Possible new developments based on HTGR technology and operating experience

Valuable experience has been gained through the Federal Republic of Germany's programme

by R. Schulten

The completely ceramic fuel elements used in high-temperature gas-cooled reactors (HTGR) can withstand very high temperatures without releasing fission products. They can be arranged in low-power density reactor core configurations which, solely by physical processes, limit both the rate of increase in temperature and the maximum temperature reached during the removal of decay heat. These basic characteristics, verified by an extensive development programme and operating experiences of HTGRs, enable an entirely new safety concept: one in which the fuel element itself becomes the containment, capable of retaining fission products during even the most severe hypothetical accidents.

Utilization of this new safety concept permits the design of simpler power plants that exclude major damage, are easier to understand, can be built, at least for the major part, by developing countries, and can be operated and maintained with confidence by them.

HTGR operating experience in the Federal Republic of Germany

The operation of two high-temperature reactors (HTR) in the Federal Republic of Germany, AVR (Arbeitsgemeinschaft Versuchsreaktoren) and THTR (Thorium-Hochtemperatur-Reaktor), together with an extensive development programme, have contributed significantly to the understanding of HTGR technology.

The AVR operated for 20 years, generating a power of 50 megawatts-thermal (MWth). Its goal was the demonstration of the feasibility and the operation of a reactor with spherical fuel elements at high temperatures. During this time several different fuel elements were tested, in part for the thorium-uranium fuel cycle and in part for the low-enrichment uranium cycle. For most of its operation time, the core outlet gas temperature was 950 degrees Celsius. The quality of the fuel elements increased year by year. The contamination of the helium circuit was extremely low. All components functioned without noticeable failures.

The strong negative temperature coefficient provided proof that all operational and accidental situations could be handled even without control rods, if necessary. Control of the reactor was largely performed using the effect of the negative temperature coefficient on reactivity.

Several particular questions referring to operation were investigated. These included the ability to maintain CO, H_2 and CH_4 contamination levels of the helium circuit to low levels, which is important to avoid corrosion. During normal operation, water and steam leakage of the steam generator were kept sufficiently low. A single big leak of the steam generator, which occurred after a rupture of one tube, was mastered without damage. After removing the water and sealing the tube, the reactor was operated again without any loss of power.

Continuous refuelling by adding and removing the pebble fuel elements under power was performed flawlessly after some repairs of the fuelling system. In 20 years, a total of almost two million fuel elements were used. The rate of damage to the fuel elements was negligible.

The same applies to the amount of dust in the primary circuit. Important knowledge of the behaviour of fission products was gained. Important research was performed on the desorption and absorption of various fission products in graphite. It was also shown that fuel elements with high burnup (100 000 MWd/t) had negligible fission product release when heated up to 1600 degrees Celsius. It should also be mentioned that safety experiments at AVR proved that, in case of a failure of both the cooling system and the nuclear control systems, the reactor was stabilized solely by the negative temperature coefficient and the decay heat was removed by conduction and radiation without doing any damage to the reactor. After these experiments, the reactor was operational again after a few days.

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The THTR power plant, which has an output of 300 MWe, and has been in operation since 1985, has continued to confirm the excellent characteristics of HTGR technology. A low level of fission product release has led to several positive effects, including a low collective dose for the operating and maintenance personnel. All calculated physical and technical data have been confirmed.

Two particular mechanical problems arose during early operation. The causes were easily recognized. The first problem was a higher than expected damage rate of the initial load of fuel elements. This was determined to have been caused by an overly dense packing of the initial load since personnel were permitted to stand and walk around on top of the core during the initial loading. Moreover, several tests were performed involving pushing the shutdown rods into the densely packed bed. Continuous cycling of the fuel has removed most of the damaged fuel and loosened the bed to a lower overall density. The damage rate has gradually decreased to expected levels. The other mechanical problem related to a reduced pebble element discharge rate as the power level of the reactor was increased. The problem was fixed by mechanically incorporating a bypass flow system in the discharge pipe. The recently discovered damaged bolts retaining the insulation system in the hot gas ducts between the reactor and the steam generators have not impeded the orderly performance of the reactor, and none of the above problems has an impact on the attractiveness of the basic HTGR technology.

The HTGR safety concept

Safety systems of conventional nuclear power plants are composed of a sensible combination of active and passive systems. Active systems are driven by an interaction of sensors, control devices, actuators, and the provision of energy. They require high-quality standards for manufacturing an operation. Passive systems do not require extremely precise construction and surveillance. Most desirable are those passive systems that work on the basis of natural laws. Thus, future safety technology will try to employ such systems as much as possible to avoid accidents.

HTGR technology has achieved this situation even for accidents that surpass the design basis accidents. Due to the high heat capacity of HTGRs, temperatures rise very slowly. As a result, active countermeasures are not required immediately after an accident. Maximum temperatures can be restricted to avoid any fission product release.

Can HTGR safety be realized in its full extent by passive means? Today's knowledge and expectations permit this conclusion. The main objective of safety measures is to avoid the release of dangerous amounts of fission products by limiting fuel element temperatures to harmless levels and to avoid corrosion. Reasons for these effects can be an increase in reactivity, decay heat, and corrosion with steam or air. As long as the fuel elements are shielded sufficiently against these effects, the surroundings of the plant cannot be harmed.

If low-enriched uranium (LEU) fuel is employed, increases in reactivity resulting in increase in temperature cannot stress the fuel. All increases in reactivity, including those that are due to steam leakage, are compensated for by the negative temperature reactivity coefficient, without having to rely on the nuclear shutdown system. Hence, reactivity accidents cannot lead to harmful increases in temperature which damage the fuel elements causing release of fission products. This counteracting effect is based on physical laws and acts passively.

The use of LEU leads to several further advantages. For instance, in case of steam leakage into the primary circuit, the change in reactivity can be kept to a minimum by choosing the right moderation ratio. The fuel cycle was changed from high-enriched uranium/thorium to LEU some years ago. At that time, it became apparent that the supply situation for uranium would render a thorium-high conversion ratio-cycle uneconomic, since it entails recycling. If LEU is used, uranium can be exploited to the same extent as it is in a light-water reactor with recycling. Moreover, immediate deposition of the fuel in a spent fuel depository without refabrication is possible and economically sensible; the ceramic coating of the fuel is a sufficient barrier against the release of fission products.

In the case of failure of the cooling system, fuel element decay heat is also overcome passively and by physical laws. The combination of heat capacity, heat transfer, and core configuration can be chosen with respect to the power output, so that a certain maximum temperature is not exceeded. Again, the release of fission products can be restrained sufficiently.

Furthermore, fuel element corrosion due to possible steam or water leakage into the core has been thoroughly analysed. As mentioned above, the increase of reactivity in this case can be controlled by choosing the moderation ratio. As a result, this accident can also be controlled without using the nuclear shutdown systems. Since all events during this kind of leakage accident take place in the range of one hour, and since during this time fuel element temperatures are not much different from normal operating temperatures, the resulting corrosion is minor and unimportant, and does not lead to the release of major amounts of radioactive fission products. Corrosion with air is possible only after a pressure loss, i.e., a loss of the coolant, resulting in an equilibrium of internal and external pressure. In this case, diffusion and natural convection will transport air into the reactor vessel, limited by a maximum cross-sectional flow area, which is always small. The result would be a slow corrosion of the fuel element surfaces. This would not lead to major damage to the core, since the air intake would be low. The maximum area of the leak is determined by the base-security of the steel vessels, pre-stressed concrete, or cast steel vessels. A state-of-the-art safety system for a small HTGR is based on only two passive components: the reliability of fuel elements at high temperatures, and the reactor's vessel that contains the primary circuit.

Now it becomes apparent that the safety technology of HTGRs could possibly be even more simplified and made more obvious. Fuel elements could be sealed or impregnated with silicon-carbon (SiC), rendering them inert to corrosion. Corrosion rates during accidents with water or air intake into the primary circuit, although already low, as just discussed, could then be made negligible. In these cases, even the integrity of the reactor vessel might not be crucial for safety; instead, the fuel elements themselves would take over the function of a safety barrier in all accidents. All reactor components, including control systems and personnel, would then serve only for the purpose of availability, their importance for safety being only minor. With such a concept, an even greater simplicity of nuclear power plants could possibly be achieved. The high-quality standards for manufacturing and surveillance of components, which were necessary up to now, could be greatly reduced. At the same time, using the fuel elements as a barrier against severe accidents is a simple and pragmatic way of avoiding severe effects. The concept would significantly reduce the costs for nuclear power plants.

The addition of SiC protection might also make it possible to eliminate an intermediate circuit since, in case of a tube rupture, the core would be sufficiently protected against corrosion to withstand steam or air intake. The same would apply to the use of gas turbines in a direct circuit, which would provide the most effective exploitation of energy for co-generation.

The described safety concept that masters reactivity accidents by means of the negative temperature coefficient, decay heat removal by conduction and radiation, as well as prevention of corrosive processes by SiC protection, could also be employed for more powerful reactors. In this case, the surface of the reactor core has to be sufficiently large compared to its volume. This could be achieved by different geometric configurations. One variation which is especially suitable for this purpose is a torus-shaped core. For example, a torus with a diameter of 16 metres, a height of eight metres, a width of two metres and a power density of three megawatts per cubic metre would allow a power in the range of 1000 MWe.

The containment of this torus could be either a prestressed concrete vessel or a pre-stressed vessel of cast steel blocks. The technology of such vessels is widely known. A scaled-down (1:10) pre-stressed vessel of cast steel blocks has been tested. These vessels are sealed by welded joints at the edges of each block, which have proved good in experiments. Operating temperatures can be as high as 300 degrees Celsius. The helium flowing back to the reactor, which has contact with and cools the inner surface of the vessel, has a temperature of 250–270 degrees Celsius. The steel blocks can be manufactured using conventional technologies. They can be prefabricated and transported to the site where they are assembled, pre-stressed, and welded. Thus, the safety features of the small modular reactors could be applied to torus reactors, in order to create bigger reactors.

The application of nuclear process heat

In the past, the main objective of nuclear power was to replace fossil energy resources used for the generation of electrical power. In the future, this replacement will be more and more important to minimize the output of CO_2 and protect the atmosphere. So far, mainly industrialized countries have been building and using nuclear power plants whereas, in the future, developing countries are also going to need this technology. However, its use for the generation of electrical power alone will probably be insufficient to achieve the necessary reduction of CO_2. Heat, as well as the refinement of fossil fuels into less polluting fuels can — and probably must — be an application of nuclear energy. Up to now, the higher temperatures required for such applications are not limited by the core but much more by the hot gas ducts and the heat exchangers. Given the speed of advances in materials sciences, most of all in ceramic materials, it seems likely that very soon, technology will permit much higher temperatures than we can handle today.

Conclusions

The worldwide economic energy system needs simple, economical nuclear power plants which are easy to build and incorporate safety concepts which exclude the possibility of major damage. Simplicity is mandatory to ensure worldwide financing of power plant construction and the capability of manufacturing components in developing countries. This can be realized most conveniently if most of the extensive safety systems of conventional nuclear power plants become superfluous and are replaced by passive safety features which do not demand precision and are more suitable for these countries.

The world's need for increasing quantities of energy, coupled with the concerns over the environmental impact of burning fossil fuels to provide this energy, demands that nuclear power begins to provide an increasing share of future needs. HTGR technology, by virtue of the unique safety concept that has evolved, the simplicity of designs that can, as a result, be developed, and the broad applicability contemplated, appears to be ideally suited to contribute significantly to this need.