8. CONCLUSIONS

The investigation of fundamental characteristics of HTGR fuel has been in progress for 30 years. All of the HTGR reference concepts from Member States utilize fuel based on the TRISO coated fuel particle with low-enriched uranium. Two specific directions for the fuel element design have been pursued, the block type in Japan and the USA, and the spherical fuel element in Germany, Russia, and China. A key design requirement in obtaining the significant safety and radiological cleanliness of the modern HTGR is the utilization of high quality fuel. High quality was first achieved in the manufacturing of the coated fuel particle in the early 1980s. Improvements since this time have consisted of steps to reduce TRISO particle defects during fuel element fabrication and in minimizing uranium contamination in these elements. Another important aspect was the development of sensitive quality control methods such as the burn-leach technique which provides the data necessary to confirm that the fuel meets the design limit of less than $6*10^{-5}$ free uranium as arising from particle defects. Now, with newer data, this design limit can be further reduced to $3*10^{-5}$ free uranium.

The main source of fission products escaping the fuel under normal operating conditions is from uranium outside of an intact SiC layer which appears as heavy metal contamination in the fuel element matrix or as defective/failed fuel particles. There are several mechanisms which can cause a particle to fail: kernel migration, interaction of fission products with the SiC, failure of the coating as a pressure vessel, and excessive diffusion through the fuel coating layers. These failure mechanisms only exist under extreme operating conditions which result in large temperature gradients within the particle or for fuel particles manufactured outside of the specification limits. The release of fission products is primarily modeled based on diffusive transport as the key phenomena. The release of short-lived gaseous fission products from a particle kernel can be analytically determined by applying the Booth formula describing the release rate over birth rate, R/B, as a function of diffusivity and decay constant.

The performance of German high quality fuel has been tested in irradiation experiments which included a total of 19 spherical fuel elements and 276,680 TRISO particles. Gas release analysis has shown that in no single case was a particle failure caused during irradiation. The statistical derivation for the operationally related failed particle fraction in the HTR-MODUL core has been determined as $4*10^{-6}$ as the expected value and $2*10^{-5}$ as the design value.

Irradiation performance of the fuel rods contained in a cylindrical graphite block for development of the prismatic block fuel has been tested in the OGL-1 gas loop. Approximately 30 fuel rods with a total of more than 500 fuel compacts have been tested in Japan in a series of 15 experiments. The results of these tests provided comprehensive performance data on aspects such as fission gas release (R/B), metallic fission product behavior, fuel compact behavior, coated particle performance, fuel rod mechanical stability, and fission product plateout in the loop. The fuel fabrication process has steadily improved throughout the OGL-1 experiments with recent fuel quality irradiation R/B performance of less than 10^{-6}, which is significantly lower than the design limit, $5*10^{-4}$.

In Russia, the feasibility of the use of "weak" irradiation ("weak" irradiation means short irradiation at room temperature) for obtaining constants necessary for the prediction of fission product release from the fuel elements during HTGR operation has been justified. In parallel, analytical methods of predicting fission product release from fuel elements have been developed. It has been shown that the reference fuel elements with nominal burnups up to ≈ 12 %FIMA provide fission product retention during normal operation and under accident conditions.

Fuel testing under off-normal non-oxidizing conditions has provided fuel performance information as a function of fuel temperature up to 2500 °C. Compared to other reactor systems, it is easy to examine coated particles, or even fuel elements (spheres, compacts) containing a large number of particles under extreme accident conditions. Heating experiments with half a million particles were performed in Germany up to core heatup temperatures of the HTR-MODUL (1620 °C) and a maximum burnup of about 9 %FIMA. Applications in future licensing procedures can be based on one coated particle failure in four fuel elements and no additional release of saftey relevant fission products, especially iodine. Japanese heatup simulation tests with batches of 100 particles showed similarly good results. Fission product release and failure fraction during heatup can be predicted by calculations with the national models. During ramp tests (Germany, Japan, Russia, USA), silicon carbide decomposition at temperatures beyond 2000 °C leads to an increase of particle failure and subsequent fission product release.

During irradiation at very high temperatures with compacts (Japan) between 1500 and 2000 °C, particle failure was only detected at 2000 °C. Reactivity tests under pulse irradiation conditions (Japan, Russia) showed that coating failure increases with the amount of energy deposition starting from 600 J/(g UO_2).

Among the postulated accidents in gas-cooled reactors are those of water and air ingress. These accidents involving oxidation of exposed fuel kernels, carbonaceous materials, SiC and ZrC, can lead to an enhanced release of fission products and to a degradation of core components. In water ingress accidents, the interaction of exposed kernels with water vapor resulted in a significant increase in the release of fission products. No effects of the concomitant interaction of water vapor with intact fuel particles were indicated.

Three irradiation experiments, HRB-17/-18 and HFR-B1, have been conducted with the deliberate introduction of water vapor. The fuel particles contained UO_2 and a known small portion had exposed kernels. A series of discrete tests was conducted with water vapor at partial pressures in the range 0.003 to 2 kPa. The released fission gas was monitored for the isotopes Kr-85m, Kr-87, Kr-88, Xe-133, Xe-135, and Xe-138. The general sequential response of the exposed fuel kernels to water vapor consists of three stages: (1) a rapid transient release of fission gas with a concomitant increase in the steady state release, (2) a period of constant steady state release, and (3) a decline in the release to prehydrolysis values upon cessation of water vapor injection. In German experiments, a significant release of the water vapor induced Kr-85 release with higher burnup was measured for irradiation experiment HFR-K6 with low enriched UO_2 fuel and for postirradiation heating tests.

Numerous experimental and theoretical efforts have been made to examine plateout distribution of fission products in the primary circuit both under normal operating and accident conditions. In-pile and out-of-pile deposition loops were operated in Germany (LAMINAR, VAMPYR-I and -II, SMOC), Japan (OGL-1), France (SAPHIR, COMEDIE), the UK (Dragon), and the USA (GA deposition loop, CPL-2 tests) to study systematically the ad-/desorption behavior of fission product on metallic surfaces as function of temperature and gas flow. The obtained experimental data as well as the measurements from the gas-cooled reactors AVR, THTR-300, Peach Bottom, Fort St. Vrain were taken to derive plateout parameters such as desorption energy or penetration coefficient to be used in corresponding calculation models for validation purposes.

Remobilization of fission products deposited in the primary circuit occurs during accident sequences by desorption due to flow change induced by temperature increase and/or system pressure drop by liftoff of dust-borne activities. Transient experiments in different countries showed an increase of the gas-borne dust by up to three orders of magnitude. Computer models were developed to calculate liftoff fractions. Various tube samples have been taken from deposition experiments to investigate the removal of cesium and iodine from metal surfaces by washoff and steamoff in leaching experiments at ORNL and at KFA Jülich. It was determined that accessible fission products are released in water ingress accidents through dissolution and chemical attack.

The decontamination of primary circuit components from plated-out activity is an option to mitigate radiological hazards to plant workers which is of particular interest for direct-cycle gas turbine HTGRs. It is also used for decommissioning purposes. Different forms of surface activities (in-diffusion into oxide layer, adsorption on metallic surface, deposited dust) may require different methods of decontamination encompassing mechanical, chemical, or electrochemical processes. The material composition was found to be an important parameter. Most of the decontamination work was dedicated to LWR components and circuits. However, decontamination work on HTGR circulators was performed in Germany and in the USA.

The ZrC coating which is the most refractory material has several potential advantages compared to the conventional TRISO-coated fuel particles such as an enhanced capability for fission product retention at very high temperatures, realizing the core with a high power density, improvement of fuel properties in the fuel production due to enabling higher-temperature sintering of the green fuel compact. The United States, Japan, and Russia have developed the ZrC-coating layer for application in the coated particles to replace the SiC layer (ZrC-TRISO coated fuel particles), although several fuel designs with use of ZrC had been attempted besides this type of fuel in the United States. It was proven in Japanese and US postirradiation heating tests that the ZrC coating has an effective retention capability for cesium at very high temperatures. Other features are a strong chemical resistivity against palladium corrosion and an effective elimination of the amoeba effect as well as an excellent high temperature performance. As a result, in the case of extreme air or water ingress accidents, the ZrC layer does not provide protection against destructive oxidation of the layer. Use of a SiC layer outside the ZrC layer would provide protection against oxidation.

In conclusion, in modern HTGR fuel the level of defective coated particles during manufacture is practically zero. Only during manufacture of fuel bodies does particle failure occur, but on a very low level. In-pile fuel performance is demonstrated by irradiation testing under HTGR-typical operating conditions with no additional failure of particles. Accident behavior resulting from unrestricted core heatup is investigated by heating of irradiated fuels: at 1600 °C, all safety-relevant fission products are retained and only at 1800 °C and higher temperatures do particles start to fail excessively and to release fission products. Fission gases and iodine are only partially released from defective or failed particles. The level of release increases during water ingress. For licensing applications, a complete set of codes and data is available for predicting fission product behavior in-core and ex-core including plateout. Alternative advanced fuels are currently being evaluated for better coated particle fission product retention at extreme temperatures and for an inherent corrosive protection of fuel elements.