Line Steel Vessel Concept. A vertical, single steel vessel is employed in this concept, with the cylindrical, pebble bed core located in the lower half of the vessel, and the steam generator in the upper half. Control rods are located in the graphite reflector surrounding the core. Coolant flow is upward through the core after which it passes through the steam generator. Heat removal systems to dissipate afterheat under postulated accident conditions are located outside the pressure vessel, and consist of water cooled pipes lining the reactor vessel enclosure; these cooling systems can remove reactor afterheat using natural-circulation heat transport methods. To provide ease in cooling the core following loss of main loop cooling, a shutdown-cooling-system loop has been added as a non-safety-related engineering feature. A confinement building is employed with this concept. This system is similar to that discussed in section 4 below.

D. 250-MW(t) PBR Side-By-Side Steel Vessel Concept. This concept employs two large steel vessels connected by a steel-duct vessel; the pebble bed core is located in one of the two vessels, and the steam generator unit in the other. Coolant flow is downward through the core, then through the center region of the duct to the steam generator. Control rods are located in the graphite reflector surrounding the core. Heat removal systems to dissipate afterheat under postulated accident conditions are located outside the reactor pressure vessel, and are

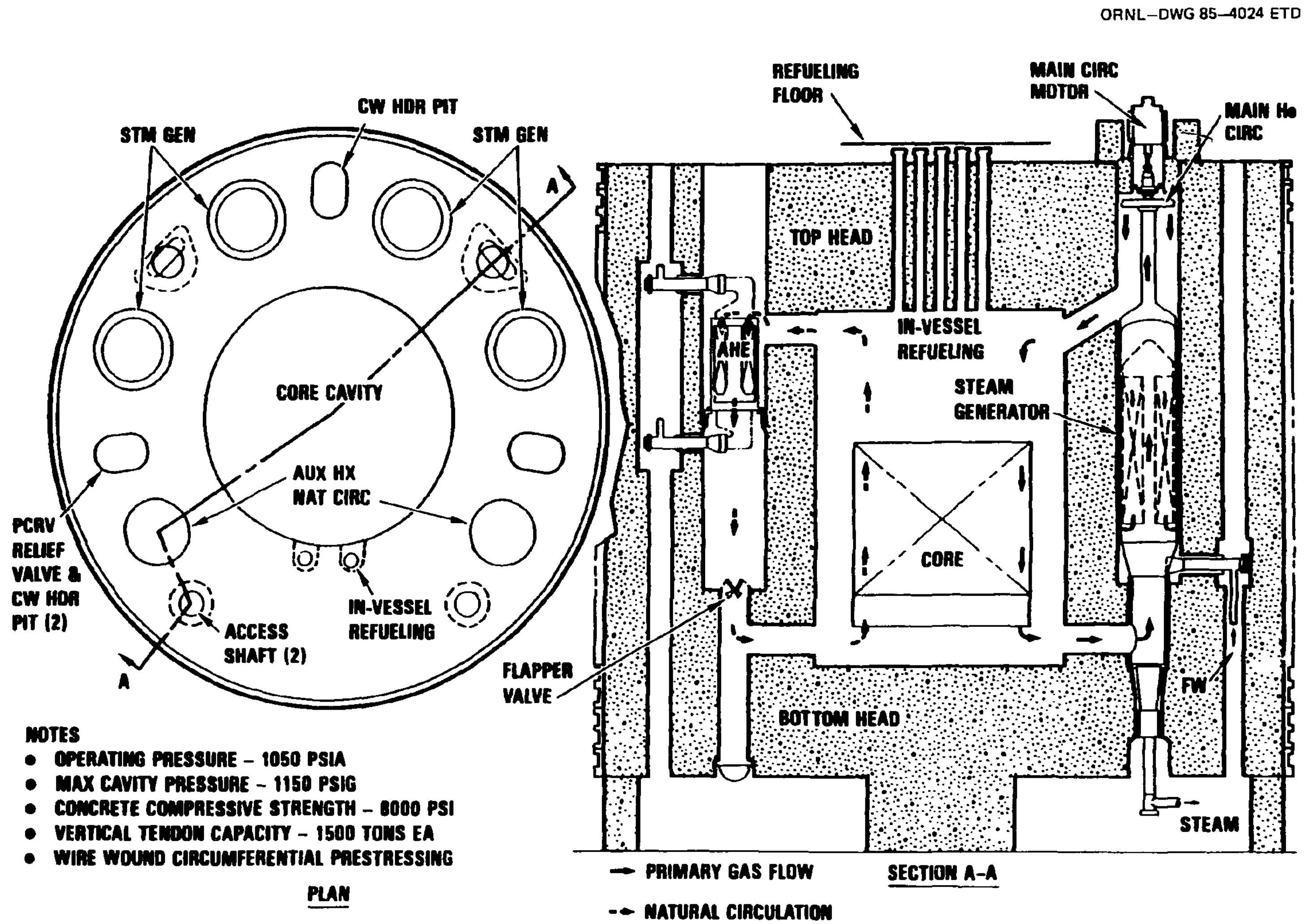

Fig. 3. 1260 MW(t) integrated HTGR concept PCRV, large annular prismatic core.

similar to those employed in the vertical-in-line concept. Also a shut-down-cooling-system loop has been added as an engineering feature. A confinement buidling is employed. This system is similar to that discussed in reference 2.

The above concepts are being investigated by a design team led by GA Technologies Inc., and which includes Bechtel Group Inc., Combustion Engineering, General Electric Co., and Stone and Webster Engineering Corp. The concepts are being evaluated against the Concept Evaluation Plan mentioned above, which includes criteria developed by a DOE chaired special task force made up of HTR program participants. These criteria consider: estimated capital and operating costs of comparable units; research and development requirements; degree of investment protection; degree of public safety; compatibility with power growth needs; and government, utility, and industrial interest in support of a concept. A concept evaluation process has been established, and further screening of concepts will occur during 1985.

4. EXAMPLE OF A MODULAR STEEL VESSEL HTR CONCEPT

In order to illustrate the technical features and performance of HTRs having a high degree of inherent safety, an example concept has been chosen. The specific concept[5] discussed here is a vertical-in-line steel vessel concept that was developed by GA with private funds, but is very similar to the vertical-in-line concept that is one of the remaining four candidate concepts within the U.S. National HTR evaluation program. It is shown in Figs. 4a and 4b. In this concept the core and four helically-coiled steam generator modules are housed within a steel vessel in a vertical in-line configuration. Helium flows upward through the core, through a central duct, and then down across the steam generator tubes in a counter-cross flow direction with the water-steam flow. After exiting the steam generator, the helium enters the circulator and then flows downward along the vessel wall to the lower plenum and returns to the core.

A key feature of the pebble bed reactor is its on-line refueling. The core is fueled with ~320,000 six-cm-diameter graphite pebbles containing coated fuel particles. During operation, pebbles are removed from the bottom of the reactor core and other pebbles are added at the top of the core so that a continuous circulation of pebbles takes place. The burnup of each discharged pebble is measured. Based on the burnup, the pebble is either withdrawn from the cycle and replaced by a fresh pebble or returned to the top of the bed.

4.1 Modes of Decay Heat Removal

Normally, decay heat is removed primarily by the steam generator via forced circulation of the helium at pressure. Decay heat can also be removed by the steam generator with the system depressurized if there is forced helium circulation. If the helium circulators are not operating and the system is pressurized, decay heat can still be removed by the steam generator through natural circulation of the helium. In all of these cases, some heat is also removed by the vessel cooling system. With a non-operational steam generator and the primary system

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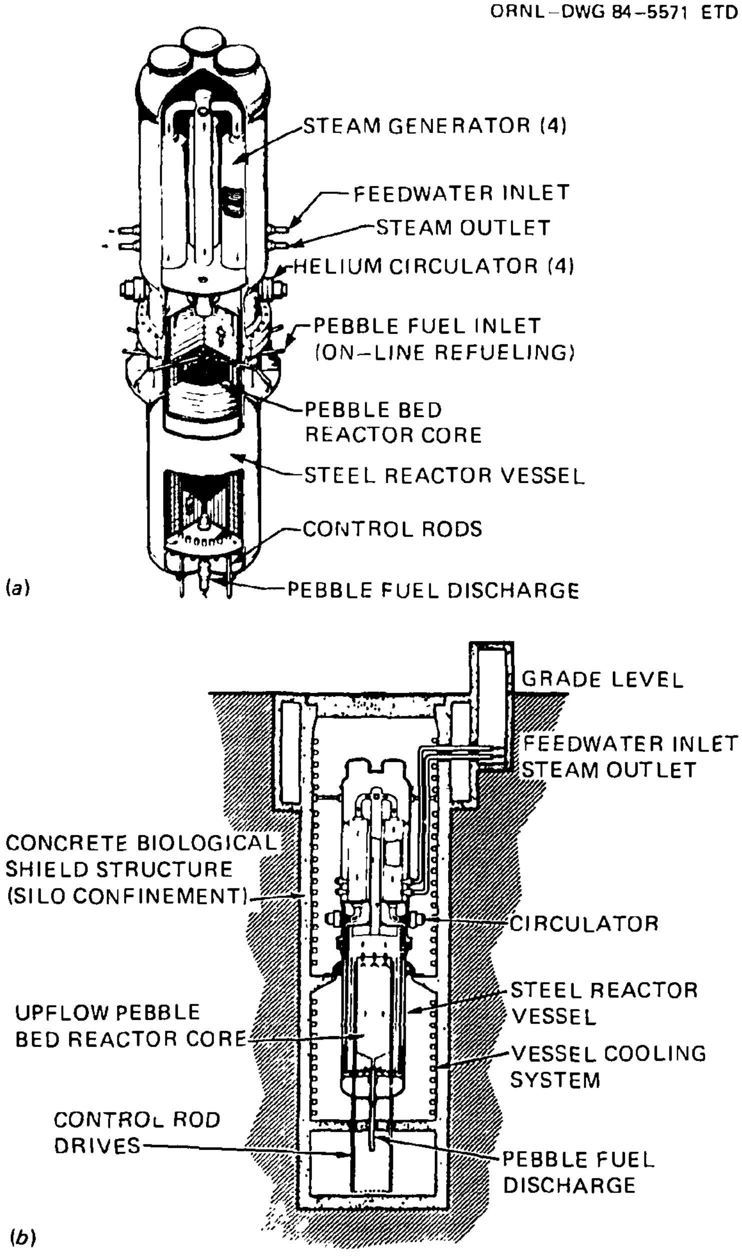

Fig. 4. (a) 100-MW(e) modular HTR, (b) modular HTR system arrangement.

either pressurized or depressurized, the vessel cooling system is capable of removing all of the decay heat without excessive fuel heatup. This system is normally active, but in the event of loss of power, it operates with natural convective flow of the water coolant (passive mode), and provides cooling of the uninsulated vessel for an extended period without makeup of water. A schematic of this system is shown in Fig. 5.

4.2 Selection of Peak Fuel Temperature Limit for Extreme Accidents

For core heatup events, there are four potential sources of fission product release from the fuel:

a) heavy metal contamination outside the fuel particle coatings resulting from the manufacturing process,

b) fission products in already failed fuel which are driven out by the heatup,

c) heatup induced failures of the particle coating, and

d) diffusion (especially of metallic fission products) through intact coatings at high temperatures.

In conventional HTGR designs, item (c) is the dominant source for extreme accident conditions. However, for inherently safe modular HTRs, the peak fuel temperature under accident conditions is estimated to be no greater than about 1600°C. For this peak temperature, it is anticipated that item (c) will be greatly reduced; in addition, items (b) and (d) would also be reduced. Further, it is expected that releases from sources (a) and (b) can be reduced, if necessary, by adopting tighter fabrication and quality assurance (Q/A) standards. The above will influence the final selection of the acceptable peak fuel temperature under postulated accident conditions.

4.3 Accident Behavior

The predicted response of the maximum core temperatures during a depressurized core heatup accident with loss of main loop cooling is shown in Fig. 6 for this example concept. Note that the peak fuel

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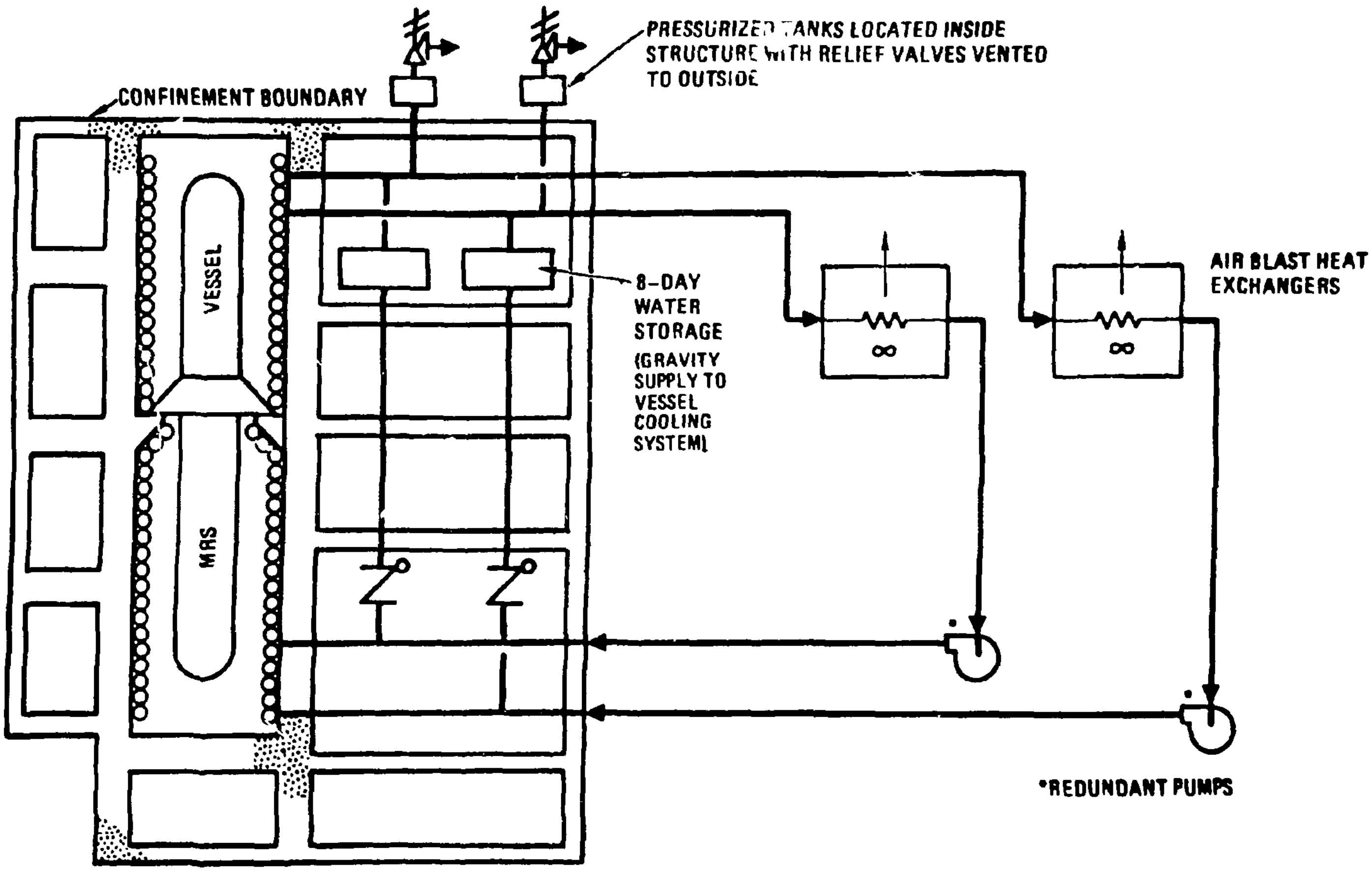

Fig. 5. Vessel cooling system with capability for passive operation.

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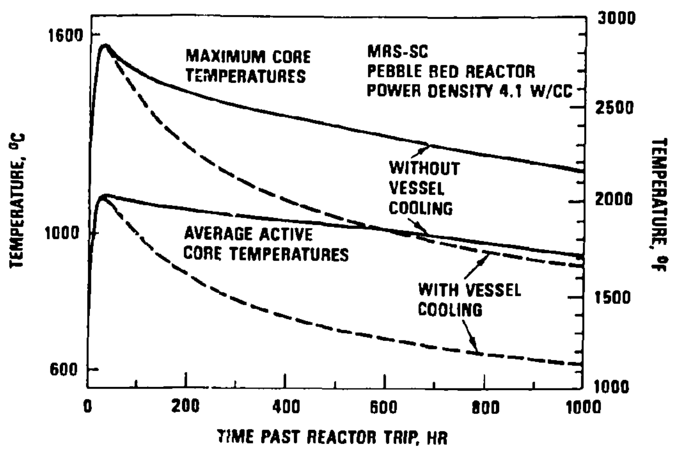

Fig. 6. Core temperatures for a 250-MW(t) modular HTR during a depressurized core heatup accident.

temperature remains below 1600°C. For the case assuming complete failure of the vessel cooling system, the peak fuel temperature is in fact no higher. However, without the vessel cooling system the reactor vessel would reach a temperature which would result in permanent damage to the pressure vessel. Thus, the vessel cooling system primarily provides investment protection. Operation of the vessel cooling system for about two weeks following the accident assures that component damage would not result even if the vessel cooling system subsequently failed.

Some of the inherent safety features of the modular HTR have actually been safely demonstrated in the AVR, where tests have been performed involving termination of forced circulation without scram.[4] In one such test both circulators were intentionally stopped with the reactor at full power and all control rods locked out of the core. The reactor quickly went subcritical due to the increasing fuel temperature and the negative temperature coefficient. Heat was removed by natural convection to the steam generator with its feedwater cooling sustained at a low rate, by a vessel cooler*, and by radiation from the outer vessel wall. Later, the reactor again went critical due to xenon decay and decreasing temperatures, with the power peaking at ~4% of full power and

*A cooling system which cools a biological shield between the inner and outer vessels of the AVR.

then stabilizing at less than 1%. The experiment was terminated by inserting the control rods. From temperature measurements in graphite regions which protrude into the core, it was inferred that the maximum fuel temperature increased only 65°C, thereby limiting the maximum fuel temperature to ~1200—1250°C. For modular HTR concepts presently being considered, the transient peak fuel temperature is expected to go higher than 1250°C primarily because of the higher core power density (4.1 W/cc vs. 2.5 W/cc for the AVR) and the higher power level [250 MW(t) vs. 45 MW(t)].

4.4 Economic Performance

At this early stage of concept development, accurate plant cost estimates and economic evaluations cannot be made. However, modular HTRs having a high degree of inherent safety should involve fewer nuclear grade facilities than are required by conventional large HTGRs (for example, a confinement rather than containment and no AHS) and emphasize shop fabrication (for example, components, reactor pressure vessel and internals). Because of the inherent safety features of this example concept, it is possible that the entire turbine plant, the waste heat rejection system, portions of the electrical plant, and miscellaneous structures could be constructed to fossil plant standards and installed at the lower labor installation rates typical of fossil power plants. This follows since capital investment cost estimates for the nuclear part of a plant generally reflect nuclear standards for design, procurement, and construction and the influence of nuclear plant safety-related quality assurance and quality control regulations and requirements; at the same time and in contrast, the capital investment cost estimates are much lower for construction practices which reflect conventional fossil power plant codes and standards.

Preliminary economic comparisons for this example modular HTR give a range of results (a specific result is shown, for example, in reference 5); these indicate that modular HTRs may have lifetime levelized busbar electric power generation costs about those of coal or lower for startup in the year 2005. These results indicate that modular HTRs might be economically attractive; however, there is uncertainty in such cost estimates.

5. SUMMARY

Results of studies to date indicate that HTR concepts can be developed such that radionuclide releases can be limited to levels that would preclude a need for emergency sheltering or evacuation of people, even during and following extreme accident conditions that assume loss of all active heat removal devices. Such HTR designs show promise of significantly reducing the amount of nuclear grade field construction required relative to that imposed on present nuclear plants. Overall cost results to date are very preliminary, but do indicate that this new approach may lead to HTR plants which are competitive with coal-fired plants. Further, there are a number of HTR concepts which exhibit a high degree of inherent safety, which might also be economic. Studies of these are continuing.

ACKNOWLEDGMENTS

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