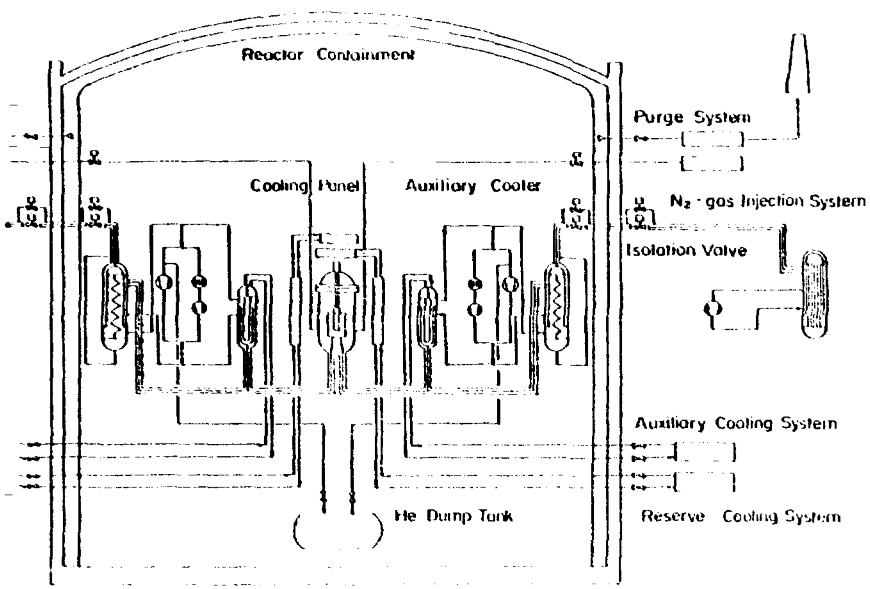

FIG. 10 ENGINEERED SAFETY SYSTEM OF EXP. VHTR

HTGR SAFETY PHILOSOPHY

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ABSTRACT

The accident at the Three Mile Island has focused public attention on reactor safety. Many public figures advocate a safer method of generating nuclear electricity for the second nuclear era in the U.S. The paper discusses the safety philosophy of a concept deemed suitable for this second nuclear era.

The HTGR, in the course of its evolution, included safety as a significant determinant in design philosophy. This is particularly evident in the design features which provide inherent safety. Inherent features cause releases from a wide spectrum of accident conditions to be low. Engineered features supplement inherent features. The significance of HTGR safety features is quantified and order-of-magnitude type of comparisons are made with alternative ways of generating electricity.

NUCLEAR SAFETY IN AFTERMATH OF TMI

The accident at the Three Mile Island nuclear plant has focused public attention on nuclear safety. The Kemeny Commission Report (Ref. 1) gave the light water reactor generally good marks for protecting the public. The regulatory apparatus, including how the Nuclear Regulatory Commission and the industry have performed, was sharply criticized but reform and not suspension of the nuclear option was the Commission's final recommendation. More attention to man-machine interfaces was clearly mandated. Before the Kemeny Report became public, the NRC and the utility industry had undertaken their own steps to assure that the lessons of the Three Mile Island accident would be fed back promptly to all nuclear utilities so that they could make design modifications and improve plant operating procedures. In June 1979, the TVA Board approved a declaration on atomic safety which can be viewed as a new national yardstick for public policy in this field. As a result of all this, the safety operating nuclear plants will certainly be improved, as will the safety of the 100,000 MW(e) of nuclear capacity now under construction.

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Three Mile Island has dramatized accident risk to the utility industry as well as to the general public. The affected utilities are having difficulty in coping with the financial impact of the accident, and it is apparent that greater consideration will be given to this aspect of nuclear power in the future. Many prominent public figures such as the first chairman of the AEC, David Lilienthal (Ref. 2), advocate a safer method of generating nuclear electricity. The second nuclear era is being mentioned with a target of, say, 1000 GW(e) of nuclear electricity.

These safety and financial concerns have prompted some discussion of the different safety characteristics (primarily inherent) of other reactors, notably gas-cooled reactors. e.g., Alvin Weinberg suggested (Ref. 3) that it might be wise to "....reopen the possibility of gas-cooled reactors..." because of those inherent safety features. This paper primarily discusses the safety philosophy of a concept deemed suitable for this second nuclear era.

ESSENTIAL HTGR FEATURES

Basic HTGR technology in the U.S. is exemplified by the proven operability of the Peach Bottom* and Fort St. Vrain** nuclear power plants.

The wealth of operating experience with the European CO_2 cooled reactors, which currently exceeds 600 reactor years, has been of considerable benefit in the development of high temperature gas-cooled reactors (HTGRs) in the U.S.. The HTGR, as typified by the design of commercial HTGRs sold and subsequently cancelled in 1970s, is distinguished from its European predecessors by the use of helium coolant and refractory, coated particle fuel imbedded in the graphite moderator.

KEY INHERENT SAFETY FEATURES

The emphasis in safety considerations throughout the design evolution of gas-cooled reactors has led to a high degree of inherent safety in the HTGR. The safety philosophy employed in the design of the HTGR is to utilize these inherent features as the first lines of defense in retaining the inventory of radioactivity and maintaining the integrity of the containment barriers. Over a wide spectrum of accident conditions postulated, the significance of each essential design features of the HTGR as it contributes to a high degree of inherent safety is illustrated in Table 1. Unique benefits are also derived by careful and optimized plant design.

*Peach Bottom was a 40 MW(e) HTGR plant operated by the Philadelphia Electric Company. It was shut down and decommissioned in 1974 after 7 years of successful operation.

**Fort St. Vrain is a 330 MW(e) HTGR plant being operated by the Public Service Company of Colorado.

Graphite Core with Refractory Fuel

The HTGR is constructed entirely of ceramic materials which maintain their integrity even at extreme temperatures. This contributes to large safety margins between normal operating temperatures and damage limits. The core structure weighs almost 3 million pounds, and the associated heat capacity together with a low power density insure that reactor temperature transients in response to disturbances proceed very gradually. The use of coated particle fuel imbedded in the core graphite gives rise to a capability to retain fission products even in the unexpected event of a sustained interruption in core cooling capability. The slow thermal response also provides for a more forgiving reactor since ample time is available to prevent transients from progressing into major accidents. In the extremely rare event that all means of core cooling are lost indefinitely, the inability of the core to melt down together with the remaining inherent features preclude the rapid release of large quantities of radioactivity.

Helium Primary Coolant

The most fundamental property of a gas such as helium, which is noncondensible over the whole range of temperatures encountered, is that it always totally occupies the space that it is in and, so confined, obeys one unique and linear temperature-pressure relationship. Because there is additionally no liquid-gas interface to be considered, a single unambiguous signal (pressure) always suffices to determine just where the coolant is. This most importantly implies that rapid depressurization can be accommodated without concern for such consequences as void formation, local core dry-out and cavitation of pumps, as would be the case with liquids confined at temperatures above their atmospheric boiling point.

The working pressure required for gas-cooled reactors is furthermore typically much below that needed to adequately pressurize a water coolant. This feature enables sufficient core cooling to be readily provided for the HTGR even at atmospheric pressure. In this sense, it can be claimed that HTGRs are immune to the so-called "Loss of Coolant Accident (LOCA), which obviates the need for coolant injection systems. Hence, it is only necessary to remove decay heat to provide adequate cooling, thereby simplifying the design of the cooling systems. These simplifications in the design requirements make it unnecessary for the operator to make quick decisions or to take prompt actions to maintain adequate cooling.

Another major benefit of helium is its inertness, which means that it cannot react chemically with other materials such as fuel cladding or core structural components. At Three Mile Island, the uncovering of the core and subsequent fuel cladding heat-up caused the zirconium-water chemical reaction that apparently resulted in damage to the fuel rods as well as the extensive liberation of hydrogen gas. The hydrogen bubble that formed complicated subsequent efforts to cool the core.

Prestressed Concrete Reactor Vessel

The HTGR utilizes a prestressed concrete reactor vessel (PCRV). This large passive structure encloses the entire primary coolant system, including the reactor core and all steam generation equipment. High strength in the PCRV is provided by redundant axial and circumferential steel tendons that prestress the concrete in compression so that cracks which might occur are self-sealing. The shielding afforded by the concrete prevents neutron embrittlement in the load-bearing tendons. Separation of the functions of sealing and load carrying is made possible with the use of a steel liner which is always in compression further limiting the possibilities for fault propagation. During postulated core heatup accidents, the PCRV retards the transport of fission products to the containment building and protects the containment from the degrading effects of reactor decay heat. These characteristics contribute to the long time scale of accident progression and provide for exceptional radioactivity retention.

ENGINEERED SAFETY FEATURES

In recognition of the potential for accident conditions that in some cases may reduce the effectiveness of some of the inherent features, engineered safety features are provided to further reduce the likelihood of accident situations developing and to help insure that even when such accidents occur, the consequences will fall within acceptable limits. The specific engineered features described below were selected for their compatibility with, and to fully exploit the benefits of, the inherent safety features of the HTGR.

In the engineering of the HTGR safety systems, it has also been the objective to exploit the simplicity of HTGR dynamics. This gives rise to an enhanced ability to predict how HTGR would behave during transient conditions and is a direct benefit of the large thermal inertia and homogeneity of the reactor core and the use of an inert single phase gas coolant. Enhanced predictability enables the design of the engineered safety systems to be kept simple and, hence, highly reliable. More importantly, the need for quick decisions and prompt actions in the face of uncertainty on the part of the reactor operator, is avoided. Hence, the inherent characteristics of the HTGR by virtue of enhanced predictability provide a "hands off" capability for the engineered safety systems in response to a wide spectrum of transients and accident conditions. These same features also enhance the ability of the control room operators to contribute to safe operation because they provide for unambiguous indication of the reactor status. Because of the simplicity and time scale of the reactor dynamic characteristics, the operator is better able to foresee how the system will behave in response to his control actions.

Key engineered features are described below.

Dedicated Decay Heat Removal System

The power conversion loops are able to remove decay heat under most accident conditions. However, the HTGR also has a dedicated, fully

redundant decay heat removal system which is separate from and independent of the power conversion system. This separation increases the resistance against common cause failures. Because of the inherent features of the HTGR and their predictability, the auxiliary cooling design is kept simple, is fully automatic and, hence, highly reliable. Its sole function is to remove reactor decay heat under the full range of operating conditions and design basis accident environments. There is no requirement to inject coolant since adequate heat removal can be obtained with the PCRV depressurized after a postulated leak in the primary system boundary. There is no ambiguity with regard to which cooling system can be operated at which temperature and pressure, etc.. As a result of the slow thermal response of the HTGR core, interruptions in core cooling system operation of several hours can be tolerated without damage to the fuel or release of radioactivity. This reparability feature contributes to a high degree of system reliability.

Additional Engineered Features

There are engineered safety features provided in the HTGR in addition to those provided for core heat removal. One is the provision for a secondary containment structure to prevent the release of any radioactivity which may escape the primary coolant boundary. This, of course, is not unique to HTGRs, but, because of the inherent features, its effectiveness in mitigating accident consequences is enhanced.

Although no chemical reactions can occur with helium, there is the possibility of graphite oxidation with air or moisture if present in the primary coolant either as impurities or as the result of postulated accident conditions. The potential for graphite oxidation was recognized early in the development of gas-cooled reactors and its safety implications in the HTGR have been minimized as the result of a defense-in-depth design philosophy.

Defense-in-depth is afforded by the use of helium in a closed cycle and an integral PCRV arrangement that encompasses the entire primary coolant system. The integral PCRV concept was introduced in the line of European gas-cooled reactors primarily to minimize the potential for air ingress following postulated leaks in pipes or ducts. In order to obtain significant quantities of air ingress with the PCRV, it is necessary to postulate either very large openings or multiple openings at different elevations, both of which require multiple structural failures which are extremely unlikely. Even for these extremely unlikely accidents, the potential for air inleakage is bounded by that inside the containment building which is insufficient to significantly affect accident consequences.

There are also possible accident scenarios that result in water inleakage to the primary coolant and hence, the potential for graphite oxidation by water. However, unlike the air reaction, the water-graphite reaction is endothermic. The engineered safety features provided for these scenarios include a moisture detection system, a steam generator isolation and dump system, and PCRV safety relief valves.

The HTGR engineered features include two redundant and diverse reactivity control systems each of which is independently capable of maintaining a cold subcritical condition in response to a wide spectrum of low probability accidents.

ENHANCED SAFETY FEATURES

The safety of the HTGR can be even further enhanced by virtue of careful safety optimization of the design. There are many combinations of added features that can be considered, and methods employing probabilistic risk assessment have been used to sort and judge these options. This allows a systemtematic ranking to be developed based on the projected frequencies and consequences of a variety of accidents and the effect on those accidents of the inclusion of design options. Other judgments that are more difficult to quantify are also included in this process, and the costs of options receive preliminary examination. The ranking study utilizes the design concept configurations, and it, therefore, provides insights regarding desirable approaches to the conceptual designs of the systems. Three enhanced features are of greatest interest. It should be pointed out that these features have not yet been fully engineered and factored into a reference design.

Natural Convection

Although the present method of removing decay heat from the reactor core involves forced circulation by the power conversion or auxiliary cooling loops, the HTGR system can be designed to reject its heat in a natural convection mode such that core overheating and associated plant damage would not occur even in the unlikely event of failure of all main and auxiliary loops or loss of their power supplies. Moreover, the complications associated with a two phase coolant that can negate the effectiveness of natural convection through the core such as experienced at TMI are removed so long as an adequate helium inventory is maintained. there is also a higher level of confidence that the conditions necessary for natural convection can be achieved without the need for the operator intervention because of the enhanced predictability and simplicity of reactor coolant dynamics alluded to earlier. Because neither the fuel nor other reactor components are damaged when the cooling systems are operated in this mode, natural convection enhances the protection of plant investment as well as the safety of the public.

Liner Cooling

The PCRV liner cooling system offers an ultimate heat sink for the residual heat for extremely remote accident scenarios when both forced and natural circulation are unavailable. The liner cooling system can be designed to insure the structural integrity of the PCRV and containment, thereby protecting public safety without the need for evacuation. This provision was included in the Fort St. Vrain design.

PCRV Depressurization

Another option is the ability to reduce PCRV helium pressure rapidly through a purification train. This could prevent the lifting of PCRV safety valves in the rare event of core heatup when the liner cooling system was working through the cooling loops were not. It could also prevent a large loss of primary helium from the PCRV in the event of a small uncontrolled leak. These actions prevent or reduce contamination of the containment which greatly eases clean-up. This provision was included in the Fort St. Vrain design.

ADVANCED CONCEPTS

In recent years, considerable interest has evolved in the application of the HTGR to direct and indirect cycle gas turbo-generators, process heat and process steam/cogeneration concepts. The nuclear side of the process steam/cogeneration HTGR plant is very similar to the steam cycle plant which has already been discussed. The gas turbo-generator and process heat applications, however, have several unique characteristics as well as higher core operating temperatures than the steam cycle plant.

In the direct cycle concept, the turbomachine (turbine and compressor) are positioned with the PCRV in cavities located below the core. In this application, the turbogenerator shaft passes through the primary coolant boundary. In both the indirect cycle and process heat concepts, a secondary helium loop is utilized with an intermediate loop heat exchanger (IHX) positioned within the PCRV. Secondary helium coolant ingresses and egresses from the IHX through code penetration closures.

The safety philosophy for these advanced concepts follows the basic philosophy of placing primary reliance on inherent and/or passive safety features of the HTGR that are common to all of the concepts mentioned above. Helium gas is used to cool the graphite core in all of the advanced concepts. In all cases, coated fuel particles are used and the entire primary coolant system is enclosed within a PCRV. A secondary containment building surrounds the PCRV in each case. In addition, engineered safety systems such as the core auxiliary cooling system and the reserve shutdown system are provided in each concept. The gas turbine concepts contains additional features such as the turbomachine overspeed control system, the internal pressure relief system, and the precooler isolation and dump system. For the process heat concepts, an external pressure relief system and a system which automatically isolates the secondary loops in response to low pressure or high radioactivity levels have been proposed. A detailed philosophy for engineered features is still evolving. It is obvious that such a philosophy will exhibit the same approach as that developed for the steam cycle.

QUANTIFICATION OF SAFETY

The significance of HTGR safety features, primarily inherent ones, has been recognized for some time on the basis of predominantly qualitative considerations such as those discussed above. However, only within the last several years has there been an appropriate yardstick developed with which to quantify their safety significance in a manner that lends itself to direct comparisons with the energy alternatives, particularly the light-water reactor and coal. Such a yardstick is provided by probabilistic risk assessment, a systematic approach for the delineation and quantification of the risks associated with technology or an activity. Although much remains to be learned about the public health and safety and investment protection aspects of alternative energy sources, a great deal of effort has already been invested in quantifying the risks associated with the LWR and the HTGR as well as non-nuclear alternatives, especially coal.

On the basis of the risk information currently available (Refs. 4,5,6), order of magnitude type of comparisons can be made among the alternatives such as those presented in Table 2. The figure of merit used here is the relative number of fatalities (early and latent) per unit-year of operation normalized to the current generation LWRs selected as a base for comparison. The contribution to this index from accidents is computed as the product of the accident frequency and its consequences. It is important to recognize, however, that the nature of the risk from burning coal is different than that of nuclear. The indicated fatalities from coal are the result of air pollution and accrue on a continual basis. Those from nuclear come from low probability power plant accidents and accrue on a random basis. Even when a reasonable account is made of this distinction by placing more importance on low probability, high consequence events, it is extremely difficult to avoid the conclusion that both nuclear options discussed are safer than coal.

The comparison between the HTGR and LWRs is more direct because the nature of the risks are the same and the estimates are obtained with, by and large, comparable methods and data. The exceptional safety margin enjoyed by the HTGR over the alternatives can be largely attributed to its inherent safety features. The consequences of accidents, for the same frequencies, are much lower for HTGRs. The enhanced safety features make the core heatup events for an HTGR even less likely to occur.

QUANTITATIVE SAFETY GOALS

Quantitative safety goals are being studied in the U.S. and in Europe. As they become better developed, they may provide the quantitative derivation or rationale for defining how safe is safe enough. Present trends in this development are to utilize PRA methodology, and more standardization of the methodology may become established as a result. This advancement in the approach to safety will be advantageous to the endeavor of nuclear power and should clarify the merit of various design options and comparison of reactor concepts. GA's contribution in that field is exemplified by the statement before the ACRS subcommittee on reliability and probabilistic assessment (Ref. 7).

CONCLUSIONS

The HTGR has, in the course of its evolution, included safety as a significant determinant in design philosophy. This is particularly evident in the design features which provide inherent safety: the graphite core with imbedded fuel particles, the helium coolant, and the prestressed concrete reactor vessel which contains all primary coolant ducts as well as the core and steam generators. These features cause releases from a wide spectrum of severe accidents to be low. Engineered features supplement inherent features. The engineered safety feature for decay heat removal, the core auxiliary cooling system, is designed to be separate from the power conversion loops, and redundant. The resistance of the auxiliary loops to common mode failures is therefore high, and that coupled with good predictability of performance and automatic actuation yield a very reliable system.

In the future, additional features such as natural convection cooling loops may reduce even further the possibility of core heatup thereby improving both safety and investment protection. This could also provide even more assurance that there was much margin being designed into the plant. A summary of the characteristics of such an advanced plant is given in Table 3.

The significance of HTGR safety features has been quantified and order-of-magnitude type of comparisons against alternative ways of generating electro power demonstrate major improvements in public safety.

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Inherent Feature	Relevant Properties	Safety Significance
Coated particle fuel	o Ceramic material	o Maintains integrity at very high temperatures.
	o Small diameter	o Small temperature rise across fuel.
	o Multiple "pressure vessels"	o High retention of radioactivity; slow controlled release under no cooling conditions.
Graphite core	o High heat capacity/low power density	o Slow response to temperature transients, ample time for prevention and mitigation of accidents.
	o Does not melt	o No "China Syndrome" type of considerations.
	o Ceramic material	o Maintains strength at very high temperatures.
Helium coolant	o Single phase	o No boiling, bubbles, liquid level or pump cavitation, coolant injection systems not required.
	o Neutronically inert	o No reactivity effects.
	o Chemically inert	o No chemical reactions with fuel or other reactor components.
	o Low stored energy	o Enhanced containment effectiveness, need for containment heat removal system.
PCRV and associated liner	o Structurally redundant	o High level of integrity (failure of individual structural measures inconsequential).
	o Concrete cooling requirement	o Independent heat removal capability.
	o Massive robust structure	o High retention of radioactivity, massive containment heat barrier.
	o Integral arrangement	o Primary system pipe/duct ruptures eliminated.
		o Air ingress potential limited to containment volume.

Table 1 Safety significance of key inherent features

Coal	1300.
Current LWR Plants*	1.0
HTGR**	0.0002

*Per WASH-1400 estimate.

**Effect of HTGR enhanced safety improvements discussed in this paper not included.

A relative comparison of risks from alternative sources of generating electricity per unit output.

Table 2

Desirable Safety Objectives	Corresponding Characteristics
Ample time to influence progression of reactor transients.	o Large graphite core with low power density. o Refractory coated particle fuel embedded in graphite. o Massive PCRV between core and containment
Simplicity, stability, and predictability of reactor dynamics.	o Single phase, inert gas coolant. o Homogeneous core with practicable geometry (no meltdown). o Negative temperature coefficient of reactivity.
Highly reliable reactivity control capability.	o Automatic reactivity control system. o Back-up system for reactivity control.
Highly reliable reactor cooldown capability.	o In-house electrical generation and rundown on power conversion loops. o Hands off, automatic, dedicated decay heat removal system. o Passive natural convection heat removal capability.
No need for evacuation even for core heatup scenarios, retention of fission product gases.	o PCRV liner cooling system capability to enhance survival. o Helium purification train capability to prevent opening of PCRV relief valves. o Inherently low consequences because of inherent safety features.

Table 3 Enhanced safety HTGR characteristics